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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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PREDICTION OF CRUSHING EQUIPMENT PRODUCTIVITY AT MINING ENTERPRISES USING THE RANDOM FOREST ALGORITHM

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Abstract. Relevance. Stable operation of crushing equipment is important for the mining, coal, and construction materials industries, because a decrease in crusher productivity affects the performance of the entire crushing and screening circuit. Under real operating conditions, equipment productivity depends on the particle size and moisture content of the rock material, discharge gap width, feed stability, and electric motor load. Therefore, it is difficult to estimate productivity only by traditional engineering calculations. Insufficient forecasting of such changes can lead to time losses, excessive energy consumption, and a decrease

in the quality of the crushed product. *Objective.* The objective of this work was to assess the possibility of applying the random forest algorithm to predict the productivity of crushing equipment using a limited set of technological parameters that can be obtained in laboratory and industrial conditions. *Methods.* The study was carried out using a laboratory jaw crusher DShch 60×100. A vibrating screen, a set of sieves, electronic scales, a tachometer, current clamps, an infrared pyrometer, and Python-based data processing tools were used. A total of 72 experimental runs were performed at discharge gap widths of 5, 8, and 12 mm, with different material moisture levels and feed modes. The Random Forest Regressor algorithm was used to build the predictive model, while linear regression was applied for comparison. *Results and conclusions.* It was found that increasing the discharge gap from 5 to 12 mm increased the average productivity from 108.4 to 183.2 kg/h, but reduced the fraction below 5 mm from 61–66 % to 34–39 %. Increasing material moisture to 3–5 % reduced average productivity from 151.8 to 137.6 kg/h. The random forest model showed $R^2 = 0.86$, MAE = 9.7 kg/h, and RMSE = 12.4 kg/h, which was better than the linear regression model. The most significant predictors were discharge gap width, initial feed size, motor current, and material moisture. The obtained results demonstrate that a simple predictive model can be used for preliminary control of crushing equipment productivity.

Keywords: crushing equipment, mining enterprise, random forest, machine learning, productivity, jaw crusher, particle size distribution, predictive model

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КЕЗДЕЙСОҚ ОРМАН АЛГОРИТМІН ҚОЛДАНУ АРҚЫЛЫ ТАУ КЕН КӘСПОРЫНДАРЫНЫҢ ҰСАҚТАУ ЖАБДЫҚТАРЫНЫҢ ӨНІМДІЛІГІН БОЛЖАУ

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Аннотация. *Өзектілігі.* Ұсақтау жабдықтарының тұрақты жұмысы тау кен, көмір және құрылыс материалдары өнеркәсібі үшін үлкен маңызға ие, себебі ұсатқыш өнімділігінің төмендеуі бүкіл ұсақтау-сұрыптау кешенінің жұмысына әсер етеді. Нақты өндірістік жағдайда жабдық өнімділігі тау жынысының ірілігі мен ылғалдылығына, шығару саңылауының еніне, материал беру сипатына және электрқозғалтқыш жүктемесіне байланысты болады. Сондықтан оны тек дәстүрлі есептеу әдістерімен дәл бағалау әрқашан мүмкін емес. Мұндай өзгерістерді алдын ала болжаудың жеткіліксіздігі уақыт шығынына, энергияның артық жұмсалуына және дайын өнім сапасының төмендеуіне алып келуі мүмкін. *Мақсаты.* Жұмыстың мақсаты зертханалық және өндірістік жағдайда алынуы мүмкін шектеулі технологиялық параметрлер негізінде ұсақтау жабдықтарының өнімділігін болжау үшін кездейсоқ орман алгоритмін қолдану мүмкіндігін бағалау болды. *Әдістері.* Зерттеулер ДЩ 60×100 зертханалық жақты ұсатқышында жүргізілді. Жұмыста вибрациялық елек, електер жиынтығы, электрондық таразы, тахометр, ток қысқыштары, пирометр және Python ортасында деректерді өңдеу құралдары қолданылды. Шығару саңылауы 5, 8 және 12 мм болған кезде, материалдың әртүрлі ылғалдылығында және беру режимдерінде 72 тәжірибе орындалды. Болжамдық модель құру үшін Random Forest Regressor алгоритмі қолданылды, ал салыстыру үшін сызықтық регрессия моделі пайдаланылды. *Нәтижелер мен қорытындылар.* Шығару саңылауын 5 мм-ден 12 мм-ге дейін арттыру орташа өнімділікті 108,4-тен 183,2 кг/сағ дейін көбейтті, бірақ 5 мм-ден кіші фракция үлесін 61–66 %-дан 34–39 %-ға дейін төмендетті. Материал ылғалдылығының 3–5 %-ға дейін өсуі орташа өнімділікті 151,8-ден 137,6 кг/сағ дейін азайтты. Кездейсоқ орман моделі $R^2 = 0,86$, MAE = 9,7 кг/сағ және RMSE = 12,4 кг/сағ көрсетті, бұл сызықтық модель нәтижелерінен жақсы болды. Ең маңызды белгілер шығару саңылауының ені, бастапқы материал ірілігі, электрқозғалтқыш тогы және ылғалдылық болды. Алынған нәтижелер ұсақтау жабдықтарының өнімділігін алдын ала бақылау үшін қарапайым болжамдық модельді қолдануға болатынын көрсетеді.

Түйін сөздер: ұсақтау жабдығы, тау кен кәсіпорны, кездейсоқ орман,

машиналық оқыту, өнімділік, жақты ұсатқыш, гранулометриялық құрам, болжамдық модель

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ПРОГНОЗИРОВАНИЕ ПРОИЗВОДИТЕЛЬНОСТИ ДРОБИЛЬНОГО ОБОРУДОВАНИЯ ГОРНЫХ ПРЕДПРИЯТИЙ С ПРИМЕНЕНИЕМ АЛГОРИТМА СЛУЧАЙНОГО ЛЕСА

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Аннотация. *Актуальность.* Стабильная и эффективная работа дробильного оборудования имеет важное значение для горнодобывающей, угольной промышленности и производства строительных материалов, поскольку снижение производительности отдельных дробилок отрицательно сказывается на функционировании всего дробильно-сортировочного комплекса. В производственных условиях производительность оборудования зависит от совокупности технологических факторов, включая крупность и влажность исходной горной массы, ширину разгрузочной щели, режим подачи материала и нагрузку электродвигателя. Многофакторный характер этих зависимостей затрудняет прогнозирование производительности исключительно традиционными расчетными методами.

Недостаточная точность прогнозирования может приводить к увеличению простоев оборудования, дополнительным энергозатратам и ухудшению гранулометрических характеристик дробленого материала. *Цель.* Оценить возможности применения алгоритма случайного леса для прогнозирования производительности дробильного оборудования на основе ограниченного набора технологических параметров, измеряемых в лабораторных и производственных условиях. *Методы.* Экспериментальные исследования проведены на лабораторной щековой дробилке ДЩ 60 × 100 с использованием вибрационного грохота, набора сит, электронных весов, тахометра, токовых клещей и пирометра. Обработка экспериментальных данных и построение прогнозных моделей выполнялись в программной среде Python. Проведено 72 эксперимента при ширине разгрузочной щели 5, 8 и 12 мм, различных значениях влажности исходного материала и режимах его подачи. Для прогнозирования производительности использован алгоритм регрессии случайного леса (Random Forest Regressor). В качестве сравнительной модели применена линейная регрессия. Качество прогнозирования оценивали с использованием коэффициента детерминации (R^2), средней абсолютной ошибки (MAE) и корня из средней квадратичной ошибки (RMSE). *Результаты и выводы.* Установлено, что увеличение ширины разгрузочной щели с 5 до 12 мм сопровождалось повышением средней производительности щековой дробилки со 108,4 до 183,2 кг/ч. При этом доля фракции размером менее 5 мм уменьшилась с 61–66 до 34–39 %. Повышение влажности исходного материала до 3–5 % приводило к снижению средней производительности со 151,8 до 137,6 кг/ч. Прогнозная модель на основе алгоритма случайного леса продемонстрировала следующие показатели качества: $R^2 = 0,86$, MAE = 9,7 кг/ч и RMSE = 12,4 кг/ч, превзойдя по точности прогнозирования модель линейной регрессии. Наиболее значимыми признаками оказались ширина разгрузочной щели, крупность исходного материала, ток электродвигателя и влажность горной массы. Полученные результаты свидетельствуют о возможности применения алгоритма случайного леса для предварительного прогнозирования и оперативной оценки производительности дробильного оборудования с учетом изменения основных технологических параметров.

Ключевые слова: дробильное оборудование, горное предприятие, случайный лес, машинное обучение, производительность, щековая дробилка, гранулометрический состав, прогнозная модель.

Introduction. In modern global mining operations, the reliability of equipment performance is becoming increasingly critical, as the extraction and processing of mineral resources are no longer solely about maximizing output volumes. These operations are inextricably linked to energy consumption, environmental impact, production costs, and the enterprise's ability to maintain continuous operation without unplanned downtime. This is particularly evident at the crushing stage; since crushing equipment sits near the beginning of the processing chain, any

drop in performance below design specifications disrupts the downstream operation of screens, mills, and transport systems—and sometimes the entire crushing and screening complex. Amidst rising global demand for minerals and increasingly complex geological conditions, predicting crusher performance has evolved from a purely technical matter into a broader operational and economic issue. Consequently, mining enterprises are gradually shifting from conventional equipment monitoring to more intelligent data analysis, although in practice, this transition is often slow and fraught with challenges.

Crusher performance depends on a multitude of factors, making it difficult to capture with a single, simple formula. Key variables include the strength and moisture content of the rock mass, the particle size distribution of the feed material, the wear level of crushing components, feed rates, start-stop frequency, screening parameters, and the performance of associated equipment. Studies have shown that even design parameters for roll crushers require adjustment based on specific structural and operational conditions, as actual operating modes differ from laboratory or theoretical design parameters (Abramkin et al., 2023). Material particle size is also crucial, as changes in the size distribution of the crushed or ground product directly impact subsequent processing stages (Khetagurov et al., 2024). Therefore, predicting crusher performance cannot rely on a single metric—such as motor power or crusher load-alone; instead, it requires an assessment of a complex set of factors that collectively define the actual state of the process. Traditionally, engineering calculations, routine monitoring, operator experience, and the statistical analysis of production data are used to address this task. These approaches have distinct advantages: they are readily understood by specialists, do not require complex digital infrastructure, and can be implemented even at facilities with limited automation. For instance, calculation-based and design-oriented approaches are well-suited for equipment selection and capability assessment during the design phase. Developments in impact crushing methods also demonstrate that refining the material breakage principle itself can yield practical benefits and enhance processing efficiency (Matveev et al., 2025). However, a drawback of these methods is their frequent lack of flexibility regarding ongoing production operations; they often fail to account for random fluctuations in raw material properties or detect hidden dependencies, and typically do not provide advance warning of when productivity is likely to decline.

Another approach involves the implementation of technical diagnostics and equipment condition monitoring systems. This approach is already gaining significant traction in the energy, mechanical engineering, and mining sectors. For instance, vibration monitoring is employed to assess the condition of diesel engines and other industrial machinery, as vibration parameters often serve as reliable indicators of changes in the technical state of components (Afanaseva et al., 2025). Similarly, the analysis of compressor equipment places great emphasis on unit condition, reliability, and the advancement of diagnostic techniques (Afanaseva et al., 2026). This path is also promising for crushing equipment, as

parameters such as vibration, motor current, bearing temperature, and load can be correlated with changes in throughput. However, there are drawbacks: facilities may lack a comprehensive sensor suite, some data may be noisy or incomplete, and equipment parameters depend not only on the machinery's condition but also on the characteristics of the incoming mined material.

In recent years, machine learning methods have been increasingly adopted, enabling the construction of predictive models based on actual production data rather than relying solely on physical relationships. In geology and mining, these methods are already being used to predict rock properties, classify geophysical anomalies, assess the state of natural systems, and identify ore bodies (Kukartsev et al., 2026; Nurgaliyeva et al., 2026; Tynchenko et al., 2026; Dolgikh et al., 2025; Spanov et al., 2019; Osipova et al., 2024). This demonstrates the utility of machine learning in scenarios involving multiple factors and complex, non-obvious interdependencies. Multidimensional models of equipment productivity are also being developed in metallurgical manufacturing—an approach conceptually similar to predicting the performance of crushing complexes (Fastyskovsky et al., 2025). Yet, machine learning has its limitations; a model may perform poorly under changing conditions if it was trained on a limited dataset. Furthermore, the results can be difficult for engineering personnel to interpret, especially when complex neural network algorithms are employed.

Against this backdrop, the random forest algorithm stands out as a convenient and practical tool. Its advantages include the ability to account for non-linear relationships between parameters, robustness against certain types of data noise, and a lack of requirement for the rigorous feature engineering demanded by some other methods. Moreover, random forest enables the assessment of factor importance—a crucial aspect of engineering analysis, as enterprises need not only to generate forecasts but also to gain insight into which parameters most strongly influence productivity. In the context of modeling the reliability of mining operations, the need to employ mathematical and statistical models to assess the state of production systems has already been highlighted (Malozyomov et al., 2024). Similarly, issues regarding the controllability of mining equipment demonstrate that technical systems should be viewed not merely as a collection of individual machines, but as an interconnected structure where parameters influence one another (Shishkin et al., 2024).

Importantly, applying random forest to forecast the productivity of crushing equipment does not require the implementation of a massive digital system. The initial stage can simply involve addressing a specific, limited task: selecting a defined set of operational parameters, preparing a training dataset, and verifying whether the model can predict changes in the productivity of a crusher or crushing circuit. This approach is valuable because it allows an enterprise to determine—without significant investment—whether further development of digital monitoring holds practical merit. Similar digital modeling approaches are already being applied to rock grinding processes in ball mills, where modeling facilitates a

better understanding of material and equipment behavior (Chanturia et al., 2025). Furthermore, energy consumption forecasting demonstrates that operational data can be effectively used to predict the future operating modes of technical systems (Klyuev et al., 2022).

It is worth noting that the productivity of crushing equipment depends not only on the machine itself but also on the state of the surrounding production infrastructure. For instance, feed hoppers and transfer points influence material feed uniformity and crusher load, while changes in processing factors can even affect the material intensity and reliability of the crushing and transfer structures (Kardashin et al., 2025). Therefore, a predictive model must view productivity as the outcome of the interaction between multiple parameters. In a broader sense, this parallels challenges in materials science and construction technology, where the properties of the final material depend on composition, additives, and structural formation conditions (Klyuev et al., 2025; Petropavlovskaya et al., 2025). Even research into the use of industrial waste demonstrates that production systems often require the simultaneous consideration of multiple factors, rendering simple explanations insufficient (Klyuev et al., 2024).

The relevance of this area of study stems from the fact that crushing equipment is a key component of a mining operation; unstable performance leads to losses in time, energy, and the productivity of the entire complex. While many enterprises already possess data—collected either automatically or manually—this information is not always utilized for predictive purposes. The Random Forest algorithm offers a sufficiently interpretable intermediate tool bridging the gap between conventional statistics and complex neural network systems. Although it does not solve every problem at once, it enables a step toward more informed management of the crushing process. The objective of this study is to develop and conduct a preliminary evaluation of a productivity prediction model for mining crushing equipment based on the Random Forest algorithm, utilizing a limited set of operational parameters.

Materials and Methods. The experimental work was designed to test the feasibility of using a random forest algorithm to predict the performance of crushing equipment—not within a massive industrial system, but using a relatively small and manageable dataset. The study did not aim to provide a comprehensive description of every process within the crushing and screening complex, as such an undertaking would require long-term industrial monitoring and an extensive sensor network. The primary objective was to simulate conditions approximating those of a mining operation and, based on the resulting parameters, evaluate whether a machine learning method could anticipate changes in crusher performance. This approach holds industrial significance, as even an early forecast of a drop in performance could enable an operator to adjust the material feed rate or inspect the equipment proactively.

The experiments were conducted at a laboratory facility dedicated to the crushing and analysis of granular materials; the equipment configuration is typical

of a mid-to-high-tier technical university. The primary equipment included a DSh 60×100 laboratory jaw crusher, a GIL-052 vibrating screen, a set of sieves (with mesh sizes of 1, 2, 5, 10, and 20 mm), a VLTE-2100 electronic balance (0.01 g precision), a MASSA-K industrial scale (up to 30 kg capacity), an ShS-80 drying oven, an AT-6 digital tachometer, a Mastech MS2108A clamp meter, a CEM DT-8861 infrared pyrometer, and a laptop equipped with Microsoft Excel, Python 3.11, and the pandas, scikit-learn, and matplotlib libraries. As this equipment is not unique and is commonly found in educational or research laboratories, the proposed methodology can be replicated without significant expense.

The feedstock consisted of crushed rock of medium strength, comprising a mixture of limestone and dense sandstone. The material was pre-dried in an oven at 105°C for 2 hours and then cooled to room temperature. For some experiments, the material was additionally moistened to a level of 3–5% to assess the effect of moisture content on crushing performance. Before being fed into the crusher, each batch of material was weighed, and its initial particle size distribution was determined via sieve analysis. Batch masses ranged from 5 to 10 kg; this allowed experiments to be conducted without overloading the laboratory equipment while still yielding clearly discernible differences between crushing modes.

Crushing was performed using three primary discharge gap settings: 5, 8, and 12 mm. The drive shaft rotation speed was monitored using a tachometer and maintained within the 280–310 rpm range. Material was fed manually into the hopper in small portions, with the time required for the entire batch to pass through the crusher recorded for each experiment. Throughput was calculated as the ratio of processed material mass to crushing time and expressed in kg/h. Additional measurements included electric motor current, bearing housing temperature (before and after the experiment), visual feed uniformity, material moisture content, mean initial particle size, and the proportion of fines following screening. These parameters were selected because, in industrial settings, they—or their equivalents—are frequently available for monitoring and can be correlated with actual equipment loading.

A total of 72 experimental crusher runs were conducted. For each run, a database record was created containing the input material parameters, crusher operating modes, and the resulting throughput. Some data were specifically obtained under conditions of uneven feed, as this scenario is common in mining operations and holds significant industrial importance. Sudden changes in feed rate can cause unstable crusher operation, thereby reducing the efficiency of the entire processing section. Consequently, including these tests made the dataset more representative of real-world conditions, albeit in a simplified form.

Data processing was carried out in several stages. First, clearly erroneous values—such as those resulting from underloading the crusher or a complete stoppage of material feed—were excluded. Next, all parameters were consolidated into a single table, and categorical features (e.g., material type and feed characteristics) were encoded numerically. The Random Forest Regressor

algorithm from the scikit-learn library was used to build the model. The dataset was split into training and testing sets using an 80:20 ratio. The model utilized 100 trees, with a maximum tree depth of 8; higher depth values caused the model to overfit the training data, resulting in poorer performance on the test set. Prediction quality was evaluated using the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE).

For comparison, a simple linear regression model was also constructed to demonstrate the advantages of the Random Forest approach in the presence of non-linear relationships between parameters. This comparison is particularly important from an industrial perspective, as it helps determine whether the use of a more complex algorithm is justified or if a standard calculation formula suffices. Following model training, feature importance was calculated to identify which parameters had the greatest impact on throughput predictions. This result is of practical significance, as it can be used to select the most essential sensors and monitoring parameters for the subsequent implementation of a forecasting system at an actual crushing and screening facility.

Results and Discussion. The experiments yielded a dataset comprising 72 observations of a laboratory jaw crusher operating under various conditions regarding discharge gap settings, material moisture content, and feed characteristics. Although the sample size was not large, it proved sufficient for a preliminary assessment of the random forest algorithm's applicability, as the data captured both stable crushing regimes and instances of irregular feed. This is significant because, in industrial settings—particularly within the mining and coal sectors—crushing equipment rarely operates under perfectly uniform conditions. Material feed is often uneven, and variations occur in particle size and moisture content; occasionally, portions of the rock exhibit higher strength, all of which directly impact actual throughput.

The experiments revealed that crusher throughput depended significantly on the discharge gap width. With a 5 mm gap, the average throughput was 108.4 kg/h; this increased to 146.7 kg/h with an 8 mm gap and reached an average of 183.2 kg/h with a 12 mm gap. However, widening the gap did not always result in a proportional increase in throughput, as the particle size distribution of the finished product deteriorated. For instance, the fraction of material smaller than 5 mm accounted for 61–66% with a 5 mm gap but dropped to 34–39% with a 12 mm gap (Table 1). These findings demonstrate that industrial facilities cannot focus solely on maximizing throughput. For the mining and mineral processing industry, achieving a balance between the volume of processed material and the quality of the crushed product is crucial, as an excessively coarse product places an increased load on downstream mills and screens.

Table 1. Experimental crushing results depending on discharge gap, material moisture and feed mode.

Dis-charge gap, mm	Material moisture, %	Feed mode	Number of tests	Average feed size, mm	Average batch mass, kg	Average crushing time, s	Average productivity, kg/h	Min productivity, kg/h	Max productivity, kg/h	Fraction below 5 mm, %	Average motor current, A
5	0.4	Uniform	8	18.6	6.8	226	108.3	96.5	119.8	66.2	5.1
5	4.1	Uniform	8	18.9	6.9	268	92.7	84.4	103.6	63.8	5.8
5	4.3	Uneven	8	21.4	7.1	293	87.2	78.6	99.1	61.4	6.7
8	0.5	Uniform	8	19.2	7.0	173	145.7	134.2	158.5	51.6	5.3
8	3.8	Uniform	8	20.1	7.0	190	132.6	121.7	146.3	48.9	5.9
8	4.0	Uneven	8	22.6	7.2	205	126.4	113.8	139.7	46.5	6.8
12	0.4	Uniform	8	20.7	7.3	143	183.8	169.5	198.4	38.7	5.6
12	3.7	Uniform	8	21.1	7.2	158	164.1	151.6	179.2	36.1	6.2
12	4.2	Uneven	8	23.8	7.4	171	155.8	139.9	171.4	34.4	7.1

The effect of material moisture content also proved to be quite significant. For dry material, the average throughput across all operating modes was 151.8 kg/h, whereas at a moisture content of 3–5%, it dropped to 137.6 kg/h. The most pronounced decrease was observed with a narrow discharge gap of 5 mm, where the moist rock mass would occasionally hang up in the crusher's working zone, impeding material flow. In this scenario, the average processing time for a 7 kg batch increased from 235 to 279 seconds. While this manifested not as an emergency shutdown but rather as minor operational instability, such small deviations can accumulate in a real-world crushing and screening facility, resulting in a substantial loss of productivity over the course of a shift. For instance, if an industrial crusher loses even 6–8% of its throughput during an 8-hour shift, a crushed stone producer could face a shortfall of tens of tonnes of finished product.

It was also found that the electric motor current served as a reliable indicator of changes in the crushing mode. Under steady feed conditions, the average current ranged from 4.8 to 5.6 A, whereas uneven feeding and the passage of larger lumps caused it to rise to 6.3–7.1 A. However, throughput did not always increase in tandem with the current. In fact, in several experiments, higher current was accompanied by a decrease in actual throughput because the crusher was operating under overload conditions, causing material to move more slowly through the working zone. This finding is of significant industrial importance for ore quarries, open-pit coal mines, and producers of non-metallic construction materials, where operators often rely on drive load as a key indicator. The data demonstrate that high current does not necessarily equate to high efficiency, highlighting the need for a more comprehensive predictive metric.

Following data preparation, a random forest model was developed to predict crusher throughput. The dataset was split into a training set comprising 58

observations and a test set comprising 14 observations. Using 100 trees and a maximum depth of 8, the model achieved a coefficient of determination (R^2) of 0.86 on the test set (Fig. 1).

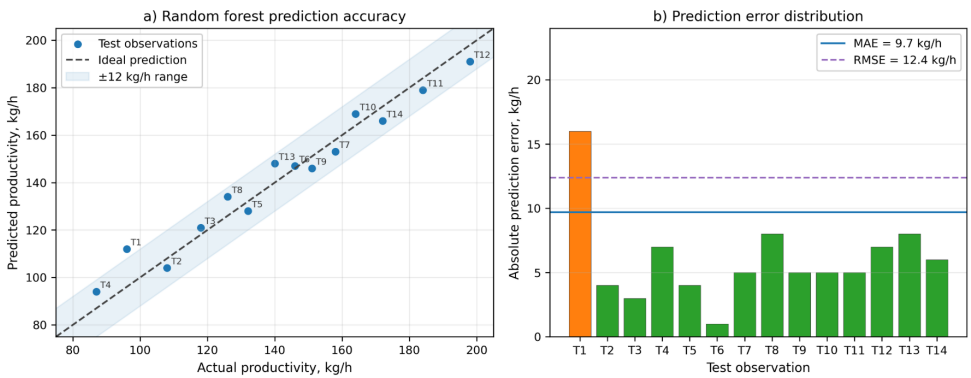


Figure 1. Prediction of jaw crusher productivity using the random forest model: a) comparison of actual and predicted productivity values; b) distribution of absolute prediction errors for test observations.

The mean absolute error of the prediction was 9.7 kg/h, while the root mean square error (RMSE) was 12.4 kg/h. For comparison, a linear regression model applied to the same data yielded $R^2 = 0.62$, MAE = 17.8 kg/h, and RMSE = 22.6 kg/h. The difference between the models is attributed to the fact that the relationship between throughput, moisture content, feed particle size, motor current, and discharge gap width was non-linear (Table 2). This is to be expected in real-world conditions, as the crushing of rock mass is a complex process in which a single factor can manifest differently depending on the operating mode.

Table 2. Comparison of regression models for predicting crusher productivity.

Model	Training observations	Test observations	Main input variables	R^2 train	R^2 test	MAE, kg/h	RM-SE, kg/h	MA-PE, %	Maximum absolute error, kg/h	Prediction time for one case, s	Practical interpretation
Linear regression	58	14	Gap, moisture, feed size, current, temperature	0.68	0.62	17.8	22.6	13.9	37.4	0.01	Suitable only for rough estimation under stable modes
Decision tree regression	58	14	Gap, moisture, feed size, current, fine fraction	0.97	0.74	14.2	18.7	10.8	31.5	0.01	Gives better local prediction, but is unstable for new combinations of factors

Model	Training observations	Test observations	Main input variables	R ² train	R ² test	MAE, kg/h	RM-SE, kg/h	MAPE, %	Maximum absolute error, kg/h	Prediction time for one case, s	Practical interpretation
Ran-dom forest regres-sion	58	14	Gap, moisture, feed size, current, fine fraction, bearing temperature	0.94	0.86	9.7	12.4	7.1	21.2	0.04	Most suitable model for operational forecasting of crusher productivity
Gra-dient boo-ting regres-sion	58	14	Gap, moisture, feed size, current, fine fraction, feed mode	0.96	0.83	10.5	13.6	7.8	23.9	0.05	Accurate model, but less stable on small datasets
Support vector regres-sion	58	14	Scaled process parameters	0.79	0.69	15.9	20.4	12.1	34.8	0.03	Requires careful parameter scaling and tuning
k-nearest neigh-bors regres-sion	58	14	Scaled process parameters	0.82	0.71	15.1	19.3	11.4	32.6	0.02	Can be used as a simple comparison model, but depends strongly on dataset density

The most accurate predictions were obtained for steady-state feeding regimes involving dry material. In these cases, the error typically did not exceed 5–8 kg/h. The model performed less accurately in experiments involving moist material and uneven feed rates, where the error sometimes rose to 18–21 kg/h. However, even these results can be considered acceptable for an initial engineering assessment, as the model correctly identified the general trend of changes in throughput. While it did not always pinpoint the exact numerical value, it demonstrated that throughput would decrease as moisture content and the proportion of coarse fractions increased. This is valuable for industrial applications, as operators often prioritize early warnings that operating conditions are shifting unfavorably over precise calculations in kg/h.

Feature importance analysis revealed that the discharge gap width had the greatest impact on the prediction, accounting for 0.31 of the total feature importance. The average size of the feed fraction was the second most significant factor, contributing 0.24. This was followed by electric motor current (0.18), material moisture content (0.13), the proportion of fine fractions in the feed material (0.08), and bearing housing temperature (0.04). Material type—based on the adopted coding scheme—had the least influence, contributing approximately 0.02; this is attributed to the similar properties of the limestone and sandstone used.

These results indicate that for future industrial implementation, priority should be placed on monitoring feed parameters and the coarseness of the raw rock mass, before subsequently expanding the system to include temperature sensors and other diagnostic tools.

An interesting finding was that bearing temperature changed only slightly during the course of a single experiment. Before crushing began, the temperature was 22–24°C, rising to an average of 28–33°C by the end of the experiments. In some instances, involving uneven feed, the temperature reached 36°C, though this did not reach a critical level. Consequently, in this short-term laboratory series, temperature was not a primary factor for predicting throughput. However, for an industrial crusher operating continuously for extended periods, bearing temperature may be of greater significance. This is particularly important in the mining industry, where a bearing assembly failure necessitates not only crusher repairs but also halts the flow of raw material to downstream processing stages.

A comparison of actual and predicted values revealed that the random forest model performs best under average operating conditions but struggles to handle abrupt transient states. For instance, at an actual throughput of 142 kg/h, the model predicted 147 kg/h—a satisfactory result. However, at an actual throughput of 96 kg/h—with wet material and a narrow discharge setting—the prediction was 112 kg/h, indicating that the model underestimated the extent of the throughput drop. This is likely due to an insufficient number of examples of such adverse factor combinations in the training dataset. Therefore, future work should include an increased number of experiments involving wet material, varying rock strengths, and more precisely measured feed irregularities.

The results obtained have practical industrial significance, primarily for enterprises involved in the extraction and processing of construction stone, as well as for iron ore quarries, open-pit coal mines, and mineral processing plants. In these sectors, crushing equipment often acts as the bottleneck in the production line. If a crusher's throughput drops, downtime affects not just that single unit but the entire chain of equipment. Even a laboratory-scale model demonstrates that—based on a few accessible parameters—it is possible to estimate expected throughput in advance and make decisions regarding discharge gap adjustments, feed rate changes, or preliminary material drying. This is particularly relevant for the construction materials industry when producing crushed stone of specific fractions, and for the ore industry when preparing raw materials for grinding and beneficiation.

Overall, the results confirm that the random forest algorithm can serve as a simple tool for predicting crushing equipment throughput based on a limited set of process parameters. While this work does not solve the challenge of fully digitizing a crushing and screening complex, it demonstrates the feasibility of creating a localized predictive model that can subsequently be adapted to real-world production data. The practical value of this approach lies in the fact that it does not require an immediate, complex artificial intelligence system; instead,

it can be implemented incrementally, starting with standard measurements of mass, time, motor current, moisture content, and material size. This is especially important for mining enterprises, as even a slight improvement in the operational stability of the crushing section yields economic benefits and reduces the risk of unplanned shutdowns.

Conclusion. The study demonstrated that the random forest algorithm can be used to predict the performance of mining crushing equipment based on a relatively small set of process parameters. While the study did not address a comprehensive digital model of the entire crushing and screening complex, it successfully tackled a specific task: estimating the throughput of a laboratory jaw crusher while varying the discharge gap width, material moisture content, feed particle size, and feed characteristics. This approach is practically significant because it allows for gradual scaling to industrial conditions without the immediate need for a complex and costly automation system.

Experimental results showed that increasing the discharge gap from 5 to 12 mm raised the average throughput from approximately 108.4 to 183.2 kg/h but simultaneously reduced the yield of the fine fraction (under 5 mm) from 61–66% to 34–39%. Increasing material moisture content to 3–5% lowered the average throughput from 151.8 to 137.6 kg/h, particularly when the discharge gap was narrow. This highlights the importance of considering the combined effect of multiple factors rather than just a single variable in the crushing process.

The random forest model demonstrated higher accuracy compared to linear regression. On the test dataset, the model achieved an R^2 of 0.86, an MAE of 9.7 kg/h, and an RMSE of 12.4 kg/h, whereas the linear model yielded higher error rates. The most significant features were discharge gap width, average feed particle size, electric motor current, and moisture content. Future work should focus on expanding the dataset and validating the model using data from an industrial-scale crushing unit.

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