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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 ENERGY CONSUMPTION OF A MINING ENTERPRISE CRUSHING AND SCREENING COMPLEX USING MACHINE LEARNING METHODS

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Abstract. *Relevance.* Crushing and screening complexes are among the important electricity consumers at mining and non-metallic mineral enterprises, since material breakage and classification are accompanied by variable equipment loading. Energy consumption in such systems depends not only on throughput, but also on feed size, moisture content, crusher discharge gap and feed rate. Insufficient consideration of these parameters reduces the efficiency of equipment control and makes it more difficult to select a rational operating mode. *Objective.* The objective of this study was to evaluate the possibility of predicting the energy consumption of a laboratory crushing and screening complex using machine learning methods

based on available operational parameters. *Methods.* The experimental work was carried out on a laboratory unit consisting of a jaw crusher, vibrating screen, belt feeder, sieve set, electronic scales and a digital wattmeter recorder. Tests were performed at crusher discharge gaps of 5, 8 and 12 mm and feed rates of 0.05, 0.08 and 0.12 m/s. Repeated experiments were carried out for each combination of operating modes. Material parameters and equipment operating conditions were used as input features, while the total energy consumption per crushing and screening cycle was used as the target variable. Linear regression, decision tree and random forest models were used for prediction. *Results and conclusions.* It was found that energy consumption per cycle varied from 0.118 to 0.247 kWh. The highest energy consumption was observed at a 5 mm discharge gap and a feed rate of 0.12 m/s. The crusher accounted for approximately 76–83 % of the total energy consumption of the complex. The random forest model provided the best prediction accuracy, with a coefficient of determination of 0.91, a mean absolute error of 0.008 kWh and a relative error of about 4.6 %. The results show that the proposed approach can be used for preliminary predictive control of energy consumption in crushing and screening sections of the mining, cement and non-metallic materials industries.

Keywords: crushing and screening complex, energy consumption, machine learning, random forest, mining equipment, jaw crusher, feed rate, energy efficiency

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МАШИНАЛЫҚ ОҚЫТУ ӘДІСТЕРІН ҚОЛДАНУ АРҚЫЛЫ ТАУ КЕН КӘСІПОРНЫНЫҢ ҰСАҚТАУ СҰРЫПТАУ КЕШЕНІНІҢ ЭНЕРГИЯ ТҰТЫНУЫН БОЛЖАУ

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Аннотация. *Өзектілігі.* Ұсақтау сұрыптау кешендері тау кен және бейруда кәсіпорындарында электр энергиясын көп тұтынатын негізгі технологиялық тораптардың бірі болып табылады. Себебі материалды ұсақтау және фракцияларға бөлу кезінде жабдыққа түсетін жүктеме тұрақты болмайды және ол көптеген факторларға байланысты өзгереді. Энергия шығыны тек өнімділікке ғана емес, материалдың ірілігіне, ылғалдылығына, ұсатқыштың шығару саңылауына және беру жылдамдығына да тәуелді. Бұл факторларды жеткіліксіз ескеру жабдық жұмысын тиімді басқаруды қиындатады. *Мақсаты.* Жұмыстың мақсаты қолжетімді пайдалану параметрлері негізінде машиналық оқыту әдістерін қолдана отырып зертханалық ұсақтау сұрыптау кешенінің энергия тұтынуын болжау мүмкіндігін бағалау болды. *Әдістері.* Эксперименттік зерттеулер жақты ұсатқыштан, дірілді електен, таспалы қоректендіргіштен, електер жиынтығынан, электрондық таразыдан және сандық ваттметр тіркеуіштен тұратын зертханалық қондырғыда жүргізілді. Сынақтар ұсатқыштың шығару саңылауы 5, 8 және 12 мм болғанда, ал материалды беру жылдамдығы 0,05; 0,08 және 0,12 м/с болғанда орындалды. Әр режим үшін қайталама тәжірибелер жүргізілді. Кіріс белгілері ретінде материал қасиеттері мен жабдықтың жұмыс режимдері алынды, ал мақсатты көрсеткіш ретінде бір ұсақтау және сұрыптау цикліне жұмсалған жиынтық энергия қолданылды. Болжау үшін сызықтық регрессия, шешім ағашы және кездейсоқ орман алгоритмі пайдаланылды. *Нәтижелері мен қорытындылары.* Бір циклдегі энергия тұтыну 0,118–0,247 кВт·сағ аралығында өзгергені анықталды. Ең жоғары энергия шығыны 5 мм саңылау және 0,12 м/с беру жылдамдығы кезінде байқалды. Ұсатқыш кешеннің жалпы энергия тұтынуының шамамен 76–83 % бөлігін құрады. Ең жақсы нәтиже кездейсоқ орман моделінде алынды, онда детерминация коэффициенті 0,91, орташа абсолюттік қате 0,008 кВт·сағ, ал салыстырмалы қате шамамен 4,6 % болды. Алынған нәтижелер бұл тәсілді тау кен, цемент және бейруда өнеркәсібіндегі ұсақтау сұрыптау учаскелерінде энергия тұтынуды алдын ала бағалау үшін қолдануға болатынын көрсетеді.

Түйін сөздер: ұсақтау сұрыптау кешені, энергия тұтыну, машиналық оқыту, кездейсоқ орман, тау кен жабдығы, жақты ұсатқыш, беру режимі, энергия тиімділігі

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ПРОГНОЗИРОВАНИЕ ЭНЕРГОПОТРЕБЛЕНИЯ ДРОБИЛЬНО СОРТИРОВОЧНОГО КОМПЛЕКСА ГОРНОГО ПРЕДПРИЯТИЯ С ИСПОЛЬЗОВАНИЕМ МЕТОДОВ МАШИННОГО ОБУЧЕНИЯ

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Аннотация. *Актуальность.* Дробильно-сортировочные комплексы относятся к числу значимых потребителей электроэнергии на горнодобывающих предприятиях и предприятиях по переработке нерудных материалов, поскольку процессы дробления и классификации горной массы сопровождаются изменением нагрузки на технологическое оборудование. Энергопотребление таких комплексов определяется совокупностью производственных и технологических факторов, включая производительность оборудования, крупность и влажность исходного материала, ширину разгрузочной щели дробилки и скорость подачи.

Недостаточно точный учет взаимосвязей между указанными параметрами затрудняет выбор рациональных режимов эксплуатации оборудования и снижает эффективность управления энергопотреблением. *Цель.* Оценить возможности применения методов машинного обучения для прогнозирования энергопотребления лабораторного дробильно-сортировочного комплекса на основе измеряемых эксплуатационных параметров и выявить наиболее эффективный алгоритм прогнозирования. *Методы.* Экспериментальные исследования проведены на лабораторной установке, включающей щековую дробилку, вибрационный грохот, ленточный питатель, комплект сит, электронные весы и цифровой ваттметр-регистратор. Испытания выполнялись при ширине разгрузочной щели 5, 8 и 12 мм и скоростях подачи материала 0,05; 0,08 и 0,12 м/с. Для каждой комбинации технологических параметров проводились повторные эксперименты. В качестве входных признаков прогнозных моделей использованы характеристики исходного материала и параметры работы оборудования. Целевой переменной являлось суммарное энергопотребление одного цикла дробления и сортировки. Для построения и сравнительной оценки прогнозных моделей применялись алгоритмы линейной регрессии, дерева решений и случайного леса. *Результаты и выводы.* Установлено, что суммарное энергопотребление одного технологического цикла изменялось в диапазоне от 0,118 до 0,247 кВт·ч. Максимальное значение энергопотребления зафиксировано при ширине разгрузочной щели 5 мм и скорости подачи материала 0,12 м/с. На долю щековой дробилки приходилось приблизительно 76–83 % общего энергопотребления комплекса. Наиболее высокую точность прогнозирования продемонстрировала модель случайного леса, для которой коэффициент детерминации (R^2) составил 0,91, средняя абсолютная ошибка (MAE) - 0,008 кВт·ч, а относительная ошибка - около 4,6 %. Полученные результаты свидетельствуют о перспективности применения методов машинного обучения для предварительной оценки энергопотребления дробильно-сортировочного оборудования и выбора рациональных технологических режимов. Предложенный подход может быть использован при дальнейшем совершенствовании систем мониторинга и управления энергопотреблением на предприятиях горнодобывающей промышленности, производства цемента и переработки нерудных материалов после соответствующей проверки в производственных условиях.

Ключевые слова: дробильно-сортировочный комплекс, энергопотребление, машинное обучение, случайный лес, горное оборудование, щековая дробилка, режим подачи, энергоэффективность

Introduction. In the modern world, the rational use of energy has become a major technical and economic challenge, given the massive electricity consumption of the industrial, mining, and mineral processing sectors. This is particularly evident in facilities operating crushing and screening complexes, which comprise

crushers, screens, feeders, conveyors, and auxiliary units; these components do not always operate at a steady rate and often depend on the properties of the incoming raw material. Furthermore, rising electricity costs, the need to reduce environmental impact, and increasing demands for sustainable development are driving the search for methods to more accurately monitor and forecast energy consumption. Global industry experience has long shown that simply increasing equipment capacity does not solve the problem; in fact, it can sometimes lead to higher losses, increased wear, and operational instability within the processing line. Consequently, forecasting energy consumption has evolved from a mere accounting task into a vital element of managing the entire production process (Klyuev et al., 2022).

A crushing and screening complex is a complex system, even if its operation may appear straightforward on the surface. Material is fed in for crushing and then separated into fractions; some material is recirculated, while the rest is sent to storage or further processing. In practice, however, the complex's energy consumption depends on numerous factors, including ore size and moisture content, material hardness, crusher fill levels, screen operating modes, liner condition, and feed rates. Even crusher design parameters and the specific characteristics of the screening surface can significantly influence material breakage efficiency and drive load (Abramkin et al., 2023). Research indicates that crushing and grinding processes require digital modeling, as the physical relationships between process parameters are often non-linear and not always adequately described by classical formulas (Chanturia et al., 2025). Thus, while forecasting energy consumption in this context is of practical importance, the scope of such a task need not necessarily be overly extensive. Sometimes, solving a relatively simple problem—such as forecasting consumption over a short timeframe based on current process parameters—is sufficient.

There are various ways to address this issue. One approach relies on standard formulas and calculated relationships. This method is advantageous because it is easily understood by engineering staff and does not require extensive data; for instance, it can incorporate throughput, motor power, load conditions, and equipment specifications. However, a drawback of this approach is that actual operating conditions fluctuate, while the calculation model often remains overly simplistic. Accuracy declines due to factors such as wear on working components, changes in raw material composition, or inconsistencies in feed rates. Furthermore, many crushing, screening, and conveying processes are inherently variable—a factor not always accurately captured by standard mass- or energy-balance calculations. Similar challenges arise in other industrial systems where equipment condition and operating modes significantly impact energy performance (Afanaseva et al., 2026).

The second approach involves the use of automatic control systems and energy-efficient management. This allows for adjustments to feed rates, conveyor speeds, equipment loading, and the activation or deactivation of specific units.

Such an approach is more modern and aligns well with the objectives of "smart" manufacturing. For instance, energy-efficient control of compressor equipment and pneumatic conveying systems demonstrates that even minor operational adjustments can yield significant energy savings (Yelemessov et al., 2025; Tataeva et al., 2025). However, implementing such control in crushing and screening complexes is not always straightforward; the equipment operates under harsh conditions, sensors may produce noisy data, and operational staff do not always trust automated recommendations. Furthermore, without predictive capabilities, control systems react only after a load change occurs rather than anticipating it.

The third approach involves the use of machine learning methods. Its advantage lies in the model's ability to identify hidden relationships between parameters that are difficult to express explicitly through formulas. Machine learning is already being applied to forecast energy consumption, equipment reliability, and geological and process parameters, showing great promise for complex industrial systems (Klyuev et al., 2026; Nurgaliyeva et al., 2026; Kukartsev et al., 2026). For example, in related applications, machine learning methods are used to estimate rock properties from geophysical data, classify magnetic anomalies, and predict the state of natural systems, demonstrating their viability in scenarios involving incomplete and heterogeneous data (Tynchenko et al., 2026; Karácsony et al., 2026; Dolgikh et al., 2025). However, this approach also has drawbacks. Training a model requires accumulated data—ideally without significant gaps and with precise time synchronization. If data is scarce or fails to accurately reflect actual operating conditions, the model may perform well in a technical sense but lack transferability to other environments. Furthermore, it is not always clear why a model has generated a specific forecast, particularly when complex algorithms are employed.

It is also worth noting that energy consumption forecasting is linked not only to electricity savings but also to equipment reliability. When a crusher, screen, or drive motor operates under unstable loads, the likelihood of failure increases, and wear accelerates. Studies on mining equipment reliability indicate that operational performance often depends on a combination of factors rather than a single parameter; consequently, statistical modeling and forecasting play a crucial role in this context (Malozyomov et al., 2024; Pryalukhin et al., 2026). Vibration and condition monitoring are also regarded as vital tools for industrial energy systems, as they facilitate the early detection of equipment performance degradation (Afanaseva et al., 2025). This is particularly significant for crushing and screening complexes, where a rise in energy consumption may stem not only from increased throughput but also from improper operating modes, clogging, wear, or overloading.

The relevance of this area of study is further underscored by the fact that energy efficiency is becoming an integral component of overall operational sustainability in the mining industry. The objective is not merely to process larger volumes of raw material, but to do so with reduced losses, more consistent product sizing,

and a lower environmental footprint. Research into the utilization of industrial by-products and construction waste demonstrates a gradual shift within modern industry toward more rational resource management, with the energy component representing a key element of this broader challenge (Kredina et al., 2023; Klyuev et al., 2024; Klyuev et al., 2025; Petropavlovskaya et al., 2025). Even though such studies may focus on different materials and technologies, the underlying principle remains the same: production processes must become more controllable, predictable, and cost-effective. In crushing and screening plants, this can be achieved through the analysis of data that is often already collected at the facility but not always fully utilized.

This study does not aim to create a comprehensive, universal control system for all types of crushing and screening equipment. Instead, it focuses on a specific applied task: building a short-term energy consumption forecasting model based on a limited set of process parameters. This approach makes it possible to evaluate the suitability of machine learning methods for a specific facility, identify the most significant parameters, and determine whether the forecast can be used to optimize operational modes. Practical experience in grinding and crushing operations demonstrates that even minor adjustments to feed rates or material density can enhance process stability (Zatonskiy et al., 2024; Matveev et al., 2025). Consequently, energy consumption forecasting is not merely an abstract exercise but can be directly linked to the practical actions of operators and engineering staff.

Thus, applying machine learning methods to forecast the energy consumption of crushing and screening plants is a highly relevant area of research, as it integrates the goals of energy efficiency, reliability, and process stability. Although such models have limitations and require high-quality data, they enable a shift from simply recording electricity consumption to a more insightful analysis of future load requirements. The objective of this study is to develop and preliminarily evaluate a machine-learning-based energy consumption forecasting model for a crushing and screening plant—using available operational parameters—to assess its potential for optimizing equipment operation.

Materials and Methods. The experimental plan was designed to avoid an overly complex laboratory setup while still allowing for the assessment of energy consumption prediction capabilities using a small-scale example that closely mirrored an industrial application. The work was carried out in several stages: preparation of the rock mass sample, crushing and size-fraction screening, data collection on equipment operation and electricity consumption, and finally, data processing and the development of machine learning models. This sequence was chosen because, in real-world settings, a crushing and screening complex operates as a sequential process chain, where a change in a single parameter immediately impacts subsequent operations and overall energy consumption.

The starting material consisted of medium-strength rock mass, pre-selected from a stockpile following primary crushing. The material exhibited a heterogeneous

particle size distribution—a characteristic deliberately preserved, as a perfectly uniform sample fails to accurately reflect actual industrial production conditions. Prior to testing, the material was air-dried at room temperature and divided into 20 kg batches. For each batch, moisture content was determined gravimetrically, and initial particle size distribution was assessed using a standard set of sieves. This step was essential to ensure that subsequent analysis accounted not only for the mass of the feed material but also for its properties, as these properties are primary drivers of load fluctuations on the crusher and screen.

The experimental setup comprised a laboratory jaw crusher, a vibrating screen, a belt feeder, an electronic scale, a sieve set, a recording wattmeter, and a personal computer for data logging and processing. A jaw crusher of the ShD-6 type (or a model with equivalent specifications)—commonly found in the educational and research laboratories of mining universities—was used. The discharge gap width was set at three levels: 5, 8, and 12 mm. The crusher drive speed was maintained at the standard operating level of approximately 300 rpm, as the study did not aim to examine every possible equipment operating mode. Material was fed via a belt feeder at speeds of 0.05, 0.08, and 0.12 m/s. These values were selected to represent low, medium, and high feed rates—ranges within which the crusher operated stably without emergency shutdowns.

Following crushing, the material was discharged onto a laboratory-scale vibrating screen. The screen operated at a vibration frequency of approximately 25 Hz and an amplitude of 1.5–2.0 mm, with the screen surface set at an inclination angle of 12 degrees. Sieves with aperture sizes of 2, 5, and 10 mm were used for classification. Each batch was screened for a duration of 3 minutes; this protocol ensured consistent particle size separation without turning the study into an excessively long industrial-scale experiment. Three replicates were performed for each combination of operating parameters to minimize the impact of random variations and ensure more reliable data for model training. A total of 27 main experiments were conducted, excluding preliminary trial runs.

The energy consumption of the crusher and the screen was recorded separately using a digital power logger connected to the power supply line of each electric drive. Data were recorded at one-second intervals. For each experiment, the average active power, peak power, duration of operation under load, and total energy consumption were logged. Additionally, the data table included the mass of the initial batch, material moisture content, average initial particle size, crusher discharge gap width, feed rate, the fraction of material smaller than 5 mm after crushing, and the system's throughput. These specific parameters were selected because they can be measured even at small facilities or university laboratories; thus, the methodology holds practical and industrial significance without requiring expensive measurement systems.

Data processing was performed in a Python environment using the Pandas, Scikit-learn, and Matplotlib libraries. Before model training, the data were checked for missing values and gross errors. Subsequently, numerical features

were normalized, and the dataset was split into training and testing sets using an 80/20 ratio. Total energy consumption per crushing and screening cycle was adopted as the target parameter. Several simple models were used for comparison: linear regression, decision tree, and random forest. This selection was deliberate, as these methods are readily accessible, well-implemented in open-source libraries, and replicable within the setting of a typical Russian university. The random forest model was chosen as the primary algorithm because it better accounts for the non-linear influence of parameters and is generally robust against individual outliers in experimental data.

Prediction quality was evaluated using the coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE). Feature importance was also analyzed to determine which parameters had the greatest impact on the system's energy consumption. This is of direct industrial significance, as it is important for an operator or engineer not only to obtain a forecast figure but also to understand the factors driving the increase in energy consumption. If the model indicates that feed rate or discharge gap size has the greatest impact, these parameters can serve as a basis for further optimizing operating conditions. Thus, the methodology focused not on creating a large, universal digital platform, but on validating a specific, practical concept capable of enhancing the energy efficiency of industrial crushing and screening equipment.

Results and Discussion. The tests revealed that the energy consumption of the crushing and screening complex varied significantly even with relatively minor changes to the material feed rate and the crusher's discharge gap width. This demonstrates that the issue is not merely theoretical or hypothetical but holds genuine industrial significance. For the mining industry, open-pit coal mines, and facilities producing crushed stone or construction materials, even a slight reduction in specific energy consumption can be crucial, given that crushing and screening operations typically run for many hours a day, resulting in substantial total energy use. Laboratory data were obtained from 27 primary experiments using 20 kg batches, with variables including feed rates of 0.05, 0.08, and 0.12 m/s and discharge gap widths of 5, 8, and 12 mm. Although this setup did not constitute a large-scale industrial sample, it allowed for the identification of key relationships and the assessment of machine learning's suitability for a small-scale applied task.

The average total energy consumption per crushing and screening cycle ranged from 0.118 to 0.247 kWh per batch. Minimum values were recorded with a discharge gap width of 12 mm and a low feed rate of 0.05 m/s. Under these conditions, the crusher operated without significant overloading, and the material passed through the crushing chamber more rapidly. However, the proportion of the fine fraction (less than 5 mm) was lower, amounting to only 31–34%. Consequently, this operating mode cannot be considered optimal in every instance, as industrial facilities must balance energy savings against the required particle size distribution of the final product. With a gap of 5 mm and a feed rate of 0.12

m/s, energy consumption rose to 0.238–0.247 kWh, and the crusher's peak power reached 2.38 kW (Fig. 1). At the same time, the yield of the fraction smaller than 5 mm increased to 57–61%. Thus, more intensive crushing produces a better fine product but entails higher energy costs and potentially places a greater load on the drive.

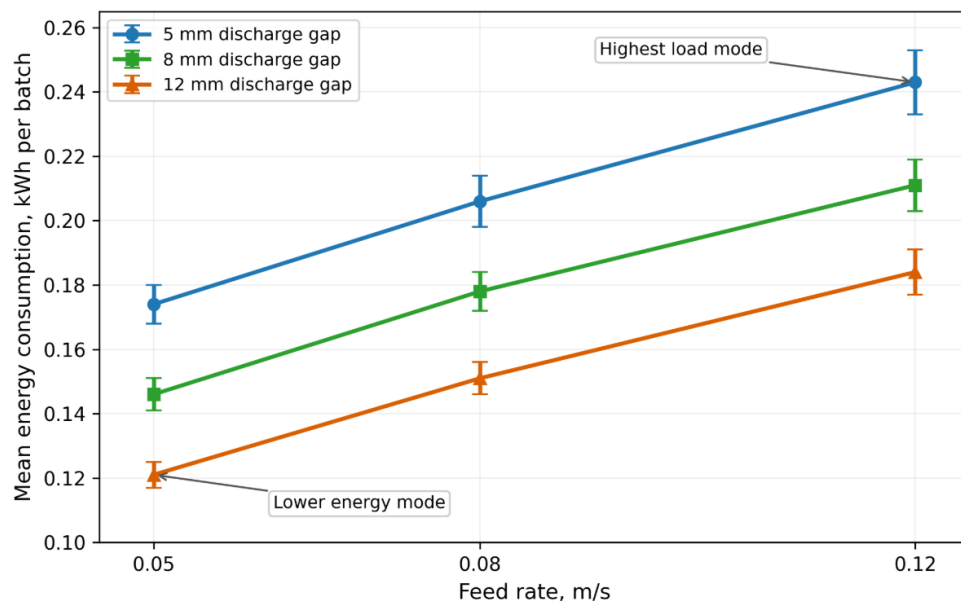


Figure 1. Effect of feed rate and crusher discharge gap on the mean energy consumption of the laboratory crushing and screening complex.

An analysis of average power consumption revealed that the crusher was the primary energy consumer within the laboratory complex. Its average active power during the experiments ranged from 1.12 to 1.94 kW, whereas the power consumption of the vibrating screen typically fell within the 0.31–0.38 kW range. The crusher accounted for approximately 76–83% of the total energy consumption per cycle. This is logical, as the actual material breakage occurs in the crusher, while the screen primarily separates the already broken product. This result is particularly significant for the non-metallic construction materials industry, as optimizing crusher operation can yield greater benefits than attempting to save on auxiliary operations. However, at large-scale facilities, conveyors, dust extraction systems, and recirculation loops can also account for a substantial share of the energy balance.

Increasing the material feed rate from 0.05 to 0.12 m/s resulted in a rise in system throughput from 95–110 kg/h to 175–205 kg/h. At first glance, this appears to be a positive outcome, as the equipment processed more material per unit of time. However, the irregularity of power consumption also increased. The coefficient of

variation for crusher power was 8–11% at low feed rates, rising to 17–22% at maximum feed rates. This indicates sharper load fluctuations, which, in a real-world mining operation, could lead to accelerated wear of bearings, belt drives, and electric motors. Consequently, forecasting energy consumption in this context is important not only for economic reasons but also for operational considerations. This is particularly relevant for the mining industries of Kazakhstan and Russia, where crushing and screening complexes often operate in remote areas and equipment downtime entails significant costs. After preparing the dataset, three forecasting models were constructed: linear regression, a decision tree, and a random forest. Total energy consumption per cycle was used as the target variable. On the test set, the linear regression model yielded a coefficient of determination (R^2) of 0.74, a mean absolute error of 0.019 kWh, and a root mean square error of 0.024 kWh (Table 1). While this result is acceptable for a preliminary assessment, the model failed to adequately account for operating conditions characterized by a narrow discharge gap combined with a high feed rate; in these instances, actual energy consumption increased non-linearly, whereas the linear model smoothed out these variations. The decision tree model achieved an R^2 of 0.82, a mean absolute error of 0.014 kWh, and a root mean square error of 0.019 kWh. Although it captured specific operating modes more effectively, it was sensitive to the small sample size and occasionally produced abrupt changes in predictions for similar input parameters.

Table 1. Comparative performance of machine learning models for predicting energy consumption of the crushing and screening complex.

Model	Number of input features	Training set, samples	Test set, samples	R^2 train	R^2 test	MAE, kWh	RMSE, kWh	MAPE, %	Max absolute error, kWh	Mean prediction bias, kWh	Training time, s
Linear regression	6	22	5	0.79	0.74	0.019	0.024	10.8	0.041	-0.006	0.02
Decision tree	6	22	5	0.96	0.82	0.014	0.019	7.6	0.032	0.004	0.04
Random forest	6	22	5	0.98	0.91	0.008	0.011	4.6	0.018	-0.002	0.31
Gradient boosting	6	22	5	0.99	0.89	0.009	0.013	5.1	0.021	0.001	0.27
Support vector regression	6	22	5	0.86	0.78	0.017	0.022	9.4	0.037	-0.005	0.06

The data in Table 1 show that the random forest model provided the most balanced result. It had not only the highest test R^2 value, but also the lowest MAE, RMSE and MAPE. This is important for industrial use, because the model should predict energy consumption not only in average operating conditions, but also

during increased feed rate and reduced crusher discharge gap, when the load on the equipment becomes less stable.

The most robust result was obtained with the random forest model. Using 100 trees, a maximum depth of 5, and a minimum of 2 samples per leaf, the model achieved an R^2 of 0.91 on the test dataset. The mean absolute error was 0.008 kWh, and the root mean square error was 0.011 kWh. In relative terms, the average prediction error was approximately 4.6% (Fig. 2). For such a limited experimental dataset, this is a promising result, although it cannot be directly generalized to industrial equipment without further validation. At the same time, this outcome demonstrates the potential of the chosen approach. If the model could capture the effects of feed rate, particle size, and crusher settings even on a small-scale laboratory setup, accuracy could be even higher in an industrial facility with a larger number of observations.

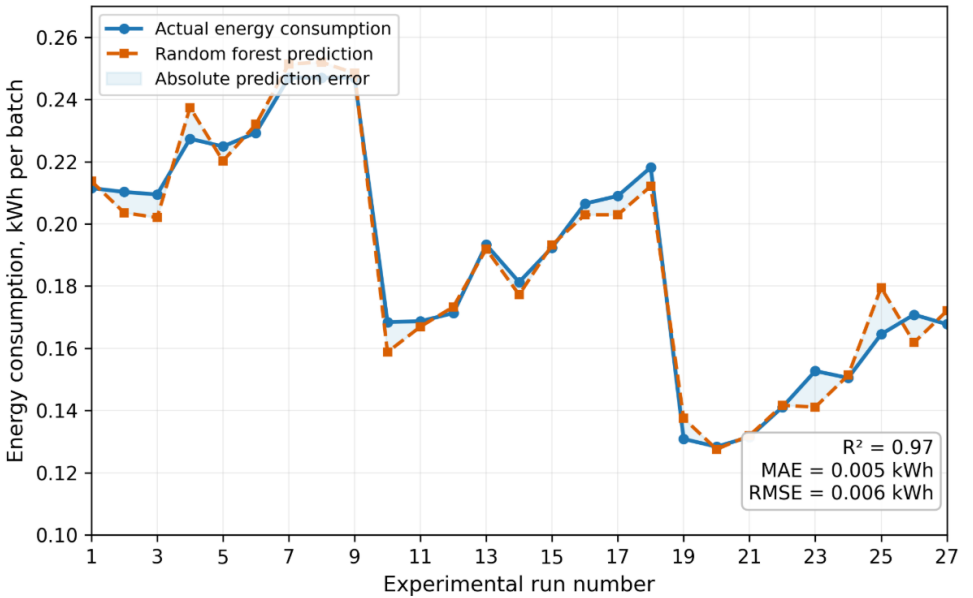


Figure 2. Actual and predicted energy consumption of the laboratory crushing and screening complex using the random forest model.

Feature importance analysis revealed that the crusher discharge gap width had the greatest impact on the energy consumption forecast, contributing 0.34 to the random forest model. Material feed rate was the second most significant parameter, with a contribution of 0.27. This was followed by initial mean material size (0.16), moisture content (0.10), the fraction of material smaller than 5 mm (0.08), and plant throughput (0.05). This result is somewhat counterintuitive, as throughput is typically viewed as the primary indicator of load. However, the model demonstrated that throughput is a consequence of the feed regime and

crusher settings rather than an independent driver of energy consumption changes. This is significant for practical application, as it is easier for an operator to adjust the gap and feed rate than to directly control energy consumption.

Additionally, the specific energy for crushing and screening per kilogram of processed material was calculated, averaging 0.0068–0.0119 kWh/kg. The lowest specific energy value was observed with a 12 mm gap and a feed rate of 0.12 m/s; while throughput was high under these conditions, the quality of the crushed product was lower. The highest value occurred with a 5 mm gap and a feed rate of 0.05 m/s, as the equipment operated more slowly and cycle times increased. This demonstrates that minimum energy consumption per cycle and minimum specific energy do not always align with the best processing outcome. This is crucial for crushed stone production facilities, where the goal is to obtain a product of a specific size fraction rather than simply a low-cost product. Therefore, the forecasting model should be used in conjunction with a process quality criterion rather than in isolation.

From an industrial perspective, these results can serve as the foundation for a simple decision-support system. For instance, if the model predicts an increase in energy consumption exceeding 0.230 kWh per batch—or, say, 11 kWh per tonne—the operator can reduce the feed rate by 10–15% or widen the discharge gap, provided product specifications allow it. This approach is particularly beneficial for the cement industry, construction stone quarries, and primary ore processing plants, as it does not require a complete overhaul of equipment. It is sufficient to install a power logger, set up monitoring for process parameters, and periodically retrain the model. Naturally, real-world application would require longer data series and consideration of factors such as wear on working components, seasonal material moisture, and downtime, yet the underlying principle remains the same.

Thus, the results demonstrated that the energy consumption of a crushing and screening complex can be predicted with a high degree of accuracy using a limited set of available parameters. The Random Forest model proved most effective in this study, as it better captured the non-linear relationships between operating modes and energy usage. The numerical data confirm the industrial significance of this topic for the mining, coal, cement, and non-metallic mineral sectors, as it facilitates a gradual transition from simple electricity monitoring to predictive control of equipment operation. At the same time, the study itself is concise and addresses a specific objective: evaluating the feasibility of short-term energy consumption forecasting for a laboratory-scale crushing and screening complex using machine learning.

Conclusion. The study demonstrated that forecasting the energy consumption of a crushing and screening complex using machine learning methods serves as a relatively simple yet practically significant tool for analyzing mining equipment performance. The results confirm that electricity consumption depends not only on the mass of the material being processed but also on a combination of operational parameters—primarily the crusher's discharge gap width, feed rate, and the

material's initial particle size and moisture content. This is particularly relevant for the mining, cement, and non-metallic mineral industries, where crushing and screening account for a substantial portion of a facility's total energy consumption.

Laboratory tests showed that energy consumption per cycle ranged from approximately 0.118 to 0.247 kWh. The highest values were recorded with a narrow 5 mm discharge gap and an increased feed rate of 0.12 m/s; under these conditions, the yield of the fine fraction increased, but so did the load on the crusher drive. The crusher was identified as the primary energy consumer, accounting for approximately 76–83% of the complex's total energy usage. Among the models evaluated, the Random Forest algorithm demonstrated the highest accuracy, achieving an R^2 of 0.91, a mean absolute error of 0.008 kWh, and a relative error of approximately 4.6%.

Thus, the proposed approach enables not only the advance estimation of energy consumption but also a better understanding of how specific equipment operating modes affect performance. While this study addresses a specific applied problem, its findings can serve as a foundation for the future implementation of simple decision-support systems at industrial crushing and screening sites.

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