MINISTRY OF EDUCATION AND SCIENCE

UNIVERSITY OF MINING AND GEOLOGY "ST. IVAN RILSKI" - SOFIA

FACULTY OF MINING ELECTROMECHANICS

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AUTHOR'S ABSTRACT

of a dissertation submitted for the award of the educational and scientific degree “Doctor (PhD)” in professional field 5.8. **"Exploration, Mining and Processing of Mineral Resources"**

scientific specialty **"Mine Mechanization"**

"STUDY OF MECHANICAL AND TECHNOLOGICAL PARAMETERS OF A ROTARY CRUSHER - ECCENTRIC TYPE"

Scientific supervisor: Assoc. Prof. Dr. Eng. Dimitar Vasilev Dimitrov

Sofia, 2026

The dissertation was discussed and approved for defense by the Department Council of the Department of Mine Mechanization at the University of Mining and Geology "St. Ivan Rilski" - Sofia on 11.05.2026.

The dissertation was developed at the Department of Mine Mechanization at the University of Mining and Geology "St. Ivan Rilski" - Sofia.

The defense of the dissertation will take place on 17.09.2026 at 10:00 in Hall No. 303 of the University of Mining and Geology "St. Ivan Rilski", Sofia, before a Scientific Jury appointed by Order No. RD-13-23 of 22.05.2026 of the Rector of the University of Mining and Geology "St. Ivan Rilski", Sofia.

The defense materials are available to interested persons in the office of the Continuing Education Sector at the University of Mining and Geology "St. Ivan Rilski" - Sofia.

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Scientific supervisor: Assoc. Prof. Dr. Eng. Dimitar Vasilev Dimitrov

Professional field: 5.8. "Exploration, Mining and Processing of Mineral Resources"

Scientific specialty: "Mine Mechanization"

The dissertation author is a full-time doctoral student at the Department of Mine Mechanization of the Faculty of Mining Electromechanics.

Title: Study of Mechanical and Technological Parameters of a Rotary Crusher - Eccentric Type.

Print run: 20 (twenty) copies.

Printed by AVANGARD PRIMA Publishing House, Sofia.

This author's abstract presents the main statements, results, conclusions and contributions of the dissertation. The text is structured according to the following logic: industrial problem, scientific gap, object and subject, aim, control factors, objective functions, methodology, results, statistical models, multi-objective optimization and contributions.

The numbering and logical content are aligned with the structure of the dissertation, while only the most essential results needed to present the scientific-applied and practical value of the work are outlined.

CONTENTS

I. GENERAL CHARACTERISTICS OF THE DISSERTATION WORK

1. Relevance of the topic, industrial problem and scientific gap

The processes of crushing and size reduction are among the main technological operations in the mining and processing industry. These processes determine the subsequent stages of beneficiation, transportation, classification and grinding. Their efficiency affects both the productivity of the entire technological line and the cost of the final product.

Under conditions of increasing requirements for energy efficiency, sustainable production and better utilization of mineral resources, the need for more efficient crushing machines acquires direct industrial importance.

The industrial problem considered in the dissertation arises from the fact that crushing and size reduction remain energy-intensive processes. In conventional solutions, part of the input energy is lost in the form of vibrations, heating, uneven loading, wear of the working elements and the production of a product with an unfavorable grain-size composition.

Therefore, the engineering task is not only to increase the throughput capacity of the machine, but to achieve a combination of productivity, quality of the finished product and limited specific energy consumption.

The rotary crusher - eccentric type (ERC) is a structural solution that combines features of several known groups of crushing machines. The eccentric motion of the rotor creates a periodic change in the working clearance, while the interaction among the rotor, the material and the counter-surface provides a combined effect on the particles.

This gives grounds for considering the machine as a promising alternative for crushing mineral and construction materials.

Despite this potential, ERC has not been sufficiently studied as an independent class of crushing machine. The literature review shows that it occupies an intermediate position between jaw, roll and rotary/cone solutions, but in existing classification schemes it is not clearly enough distinguished.

This creates a scientific gap: there is no comprehensive methodology that connects the structural and kinematic features of ERC with quantitatively measurable technological indicators.

The scientific gap is also manifested in the insufficient clarification of the influence of the main control factors on the crushing process.

The available literature considers individual designs, energy hypotheses and general dependencies; however, for the specific machine it is necessary to establish how the actual rotational frequency, the width of the discharge opening and the number of working chambers simultaneously affect mass productivity, grain-size composition and specific energy consumption.

The relevance of the study is determined precisely by this twofold need: on the one hand, industry needs machines with higher efficiency and better quality of the final product; on the other hand, theory and engineering practice need a verified methodology for studying and evaluating ERC.

The dissertation places these two aspects in a unified logical framework and considers the machine not only as a design, but as a system of interrelated mechanical, kinematic, dynamic and technological parameters.

In this sense, the study has both scientific-applied and practical orientation. Its scientific-applied value consists in distinguishing ERC as an object of independent engineering-technological analysis and in defining a system of factors and objective functions.

The practical value is expressed in the possibility that the obtained results may support the design, adjustment and operation of similar machines under real technological conditions.

The main logic of the author's abstract follows this formulation. First, the industrial problem is outlined, after which the scientific gap is formulated. Then the object, subject, aim and tasks of the study are defined.

At the next stage, the control factors and objective functions are presented, while the results are considered through theoretical analysis, CAD/FEM modelling, experimental studies, grain-size assessment, statistical modelling and multi-objective optimization.

Thus, the text is not a mechanical abridgement of the dissertation, but a consistent presentation of the scientific thesis.

2. Object and subject of the study

The object of the study is a rotary crusher - eccentric type (ERC), considered as a machine for mechanical size reduction of mineral and construction materials. In the work it is analyzed through the design of the rotor, the crushing chamber, the eccentric mechanism, the working clearance, the number of chambers and the rotational operating modes.

The subject of the study comprises the interrelations among the mechanical, kinematic, dynamic and technological parameters of the machine. This means that the focus is not only on the design itself, but on how changes in operating mode and geometry affect the final technological result.

The main relations considered are the dependencies among rotor rotational frequency, width of the discharge opening, number of working chambers, mass productivity, quality of the crushed product, vibration behavior and specific energy consumption.

In this way, the subject covers both the machine as a mechanical system and the crushing process as a technological result.

3. Aim of the dissertation work

The main aim of the dissertation is to study the relationships between the main parameters of the rotary crusher - eccentric type and its energy efficiency, productivity and quality of the crushed product.

The aim incorporates a combined approach that includes theoretical modelling, 3D CAD modelling, FEM/CAE simulations, experimental studies and statistical processing of the results.

The aim is formulated so that it is not limited to describing the design or to a single measurement of separate indicators. It presupposes the study of the entire system of factors through which the working process can be evaluated.

This makes it possible to move from qualitative observations to quantitative dependencies and to a rational selection of operating modes.

4. Research tasks

- To analyze the current state of crushing machines and clarify the place of ERC in classification schemes.
- To substantiate the structural and technological significance of the rotary crusher - eccentric type as a machine with intermediate characteristics between known crushing solutions.
- To develop a theoretical framework for determining the main kinematic, mechanical and technological parameters of the machine.
- To create a 3D CAD model of ERC and use it as a basis for geometrical, strength and simulation studies.
- To perform a FEM/CAE evaluation of the stress-strain state of the main elements under specified operating loads.
- To develop an experimental setup and methodology for studying the working process at controlled values of the main factors.
- To conduct experimental studies with limestone and diabase at different values of frequency, discharge opening and number of chambers.
- To perform grain-size analysis of the finished product and determine the influence of the operating mode on the mean particle size and the share of fine fractions.
- To process the results statistically and evaluate the regression models by R^2, adjusted R^2, P-Value and F-criterion.

- To apply multi-objective optimization to determine rational compromise operating modes of ERC.

5. Control factors and objective functions

The study is structured around three main control factors. They were selected because they can be varied in a controlled manner under laboratory conditions and have a direct influence on the crushing process. Their role is to provide a clear relationship between the machine settings and the measurable output indicators.

Table 1. Control factors.

Control factor	Symbol	Levels/meaning	Role in the process
Actual rotational frequency of the rotor	n	15; 20; 25 Hz	Determines the intensity of the impact, the number of contacts and the dynamic loading.
Width of the discharge opening / working clearance	bmin	3; 4; 5 mm	Determines the throughput capacity and the size of the finished product.
Number of working chambers	z	1; 2	Influences the uniformity of loading and the intensity of the process.
Type of material	M	limestone; diabase	Considered as an experimental condition, not as a main control factor.

The objective functions are defined so that the process is evaluated simultaneously in terms of quantity, quality and energy efficiency. This is important because productivity alone is not sufficient for evaluating a crushing machine. It is necessary to know what product is obtained and what energy consumption is required for obtaining it.

Table 2. Objective functions.

Objective function / indicator	Symbol	Criterion	Meaning
Mass productivity	Qm	Maximization	Quantity of processed material per unit time.
Grain-size composition / mean diameter / D80	y0, Davg, D80	Minimization of Davg/D80 when a finer product is sought	Quality assessment of the finished product.
Specific energy consumption	W = Pavg / Qm	Minimization	Energy consumption related to the quantity of material produced.

This system of factors and functions makes it possible to avoid one-sided evaluation. At a higher frequency, a finer product may be obtained, but with higher energy consumption.

At a larger discharge opening, productivity may increase, but product quality may deteriorate. It is precisely for this reason that the dissertation proceeds to multi-objective evaluation and a rational compromise mode.

6. Research methodology

The methodology of the dissertation is constructed as a sequential engineering scheme. It begins with literature and classification analysis, proceeds through theoretical determination of the parameters, 3D CAD and FEM/CAE study, continues with experimental verification and ends with statistical processing and multi-objective optimization.

Table 3. Research methodology.

Stage	Content	Result
Literature analysis	Review of crushing machines, energy hypotheses, classification and application of ERC.	Determination of the scientific gap and the classification position of ERC.
Theoretical analysis	Kinematics, productivity, power, inertial and peripheral forces.	Formation of an analytical basis for process assessment.
3D CAD and FEM/CAE	Geometrical modelling, static and modal analysis.	Evaluation of structural serviceability and dynamic stability.
Experiment	40 main tests with limestone and diabase under controlled factors.	Experimental database for Qm, Davg/D80, W and vibrations.
Grain-size analysis	Sieve analysis and determination of mean size and fraction shares.	Assessment of the quality of the finished product.
Statistics and optimization	Regression models, ANOVA, R^2, P-Value, F-criterion, utility function.	Rational working region and integrated assessment of efficiency.

7. Scientific novelty and practical applicability

The scientific novelty of the dissertation consists in the systematic consideration of ERC as an independent object of study. The machine is placed in a classification context, the main control factors are defined and objective functions are selected through which the real efficiency of the process can be evaluated.

It is particularly important that the quality of the product is considered through grain-size indicators, while the energy assessment is formulated through specific energy consumption rather than through an unrelated mixing of power and energy.

The practical applicability is expressed in the creation of a methodology that can support the selection of an operating mode.

The obtained experimental data, grain-size dependencies, statistical models and multi-objective assessment can be used when adjusting the laboratory machine, in future improvement of the design and for preliminary assessment of similar crushing systems.

A substantial advantage of the approach is that it does not claim an absolute universal optimum. Instead, it formulates a rational working region valid within the experimental plan and under clearly specified limitations.

This makes the conclusions practically applicable because it accounts for the real contradiction among productivity, energy consumption and quality of the final product.

II. CONTENT OF THE DISSERTATION WORK BY CHAPTERS

1. Chapter I. Literature review and classification position of ERC

Chapter One presents a literature review of the current state of machines and processes for crushing. The classical theoretical formulations for material fracture, the main types of crushing machines and the specific features of their application are considered.

The review places ERC in the context of the development of crushing equipment and shows why this type of machine deserves independent study.

The crushing process is a complex mechanical process in which the fracture of the material depends on the physico-mechanical properties of the particles, the manner of loading, the geometry of the working chamber, the impact velocity and the conditions for discharging the finished product.

Various hypotheses and empirical dependencies have been developed in the literature, but they often provide a general basis and cannot directly describe the specific behavior of a particular machine without experimental verification.

The review considers jaw, roll, rotary and cone solutions. Jaw crushers are widely used for primary crushing and are characterized by a robust design, but their working process is associated with uneven loading, cyclic action and high peak forces.

Roll crushers provide more uniform action and control over product size, but require synchronized motion of two working elements and precise adjustment of the gap.

Rotary and cone machines offer high productivity, but their operating modes and working chambers differ substantially from the design considered here.

ERC is distinguished by eccentric motion of the rotor and periodic variation of the working clearance. This enables it to combine qualities of different machine groups. On the one hand, compression action characteristic of jaw solutions is realized; on the other hand, more uniform rolling and pressing action is obtained, close to the logic of roll machines.

This intermediate structural-technological position is the main reason for considering ERC as a machine with its own place in the classification.

The literature review shows that solutions of this type are connected with developments of "Weserhütte" and with later designs known under various commercial and engineering names. Internationally, interest in eccentric rotary crushers is also maintained by modern industrial developments aimed at compactness, energy efficiency and application in confined spaces.

The Bulgarian school has made a significant contribution to the development of similar solutions, which further substantiates the relevance of the study. The classification clarification of ERC is particularly important in Chapter One. In existing schemes, the machine can often be considered an intermediate or hybrid design.

However, this is not sufficient for engineering assessment. It is necessary to distinguish it according to structural design, technological purpose, scale of application and specific features of the working process. In this way, a basis is created for a clearer formulation of the object of the study.

The comparative analysis in the chapter shows that ERC possesses potential structural and technological advantages: compactness, uniform loading, possibility of adjusting the working clearance, stabilization of the process and prospects for lower specific energy consumption.

However, these advantages cannot be accepted solely on the basis of design logic. They must be verified through theoretical calculations, simulations and experimental data.

On this basis, the literature review identifies the essential scientific gap: there is no sufficiently complete study of the quantitative relationships between the control factors of ERC and the output indicators of the process.

There are insufficient data on how frequency, discharge opening and number of chambers simultaneously affect productivity, grain-size result and energy consumption. Precisely this gap determines the direction of the following chapters.

The conclusion from Chapter One is that ERC should be considered not as an incidental structural variety, but as a promising yet insufficiently studied class of crushing machine. It has a distinct place among traditional solutions and requires its own research methodology.

This methodology must simultaneously account for the mechanical operation of the rotor, the geometry of the working chamber, the experimental conditions and the final technological result.

2. Chapter II. Aim and tasks of the dissertation work

Chapter Two formulates the aim and tasks of the dissertation. It performs a transitional role between the literature review and the author's own research. After Chapter One establishes the need for an independent study of ERC, Chapter Two defines exactly what must be studied and through what sequence of actions the stated aim can be achieved.

The aim is directed toward establishing the relationships among the structural, kinematic, dynamic and technological parameters of the machine. It is not reduced to a description of the machine, but to the search for quantitative dependencies that can serve for evaluation and rational selection of an operating mode.

This is essential because, in crushing machines, a change in one parameter often leads to opposite effects on different indicators. The tasks are arranged so as to follow the natural logic of the research.

First, the existing information is analyzed and the classification position of the machine is formulated. Then theoretical dependencies for productivity, power and loading are developed.

At the next stage, a CAD model is created and simulation evaluation is performed. This is followed by the experimental setup, measurement, grain-size analysis, statistical processing and optimization.

Such ordering is important for the work. If one starts only with the experiment, without a theoretical and structural basis, the results would be difficult to generalize.

If the work remains only at the level of theory and simulation, the real behavior of the machine will not be demonstrated. The combined approach provides a link between model and practice.

Chapter Two also outlines the methodological algorithm of the study. It can be presented as the following sequence: literature analysis -> problem formulation -> theoretical dependencies -> 3D CAD model -> FEM analysis -> experimental plan -> measurement of technological and dynamic indicators -> grain-size assessment -> regression models -> multi-objective optimization -> conclusions and contributions.

In this way, the aim and tasks set the framework of the dissertation and allow the results to be evaluated against clearly defined criteria. This is especially important in the author's abstract because the reader must see that each subsequent chapter has a function in the overall line of proof.

3. Chapter III. Theoretical determination of main mechanical and technological parameters

Chapter Three presents the theoretical basis of the study. It considers the structural arrangement and operating principle of ERC, as well as the main dependencies needed for preliminary assessment of productivity, power and loading. The chapter is of key importance because it creates the transition from the classification substantiation to the real engineering study of the machine.

Structurally, ERC includes a rotor, an eccentric mechanism, a housing, a counter-surface, a discharge opening and one or two working chambers. The working process is characterized by a periodic change in the distance between the rotor and the counter-surface.

The theoretical dependencies for the crushing process include an assessment of productivity, power and force effects. When determining productivity, the working volume of the chamber, the rotational frequency and the conditions for material passage through the discharge opening are taken into account. Thus, it is shown why the width of the opening bmin is simultaneously a factor for throughput capacity and for the size of the finished product.

When determining power and energy loading, a distinction is made among instantaneous electrical power, expended energy and specific energy consumption.

This distinction is important because physically different quantities should not be mixed in the analysis. Power characterizes loading over time, energy is an integral quantity, and specific energy consumption provides a technologically comparable indicator related to the produced mass.

Particular attention is paid to force loading. In the work, inertial, peripheral and contact forces are distinguished. Inertial forces are related to mass and acceleration and can be estimated through measured vibration accelerations.

The peripheral or tangential force is determined through the torque and the radius of application. The real contact crushing force, however, is connected with the direct contact among material, rotor and liner and should not be mechanically identified with the first two quantities.

This terminological and physical distinction increases the scientific precision of the work. It shows that the study does not use a simplified single force for all phenomena, but considers the separate loads according to their origin and role.

In this way, the results from vibration measurements, torque and simulation analysis can be used correctly without overestimating their significance.

A 3D CAD model of ERC is developed in Chapter Three. The model serves as a basis for geometrical analysis, determination of the volumes of the crushing chambers and preparation of the simulation studies. Through it, the main units are visualized and a link is created between the design and the parameters that are later used in the experiment. The CAD model has not only an illustrative, but also a computational function.

FEM/CAE analysis is used to evaluate the stress-strain state of the rotor and the related structural elements. Under specified boundary conditions and loads, stresses, deformations and the safety factor are determined. The results show whether the structure operates within permissible limits and whether there is a risk of unfavorable stress zones under the considered operating modes.

The modal analysis is important for the assessment of dynamic stability. The dissertation notes that the natural frequencies of the rotor are significantly higher than the operating frequencies. This is an important result because it reduces the probability of resonance phenomena in the considered operating range. Thus, the theoretical and simulation part creates a prerequisite for the safe conduct of the experiments.

The conclusions from Chapter Three can be summarized as follows: the eccentric motion of the rotor creates conditions for intensive but controllable action on the material; the geometry of the chamber and the width of the discharge opening are decisive for productivity and product size; force quantities must be considered separately; CAD and FEM analysis confirm the structural serviceability of the machine within the specified limits.

This chapter is particularly important for the author's abstract because it demonstrates that the dissertation is not based only on experimental observations. Before the real tests, an engineering basis is built that makes it possible to understand how and why the separate factors influence the process. Consequently, the experimental part is not isolated, but is a logical continuation of the theoretical formulation

.

Table 4. Theoretical framework.

Indicator	**Generalized dependency / idea**	**Interpretation**
Productivity	Qm = f(n, bmin, z)	Depends on frequency, working volume and discharge conditions.
Specific energy consumption	W = Pavg / Qm	Shows the energy cost per unit of produced material.
Inertial loading	Fin = m·a	Evaluates the dynamic effect from measured vibration accelerations.
Peripheral force	Ft = M / r	Characterizes the loading of the rotor from the torque.
Contact crushing force	Related to material-rotor-liner contact	Not directly identified with Fin or Ft.

4. Chapter IV. Experimental setup, results and grain-size analysis

Chapter Four is one of the most essential parts of the dissertation because in it the theoretical and simulation formulations are verified through real experimental data.

The studies were carried out under controlled laboratory conditions using two materials - limestone and diabase. This makes it possible to trace the influence of the operating mode not only on one specific material, but also under different physico-mechanical characteristics.

The experimental program is constructed as a mixed factorial design. The main control factors are the actual rotational frequency n, the width of the discharge opening bmin and the number of working chambers z. Frequency is considered through its actually measured value, not only through the setting of the frequency inverter. This is an important clarification because the actual operating mode of the machine must be used in statistical processing.

The main plan includes 36 tests and 4 repeat tests in the central region of the plan, i.e. a total of 40 tests. The repeat tests are necessary for assessing the reproducibility and stability of the measuring system.

The additional verification tests are considered separately and do not change the structure of the main factorial plan.

For each test, the sample mass, material moisture, processing time, discharge opening settings, number of chambers and rotational frequency were controlled.

The materials were preliminarily prepared by drying and sieving. This control is necessary because even small differences in the feed material may lead to changes in the final result during grain-size analysis.

The measuring system includes means for recording electrical, vibration and kinematic parameters. The vibration behavior is monitored by an accelerometer, the actual rotational frequency is determined by a tachogenerator, and power and energy loading are evaluated through electrical measurements.

The data were recorded and processed using specialized software, which allows subsequent statistical and spectral processing.

The main results of the experiment are grouped around the objective functions. Mass productivity Qm shows how much material passes through the machine under a specific operating mode. The grain-size indicators Davg and D80 show what product is obtained. Specific energy consumption W shows the energy cost of the produced mass. Thus, each operating mode can be evaluated simultaneously in the three directions.

Grain-size analysis is particularly important because it demonstrates how the operating mode of the machine affects the final product. It is not sufficient to show that the machine passes more material. It is necessary to establish whether the obtained product is finer, more uniform and technologically suitable. Therefore, sieve analysis and calculation of the mean size are a key part of the experimental assessment.

Increasing the frequency from 15 to 25 Hz leads to a decrease in the mean diameter Davg and to an increase in the fine fractions. At lower frequencies, coarser and medium fractions predominate, while at higher frequencies the share of particles below 2 mm increases. This proves that frequency is a strong kinematic factor influencing the intensity of size reduction.

The influence of the discharge opening is opposite in its technological meaning. A smaller opening produces a finer product, but increases the loading and may increase the specific energy consumption.

A larger opening facilitates the passage of material and increases the throughput capacity, but the finished product becomes coarser. This shows why

bmin cannot be selected one-sidedly, but must be considered as a compromise parameter.
The number of working chambers affects the uniformity of the process. Operation with two chambers creates the possibility for more even distribution of loading and stabilization of the process. This result is of practical importance because it shows that the structural configuration of the machine can be used as a means of improving technological behavior.

The comparison between limestone and diabase shows that the type of material is a substantial experimental condition. Harder and more resistant materials change productivity, the grain-size result and energy consumption. Therefore, the material should not be treated as a formal background of the experiment, but as a factor in the interpretation of the results, although it is not a main control factor in the selected scheme.

The vibration results are used to assess the dynamic state of the machine. They provide information about the stability of the operating mode, possible changes at different frequencies and the behavior of the structure during real operation. At the same time, an important clarification is made: vibrations are not used as direct proof of the real contact crushing force, but as a diagnostic indicator.

The comparison between computational estimates and experimental results shows that the theoretical dependencies provide a useful engineering basis, but the final assessment of the process must be made through real measurements.

The conclusions from Chapter Four are a principal evidentiary element of the work. They show that ERC operates stably within the considered range, that n, bmin and z have a clear influence on the results, that grain-size analysis reveals the quality of the product and that the experimental data can serve for statistical modelling and multi-objective assessment.

For the author's abstract, this chapter should be presented in comparatively greater detail. The reason is that it is precisely here that the real operation of the machine and the relationship between operating mode and product are visible. The grain-size curves and mean diameters are a strong argument because they show not only theory, but a concrete technological result.

Table 5. Main conditions of the experimental program.

Element of the experiment	**Accepted value / description**
Materials	limestone and diabase
Rotational frequency n	15; 20; 25 Hz
Discharge opening bmin	3; 4; 5 mm
Number of working chambers z	1; 2
Main plan	36 main tests + 4 repeat tests = 40 tests
Mass of a single sample	3 kg
Processing time	45 s
Main measurements	power, frequency, vibrations, mass, time, grain-size composition

Main output indicators	Qm, Davg/D80, W

Grain-size analysis

Grain-size analysis in the dissertation has independent evidentiary value. Through it, not only the presence of a crushing process is evaluated, but also the quality of the final product. This is important because an efficient crusher must provide a technologically useful product, not merely pass material through the machine.

In sieve analysis, the finished product is divided into fractions, the mass share of each fraction is determined and generalized indicators are calculated. The mean diameter Davg is used as a quantitative assessment of the average size, while D80 indicates the characteristic size below which 80% of the material passes. Thus, the granulometric picture can be transformed into comparable numerical indicators.

The obtained dependencies show that increasing the frequency shifts the grain-size curves toward finer fractions. This is logical because, at higher frequency, the material is subjected to more intensive and more frequent action. At the same time, increasing the frequency cannot be an unconditional recommendation because it also leads to higher energy loading.

This is exactly where the need for multi-objective assessment appears. If only minimum Davg is sought, a mode with the most intensive size reduction would be selected. If only maximum Qm is sought, a larger discharge opening and higher throughput capacity may be selected. If only minimum W is sought, the choice may be different. Therefore, grain-size analysis is an integral part of the overall optimization logic.

5. Chapter V. Statistical analysis and multi-objective optimization

Chapter Five processes the experimental results by statistical methods and lays the foundation of multi-objective optimization. It is the logical culmination of the dissertation because it turns individual measurements into models, dependencies and criteria for selecting an operating mode. Without this chapter, the experiment would remain a set of data; through statistical processing it becomes an instrument for engineering decision-making.

The statistical analysis is directed toward evaluating the influence of n, bmin and z on Qm, Davg/D80 and W. Regression dependencies and criteria for evaluating model adequacy are used for this purpose. The main indicators are the coefficient of determination R^2, adjusted R^2, P-Value and the F-criterion.

These indicators allow one to judge whether the model describes the experimental data sufficiently well and whether the factors are statistically significant.

It is particularly important that the dissertation does not automatically accept every obtained model as a reliable predictive basis. If a given model or factor does not satisfy the statistical criteria, it is not used for final optimization, but only for orientational assessment of trends.

This increases the scientific correctness of the analysis and prevents overestimation of the results.

The regression models have two main functions. The first is analytical - they show the direction and strength of influence of the separate factors. The second is predictive - when the model is statistically acceptable, it can be used to calculate values within the considered experimental region. Thus, a connection is created between the specific tests and the more general engineering assessment.

Multi-objective optimization is necessary because the main goals of the process are partly contradictory. It is not possible unconditionally to maximize productivity, minimize energy consumption and obtain the finest fraction all at the same time.

In the real technological process, a rational compromise is sought. For this reason, the dissertation introduces a generalized utility function that combines the normalized objective functions.

In the multi-objective formulation, the vector of control factors is written as X = (n, bmin, z). The partial objective functions are f1 = Davg(n,bmin,z), f2 = Qm(n,bmin,z) and f3 = W(n,bmin,z). Because these quantities have different dimensions and different directions of optimization, they are normalized into dimensionless form.

For functions that are minimized, the lower value is more favorable; for productivity, which is maximized, normalization is reversed so that all indicators follow the same logic.

The generalized utility function U serves as an integral criterion for comparing operating modes. In the unweighted approach, all objectives are accepted with equal importance. In the weighted approach, coefficients are introduced through which different technological priorities can be taken into account.

For example, priority may be assigned to a finer product, lower energy consumption or higher productivity, depending on the specific production task.

An important result is that optimization is formulated as a search for a rational working region, not as an absolute universal optimum. This is the correct approach because the laboratory model, material type, factor limits and statistical reliability of the models limit the validity of the obtained results. Therefore, the optimum is valid within the specified experimental plan.

The comparison between the unweighted and weighted approach has methodological significance. It shows that the selection of an operating mode can change when technological priorities change. If all objectives are equally weighted, the rational mode may lie in one region.

If product quality and energy consumption carry greater weight, the preferred region may shift. This is practically useful because different production operations have different requirements.
The conclusions from Chapter Five show that statistical processing and multi-objective optimization are applicable to ERC, but only under clearly defined factors, objective functions and validity limits.

They provide an instrument for the joint evaluation of technological, production and energy indicators and make it possible to formulate rational recommendations for operation of the machine.

Table 7. Elements of the statistical analysis.

Element of the statistical analysis	Content	Significance
R^2 and adjusted R^2	Assessment of the variance explained by the model.	Shows how well the model describes the data.
P-Value	Assessment of statistical significance.	At $P \leq 0.05$ the model/factor is accepted as statistically significant.
F-criterion / F-Ratio	Verification of the significance of the regression dependency.	Shows whether the model has statistical meaning.
Normalization	Reducing the different indicators to dimensionless form.	Allows comparison of Davg, Qm and W in one function.
Generalized function U	Integral criterion of utility.	Serves for selecting a rational compromise operating mode.

Logic of multi-objective optimization

Multi-objective optimization in the work is not only a mathematical operation, but an engineering logic for selecting an operating mode. Every crushing machine can be adjusted in different ways, but the choice of setting must be justified.

For ERC, this means answering the question of at what frequency, discharge opening and number of chambers the best combination of quantity, quality and energy economy is achieved.

The generalized function U allows the different operating modes to be ordered by complex efficiency. The mode with a lower value of U is considered more favorable when the normalization criteria and weights are clearly specified.

This does not mean that it is universally the best under all conditions, but that it is the best within the specific task and the specific data.

This approach is a strong element of the dissertation because it shows that the author is not seeking a one-sided maximum or minimum. In real practice, compromise is inevitable.

A good operating mode is not the one that maximizes only one quantity, but the one that provides an acceptable and technologically useful combination of the main indicators.

Extended summary of the methodological scheme

The methodological scheme of the dissertation is important not only as a sequence of research actions, but also as a way of connecting different levels of analysis.

The first level is structural - it answers the question of how the machine is arranged and what geometrical parameters determine the working chamber. The second level is kinematic, which considers how the rotor moves and how the working clearance changes over time.

The third level is dynamic; it accounts for vibration behavior, inertial effects and loading of the main elements. The fourth level is technological, which evaluates the final result through productivity, grain-size composition and energy consumption.

This multi-layered structure is necessary because the crushing process cannot be explained by a single indicator. For example, a high rotational frequency increases the number of impacts on the material, but at the same time changes the dynamic loading and energy indicators.

A smaller discharge opening improves product fineness, but may limit throughput capacity and increase loading. Therefore, every assessment must be complex.

The methodological scheme begins with literature analysis because it substantiates why ERC must be studied independently. If the machine is considered only as a variety of jaw or roll crusher, some of its specific properties remain hidden.

Therefore, the literature review has not only an informational but also a formulative function - it defines the scientific gap and provides grounds for the choice of object and subject.

The next stage is theoretical analysis. It provides a primary engineering picture of the process. It considers dependencies for productivity, power, inertial and peripheral loads. These dependencies are not used as a final description of the real process, but as a basis for formulating expected trends that are then verified experimentally.

The CAD and FEM/CAE stage performs a linking role between theory and experiment. On the one hand, the CAD model determines real geometrical parameters that participate in the calculations. On the other hand, FEM analysis verifies whether the structure can withstand the considered loads. Thus, a situation is avoided in which the experiment is conducted without preliminary structural evaluation.

The experimental part provides the real data needed to demonstrate the influence of the factors. It is organized so as to obtain comparable results under different combinations of n, bmin and z. An important feature is that the actually measured frequency is used, not only the parameter set on the inverter. This increases the reliability of subsequent statistical processing.

Grain-size analysis represents the technological verification of the working result. It transforms the obtained mass of material into measurable fractions and generalized indicators.

Thus, the quality of the product is evaluated quantitatively, not descriptively. This is important in the defense of the work because it shows the concrete effect of the operating mode on the final product.

Statistical processing and multi-objective optimization complete the methodology. Through them, the separate results are converted into dependencies, and the dependencies into a basis for selecting an operating mode. It is emphasized that the rational mode is valid within the considered experimental region and when the statistical reliability of the models is proven.

Extended interpretation of the control factors

The rotational frequency n is the most active kinematic factor in the study. When it increases, the number of interactions among the rotor, material and counter-surface per unit time increases.

This leads to more intensive size reduction and to a decrease in the mean particle size. At the same time, the higher frequency increases dynamic loading and may lead to higher energy consumption. Therefore, n should not be considered only as a means of finer crushing, but as a parameter that simultaneously affects quality, productivity, vibrations and energy.

The width of the discharge opening bmin is the geometrical factor with the most direct technological importance. When bmin decreases, the material is retained more intensively in the size-reduction zone and receives a higher degree of reduction.

This improves the grain-size result, but may increase the resistance to passage and the loading of the machine. When bmin increases, the material is discharged more easily, productivity may increase, but the finished product becomes coarser. Therefore, bmin is a typical compromise factor.

The number of working chambers z is a structural-operating factor that affects the distribution of loading and the uniformity of the process. In a single-chamber configuration, the action is concentrated in one zone, while in a two-chamber configuration the process can be distributed more uniformly.

This is important for stability, vibrations, productivity and product quality. In the work, z is considered a controllable parameter because the chamber configuration can be set in the experimental setup.

The type of material is not included as a main control factor in the sense of a machine setting, but it has substantial importance for interpretation. Limestone and diabase have different physico-mechanical properties, which affects fracture, productivity and energy consumption. Therefore, the results must be interpreted with regard to the material and not transferred mechanically from one material to another.

The combined influence of n, bmin and z is more important than the isolated influence of each factor. For example, high frequency at a small discharge opening may produce a very fine product, but with higher loading. A larger opening at higher frequency may increase productivity, but change the fractional composition. Two-chamber operation may stabilize the process, but its effect must be evaluated together with the other settings. This is precisely why a factorial experiment and statistical processing are necessary.

In the defense of the work, it is important to emphasize clearly that the control factors are selected according to two conditions: they can be controlled and they have physical meaning for the process. This distinguishes n, bmin and z from derived quantities that are calculated or measured but are not direct machine settings. Thus, the factor scheme remains clear and defensible.

Extended interpretation of the objective functions

Mass productivity Qm is the main quantitative indicator. It shows what mass of material is processed per unit time. Under industrial conditions, productivity is critical because it determines the capacity of the entire technological line.

Nevertheless, Qm cannot be the only criterion for efficiency. A mode with high productivity may produce an excessively coarse product or be energetically unfavorable.

The grain-size indicator Davg/D80 is the qualitative center of the study. It shows the real result of the crushing. A lower mean diameter or lower D80 means a finer product, but this must be evaluated in relation to the required technology. The finest product is not always the most economical, but in the study it is an important indicator of the degree of the machine's action on the material.

Specific energy consumption W is the energy criterion. It is more informative than instantaneous power because it connects energy consumption with the produced mass. If power is high but productivity is also high, specific energy consumption may remain acceptable.

Conversely, a mode with low power but very low productivity may be technologically disadvantageous. Therefore, W is the correct indicator for energy assessment.

The three objective functions are partly contradictory. This is the essence of the engineering task. If only Qm is optimized, quality may be neglected. If only Davg is optimized, high energy intensity may result. If only W is optimized, insufficient productivity or an unsuitable product may result.

The generalized utility function does not replace the separate objective functions, but combines them for comparison. Each of them is first normalized so as to be comparable with the others. Then an unweighted or weighted approach can be used. The unweighted approach is suitable for an initial comparison, while the weighted approach is suitable when technological priorities are clearly specified.

The contribution here is that the objective functions are formulated in an engineering and measurable way. Instead of general statements about efficiency, the dissertation uses concrete indicators.

This allows the results to be verified, compared and used in future experiments.

Detailed role of grain-size analysis

Grain-size analysis occupies a central place in proving the technological efficiency of ERC.

In crushing machines, the final product is evaluated not only by the total mass, but also by the distribution of particles by size. This distribution determines whether the product is suitable for subsequent use, classification, beneficiation or construction application. Therefore, grain-size analysis is a direct link between the mechanical action of the machine and the technological value of the obtained material.

In the dissertation, grain-size analysis is based on sieve separation of the product into fractions. For each fraction, the mass share is determined, after which generalized indicators are calculated. This makes it possible to compare different operating modes through numerical results, not only through visual observation. Thus, subjective assessment is avoided and the possibility for statistical processing is created.

Increasing the frequency leads to a shift of the grain-size characteristic toward smaller sizes. This is a logical consequence of the more intensive action, but it also has practical significance. If the aim is to obtain a finer product, increasing the frequency is an effective means. However, if the aim is maximum productivity with limited energy consumption, it must be checked whether increasing the frequency is justified.

The discharge opening affects grain-size through the residence time and conditions of the material in the size-reduction zone. A small opening means stricter control over the maximum size of outgoing particles, but creates greater resistance.

A larger opening allows faster passage, but reduces the degree of size reduction. Therefore, grain-size analysis is a direct way to evaluate the actual effect of changing bmin.

The number of chambers also affects the fractional composition because it changes the organization of the working process. With two chambers, the material may be subjected to more uniform and distributed action, which affects product size and stability. This result is important for future structural improvement of the machine.

In the author's abstract, grain-size analysis must be presented as evidence of product quality. It answers the question: what happens to the material after passing through the machine. This question is especially important because productivity without information about quality is an incomplete assessment of the crushing process.

The grain-size results also have an optimization function. They participate as a qualitative objective function and determine whether a given operating mode is technologically acceptable. In combination with Qm and W, they make it possible to find a mode that not only produces enough material, but also provides the desired size at a reasonable energy cost.

Detailed role of statistical verification

Statistical verification is necessary because experimental data in crushing processes contain natural variation. Differences in particles, feeding, local loading and dynamic behavior can lead to dispersion of the results. Therefore, it is not enough to construct graphs; it is necessary to verify whether the obtained dependencies are statistically significant.

The coefficient R^2 shows what part of the change in the output indicator is explained by the model. A high R^2 is useful, but by itself it is not sufficient. If the model has many terms or if the data are limited, a high value may be obtained without real predictive reliability. Therefore, adjusted R^2 is also used, as it accounts for the structure of the model.

P-Value is particularly important for assessing statistical significance. At the commonly accepted threshold $P \leq 0.05$, it can be accepted that the probability of the observed effect being random is sufficiently small. If the P-Value is unsatisfactory, the model should not be used as the final basis for optimization. This rule is important for the correctness of the work.

The F-criterion or F-Ratio serves to assess the overall significance of the regression dependency. It supplements the information from the P-Value and allows verification of whether the model has statistical meaning. In combination, these criteria determine which dependencies can be used for prediction and which should remain only as orientational trends.

Statistical processing allows reliable dependencies to be separated from uncertain ones. This is particularly important in multi-objective optimization. If inadequate models are included in the generalized utility function, the final optimization result may be misleading.

Therefore, the dissertation correctly emphasizes that multi-objective assessment should be based only on statistically acceptable dependencies or on real experimental values.

The practical meaning of statistics is to transform the experiment into an engineering solution. A table of results shows what has been measured. A statistically verified model shows how the factors influence the process and how behavior within the studied region can be predicted. This is the difference between experimental description and a scientific-applied result.

Formulation of multi-objective optimization

Multi-objective optimization must be formulated carefully. In the dissertation, it does not mean that an absolute universal machine setting has been found for all materials and all conditions.

It means that, within the conducted tests and the specified factor levels, a rational working region can be determined in which the three main criteria are balanced.

This cautious formulation is scientifically correct. The laboratory model operates within certain limits of frequency, discharge opening and number of chambers. The materials are specific - limestone and diabase.

The generalized utility function U serves as a comparison instrument. When all partial functions are normalized, the operating modes can be ordered according to their complex efficiency.

If weighting coefficients are used, they must be justified by technological priorities. For example, in production where product quality is leading, the weight of Davg/D80 may be greater. In production where capacity is critical, Qm may carry greater weight.

It is important to emphasize that U does not cancel the physical meaning of the separate indicators. It does not explain why a given mode is good; it helps compare the modes. The explanation remains in the mechanical and technological interpretation: frequency increases intensity, the opening regulates size and throughput, the number of chambers affects uniformity, and the material determines resistance to fracture.

Thus, multi-objective optimization is a concluding but not independent element. It is strong only because before it there are theory, CAD/FEM, experiment, grain-size analysis and statistics.

This must be clearly presented in the author's abstract in order to avoid the impression that optimization is a formal mathematical operation without a sufficient experimental basis.

Relationship between results and practical application

The practical application of the dissertation is related to the possibility of using the results in the adjustment and development of rotary crushers of eccentric type. The most direct applicability is to the laboratory machine for which the concrete data were obtained.

For it, ranges of frequency, discharge opening and chamber configuration can be recommended according to the desired combination of productivity, quality and energy consumption.

The approach to grain-size analysis is also practically useful. Production machines are often evaluated by capacity, but product quality is just as important. By including Davg/D80 in the objective functions, a more complete assessment is created.

The energy assessment through W = Pavg/Qm has direct application when comparing operating modes. It makes it possible to determine whether an increase in productivity justifies the higher power or whether a finer product is obtained with excessive energy consumption. This is especially important under conditions of high electricity costs.

Finally, the integrated assessment through U can be used as an auxiliary tool in selecting an operating mode. It does not replace the engineering decision, but makes it better justified. Instead of choosing a mode by intuition or by one indicator, several modes can be compared according to a complex criterion.

6. Chapter VI. Conclusion

Chapter Six of the dissertation summarizes the main results from the theoretical, simulation, experimental and statistical study of the rotary crusher - eccentric type. The conclusion has a summarizing character and connects the results of the preceding chapters into a unified engineering assessment of the studied machine.

The main role of this chapter is to show that the development does not end only with separate calculations, experiments or statistical models, but reaches a complete methodology for evaluating the working process of ERC It combines the structural, kinematic, technological, energy and statistical aspects of the study.

The conclusion states that the dissertation applies a complex approach to the study of a rotary crusher - eccentric type, including structural and kinematic analysis, 3D CAD modelling, FEM evaluation of loading, experimental measurements, grain-size analysis and statistical processing of the results.

In this way, a consistent connection is built among the theoretical formulations, the real experimental data and the obtained mathematical models.

An essential conclusion from the chapter is that the study is structured around clearly defined control factors: rotor rotational frequency n, width of the discharge opening/working clearance b / bmin and number of working chambers z. These factors are considered as the main input parameters through which the working process of the machine can be influenced.

On the other hand, the efficiency of the process is evaluated through objective functions related to mass productivity Qm, grain-size composition and mean diameter of the finished product Davg / D80, as well as specific energy consumption W. Thus, the crushing process is considered simultaneously in three directions: quantity of produced material, quality of the crushed product and energy efficiency.

The conclusion emphasizes that the rotary crusher - eccentric type has a specific structural and technological place among crushing machines. It should not be considered only as a variety of roll, jaw or rotary crusher, but as a machine with its own operating principle, its own kinematic scheme and a specific interaction between the working element and the material being crushed.

On the basis of the literature analysis, the conclusion is made that ERC occupies an intermediate but independent place among classical crushing solutions. This is precisely what substantiates the need for its separate study and for its inclusion in the classification schemes of crushing machines as an independent structural-technological class.

In the theoretical part, the results from the determination of the main mechanical and technological parameters of the machine are summarized. The kinematic dependencies, productivity, power, force loading and the influence of geometrical parameters on the working process are considered.

Through 3D CAD modelling and FEM analysis, an evaluation of the stressed and deformed state of the working elements is made, which makes it possible to assess the structural reliability of the machine.

From the experimental studies, it is concluded that changes in rotational frequency, discharge opening and number of chambers have a direct influence on productivity, grain-size composition and energy consumption. The obtained results confirm that the operating mode of ERC must not be selected according to one single indicator, but through simultaneous consideration of several interrelated criteria.

Grain-size analysis has particular importance in the conclusion. Through it, it is demonstrated that the operating mode of the machine directly affects the quality of the final product. It has been established that increasing the rotational frequency increases the intensity of size reduction, leading to a decrease in the mean particle size and an increase in the share of finer fractions. This shows that grain-size composition is a main technological indicator for evaluating the efficiency of ERC.

The conclusion also summarizes the results of the statistical analysis. Through regression models, the influence of the control factors on the main output indicators is described. The obtained dependencies make it possible to predict the behavior of the machine under different operating modes and to determine rational settings according to the technological aim.

Multi-objective optimization is presented as the logical completion of the study. It shows that it is not possible unconditionally to achieve maximum productivity, minimum energy consumption and the finest grain-size composition all at the same time.

Therefore, it is necessary to seek a rational compromise operating mode in which the machine operates effectively both from the point of view of productivity and from the point of view of product quality and energy consumption.

Chapter VI also indicates future directions for development of the research. They are related to expansion of the experimental base, testing of other materials, improvement of the design, refinement of the mathematical models and application of the obtained dependencies in the design and control of rotary crushing machines of eccentric type.

In summary, the conclusion proves that the dissertation fulfills the stated aim. A methodology for complex study of ERC has been created, quantitative dependencies between the control factors and the objective functions have been established, regression models have been built and multi-objective optimization has been applied for selecting rational operating modes.

Chapter VI completes the logic of the dissertation and prepares the transition to the formulation of the contributions.

7. Chapter VII. Contributions of the dissertation work

Chapter Seven formulates the contributions of the dissertation. They summarize the results of the theoretical, structural-simulation, experimental, grain-size and statistical studies conducted on the rotary crusher - eccentric type.

The contributions are formulated not as a general theory of crushing, but as scientific-applied and applied results relating to the specific studied ERC machine, its design, operating modes, control factors, objective functions and evaluation methodology.

The dissertation explicitly states that the contributions relate to the specific machine, its design, operating modes and evaluation methodology, and are not presented as a universal theory of crushing.

The main contribution of the dissertation is that the rotary crusher - eccentric type is considered as an independent object of scientific and engineering research. Its place in the classification of crushing machines is substantiated by showing that it combines structural and kinematic features of different groups of crushing machines, but is not clearly enough distinguished in existing classification schemes.

This is an important scientific-applied contribution because it brings clarity to the place of ERC among jaw, roll, cone and rotary solutions.

The chapter emphasizes that a complex approach to the study of ERC has been developed. This approach includes structural modelling, kinematic analysis, 3D CAD modelling, FEM evaluation of the working element, experimental measurement of operating modes, grain-size analysis, energy assessment and statistical processing of the results.

In this way, the contribution is not only in a single experiment or a single formula, but in building a complete methodology for engineering assessment of the machine.

A substantial contribution is the formulation and use of clearly defined control factors: actual rotor rotational frequency n, width of the discharge opening/working clearance bmin and number of working chambers z. These factors are considered as main input parameters through which the crushing process can be controlled.

The dissertation states that precisely these parameters actually regulate the operation of the machine, while the type of material is taken into account as a control/grouping factor in the analysis.

The scientific-applied contributions also include the definition of the objective functions through which the efficiency of the process is evaluated. The main indicators are mass productivity Qm, qualitative grain-size indicators Davg / D80 / y and specific energy consumption W.

These indicators allow the process to be evaluated simultaneously in terms of quantity, quality and energy efficiency. The dissertation specifies that the grain-size composition is represented through concrete numerical indicators from sieve analysis, not only as a general distribution.

A particularly important contribution is the experimental establishment of the influence of the control factors on the technological indicators of the process.
Through the conducted tests, it is shown how changes in rotational frequency, discharge opening and number of chambers affect productivity and, from there, the mean product size, degree of size reduction and specific energy consumption. This transforms the study from descriptive into quantitatively substantiated.

Grain-size analysis of the finished product should be presented as a separate contribution. It demonstrates how the operating mode of the machine affects the quality of the final product.
Through sieve analysis and calculation of indicators such as Davg and D80, a basis has been created for a real technological assessment of ERC. This is a very strong part of the work because it shows not only how much material the machine processes, but also what product is obtained after crushing.

Chapter Seven also emphasizes the contribution of statistical processing. Through regression models, the quantitative relationships between the control factors and the output indicators are described. These models make it possible to predict the behavior of the machine under different operating modes and to make an engineering-based selection of working settings.

The application of multi-objective optimization is also part of the contributions. It allows productivity, product quality and energy consumption to be taken into account simultaneously. Thus, a one-sided assessment based on only one indicator is avoided and a rational compromise operating mode is reached.

This is important because in real operation it is not sufficient for the machine only to have high productivity; it must also provide a suitable grain-size composition at acceptable energy consumption.

The applied contributions are related to the development and use of an experimental setup for studying ERC. It includes control of rotational frequency, discharge opening, number of working chambers, sample mass and moisture, processing time, energy indicators, vibration state and grain-size composition of the finished product.

Another applied contribution is the creation of an experimental database for the operation of ERC when crushing limestone and diabase. This database can be used for comparing operating modes, adjusting the laboratory machine, future improvement of the design and expanding the studies to other materials.

The practical value of the contributions is expressed in the fact that the results can be used in the design, adjustment, testing and optimization of rotary crushers of eccentric type and similar crushing systems. In doing so, the scale of the machine, the type of material and the limits of the laboratory tests performed must be taken into account.

Chapter VII also includes the publications related to the dissertation. They show that the main results have been presented to the scientific community and are connected with the design, operating principle, study and evaluation of the rotary crusher - eccentric type.

8. Chapter VIII. Appendices

Chapter Eight of the dissertation presents the appendices, which supplement and evidentially support the theoretical, experimental and statistical studies carried out.

This part does not have the character of an independent theoretical chapter, but it is of substantial importance for the traceability of the results because it contains primary and processed data, graphical materials, photographs, diagrams and additional grain-size analyses.

The main role of the appendices is to show that the conclusions in the dissertation are not made only on the basis of summarized results, but are supported by a real experimental database. They include data from sieve analysis, visual documentation of the material, technical diagrams of the measuring system and additional comparative graphs through which the influence of operating modes on the final product is traced.

Subsection 8.1 presents tables with the grain-size characteristics. They contain the data from sieve analysis of the finished product and serve as a basis for determining the mean diameter Davg, the characteristic size D80, the cumulative yield by fractions and the quality of size reduction.

These tables are particularly important because through them the transition is made from experimentally measured mass by fractions to a quantitative assessment of the quality of the finished product.

Subsection 8.2 includes photographs of the material from the selected range. These images have supplementary evidentiary value because they visually show the condition of the product after crushing under different operating modes. Through them, the grain-size analysis is supported and a clearer idea of the actual appearance of the crushed material is given.

Subsection 8.3 presents the electrical connection diagram. It documents the technical implementation of the experimental setup and shows how the elements used for control, measurement and recording of the working parameters are connected. This is important because it demonstrates that the experiments were conducted under controlled and reproducible conditions.

Subsection 8.4 describes the measuring system. The appendices provide technical parameters of the ADXL330 three-axis accelerometer, as well as information about the NI-USB 6001 analog-to-digital converter, through which the analog signals are converted into digital form for subsequent processing and recording.

This part is important because it connects the experimental results with the actual measuring equipment. Thus, it is shown that the vibration and working indicators were not evaluated approximately, but were recorded through a specific measuring system.

Subsection 8.5 presents comparative analyses of the grain-size characteristics by main groups. They compare the results at different rotational frequencies, different discharge openings, different numbers of crushing chambers and different material.

Such comparative graphs make it possible to trace more clearly the influence of the control factors on the quality of the finished product. The appendices provide graphs for ERC operation at specified frequencies of 15, 20 and 25 Hz, different values of the discharge opening and materials such as limestone and diabase.

Subsection 8.6 presents grain-size characteristics of the finished product. This is one of the most important parts of the appendices because it expands the analysis from Chapter IV and provides additional graphs for individual samples.

For example, the appendices indicate a grain-size characteristic at minimum working clearance b = 3 mm and calculated mean diameter Davg = 3.75 mm, as well as separate characteristics for samples at frequency n = 25 Hz, minimum working clearance bmin = 3 mm, one or two working chambers and limestone as material.

Through these additional graphs, it is demonstrated that the grain-size composition of the finished product is directly dependent on the operating mode of the machine. The appendices confirm that changing the frequency, working clearance and number of chambers leads to changes in the distribution by fractions, the mean particle size and the quality of size reduction.

In summary, Chapter VIII performs the role of an experimental and evidentiary base for the dissertation. It contains the data and materials through which the main conclusions from the experimental part, statistical analysis and multi-objective optimization are verified and supported.

The appendices show that the results are traceable, measurable and based on real experimental data. Therefore, in the author's abstract Chapter VIII should be presented not as a separate scientific thesis, but as a supporting part that demonstrates the reliability of the conducted experiments and the justification of the conclusions drawn.

III. GENERAL CONCLUSIONS

1. The dissertation applies a complex methodology for studying a rotary crusher - eccentric type, which combines literature analysis, theoretical dependencies, 3D CAD modelling, FEM/CAE evaluation, experimental measurements, grain-size analysis, statistical processing and multi-objective optimization.
2. The literature review shows that ERC occupies an intermediate position among known crushing solutions, but is not sufficiently clearly distinguished as an independent class in classification schemes. This substantiates the need for an independent study of its structural and technological features.
3. It has been established that the main control factors of the process are the actual rotational frequency n, the width of the discharge opening bmin and the number of working chambers z. The type of material is considered as an important experimental condition that affects the interpretation of the results.
4. The technological efficiency of ERC is evaluated through mass productivity Qm, grain-size indicators Davg/D80 and specific energy consumption W. Thus, the process is considered simultaneously in terms of quantity, quality and energy efficiency.
5. The theoretical analysis shows that the eccentric motion of the rotor creates conditions for periodic variation of the working gap and for intensive action on the material. The geometry of the chamber and the width of the discharge

opening have direct importance for productivity and size of the finished product.

6. The created 3D CAD model provides a geometrical basis for determining the structural parameters, the volume of the crushing chambers and the initial assumptions for simulation and experimental studies.
7. The FEM/CAE analysis confirms that, under the considered loads, stresses and deformations in the main elements remain within permissible limits. The modal analysis shows that the natural frequencies are significantly higher than the operating frequencies, which reduces the risk of resonance in the studied range.
8. An important distinction is made in the work among inertial forces, peripheral/tangential forces and real contact crushing forces. This distinction provides a more precise mechanical interpretation and prevents the mixing of different physical quantities.
9. The experimental studies prove the serviceability of the laboratory ERC and show that changes in n, bmin and z have a substantial influence on the productivity, grain-size result and energy loading of the process.
10. Increasing the frequency from 15 to 25 Hz leads to intensification of size reduction, a decrease in mean diameter Davg and an increase in the share of fine fractions. This confirms the leading role of frequency as a kinematic factor.
11. Decreasing the discharge opening contributes to obtaining a finer product, but increases loading and may worsen energy efficiency. Increasing the opening increases throughput capacity, but leads to a coarser product. Therefore, bmin must be selected as a compromise.
12. Grain-size analysis is a key evidentiary element of the work because it shows how the machine operating mode affects the final product. Through Davg, D80 and the fractional composition, the technological effect of changing the working parameters is demonstrated.
13. Vibration measurements provide information about the dynamic behavior and stability of the operating mode, but they are not used as an independent basis for directly determining the real contact crushing force.
14. Statistical processing makes it possible to assess the influence of the factors and the adequacy of the regression models. Models or factors with unsatisfactory statistical indicators are not used as a final predictive basis for optimization.
15. Multi-objective optimization through a generalized utility function allows complex evaluation of the operating modes. It does not prove a universal

absolute optimum, but determines a rational compromise working region within the experimental plan.

16. The obtained results show that ERC can be evaluated through an integrated system of indicators combining productivity, grain-size composition, energy consumption and dynamic behavior. This creates a basis for a more justified selection of operating modes and for future improvement of the design.

Summary of the conclusions according to the scientific logic of the work

The most important general conclusion is that the dissertation builds a consistent relationship between the industrial problem and the engineering solution. The problem is the energy intensity and the need for more efficient crushing machines.

The scientific gap is the insufficient study and classification distinction of ERC. The methodology includes theory, CAD/FEM, experiment, grain-size analysis, statistics and optimization. The result is a system of quantitative dependencies and rational modes through which the machine can be evaluated by productivity, quality and energy efficiency.

Each part has a clear function. The literature review substantiates why the machine must be studied. The theoretical part shows what parameters control the process. The CAD/FEM analysis verifies structural serviceability. The experiment demonstrates the real behavior. Grain-size analysis shows the quality of the product. Statistics assesses the reliability of the dependencies. Multi-objective optimization provides an engineering-applicable conclusion.

IV. SCIENTIFIC-APPLIED AND APPLIED CONTRIBUTIONS

1. Scientific-applied contributions

- The place of the rotary crusher - eccentric type in the classification of crushing machines is substantiated by showing that ERC combines structural and kinematic features of several groups of crushing machines, but requires independent classification consideration.
- A system of control factors for the study of ERC is defined: actual rotational frequency n, width of the discharge opening bmin and number of working chambers z. This creates a clear basis for experimental and statistical modelling.
- The main objective functions for process evaluation are determined: mass productivity Qm, grain-size indicators Davg/D80 and specific energy consumption W. Thus, the process is evaluated simultaneously by quantity, quality and energy efficiency.

- A complex theoretical-experimental methodology for studying ERC is developed and applied, including structural analysis, kinematic dependencies, CAD/FEM modelling, experimental measurements, grain-size analysis and statistical processing.
- The grain-size composition of the finished product is reduced to quantitatively measurable indicators, which allows comparison of operating modes at different frequencies, openings, number of chambers and materials.
- The mechanical interpretation of loading is refined by distinguishing inertial, peripheral and contact forces, which increases the correctness of the analysis of the working process.
- Preconditions are created for regression modelling of the influence of n, bmin and z on the technological indicators, using statistical criteria for assessing model adequacy.
- Multi-objective optimization is applied through a generalized utility function, which allows determination of a rational working region under conflicting objectives - fine size reduction, high productivity and low energy consumption.
- An integrated approach is proposed for evaluating the efficiency of ERC, combining technological, energy, grain-size and dynamic indicators.

2. Applied contributions

- A spatial 3D CAD model of the laboratory ERC is created and used to determine geometrical parameters, volumes of the crushing chambers and initial assumptions for simulation studies.
- A FEM evaluation of the stress-strain state of the rotor and related elements under specified operating loads is carried out, serving for assessment of structural stability.
- An experimental setup for studying ERC is developed and applied, including control of frequency, discharge opening, number of chambers, mass and moisture of the samples, processing time, energy indicators, vibrations and grain-size composition.
- An experimental database for crushing limestone and diabase is obtained, which can be used when comparing operating modes and in future improvement of the laboratory machine.
- Practical guidelines are formulated for selecting operating modes through simultaneous consideration of n, bmin, z, Qm, Davg/D80 and W.

- The results can be used in the design, adjustment and experimental study of rotary crushers of eccentric type and similar crushing systems, while taking into account the scale of the machine and the type of material.

3. Arrangement of the contributions around the main thesis

The contributions of the dissertation should not be perceived as separate unrelated results. They are arranged around one main thesis: ERC can be studied, evaluated and optimized as an independent structural-technological class of machine through a system of control factors, objective functions, experimental data, regression models and multi-objective assessment.

The strongest contribution is the classification and methodological distinction of the machine. It is followed by the quantitative dependencies, grain-size analysis, regression models, rational modes and integrated assessment of efficiency.

Thus, the contributions form a complete scientific-applied line, not merely a list of technical actions.

V. PUBLICATIONS RELATED TO THE DISSERTATION WORK

Main results of the dissertation are presented in the following publications:

1. DESIGN AND OPERATING PRINCIPLE OF THE ROTARY CRUSHER - ECCENTRIC TYPE "ERC", Mining and Geology, 2025, ISSN 0861-5713, ISSN 2603-4549 (Online).
2. STATIC AND MODAL ANALYSIS OF AN ECCENTRIC ROTOR OF AN ECCENTRIC ROTOR CRUSHER ERC, Mining and Geology, 2026, ISSN 0861-5713, ISSN 2603-4549.

The publications present the structural-functional basis of the machine and the simulation assessment of the eccentric rotor. They are directly connected with the main parts of the dissertation and support the scientific-applied orientation of the study.

VI. CONCLUSION

The dissertation considers the rotary crusher - eccentric type as a promising but insufficiently studied machine for size reduction. The study is motivated by the industrial problem of increasing the efficiency of crushing processes and by the need to clarify quantitatively the relationships between the machine parameters and the process results.

The work applies a methodology for theoretical, simulation, experimental and statistical study of ERC. It combines mechanical, kinematic, dynamic and technological parameters and allows the process to be evaluated through productivity, quality of the crushed product and specific energy consumption.

The experiments conducted with limestone and diabase show the influence of the actual rotational frequency, the discharge opening and the number of working chambers on productivity, grain-size composition and energy indicators.

Grain-size analysis proves that increasing the frequency leads to a decrease in the mean particle size and an increase in the fine fractions, but the choice of operating mode must also take into account the energy cost of size reduction.

Statistical processing and multi-objective optimization make it possible to formulate rational working regions in which a balance among quantity, quality and energy efficiency is sought. This is a substantial practical result because real operation requires compromise, not one-sided optimization of a single indicator.

The obtained results have scientific-applied value because they distinguish ERC as an independent object of study and propose a system for evaluating its efficiency.

The practical value is expressed in the possibility of using the methodology and dependencies in the design, adjustment, experimental study and future improvement of similar crushing machines.

In conclusion, it can be accepted that the dissertation contributes to the development of theory and practice in the field of rotary crushing machines by proposing a consistent approach for analysis, experimental verification and rational selection of operating modes of a rotary crusher - eccentric type.

Table 8. Main theses.

Main thesis	**Content**
Industrial problem	Crushing is an energy-intensive process and requires machines with better productivity, quality and energy efficiency.
Scientific gap	ERC is not sufficiently clearly distinguished and quantitatively studied as an independent class of machine.
Methodology	Theory + 3D CAD + FEM + experiment + grain-size analysis + statistics + multi-objective optimization.
Result	Dependencies and rational modes are determined through n, b, z, Qm, Davg/D80 and W.
Contribution	Integrated assessment of the efficiency of ERC and methodology for future application.

This author's abstract presents the main results, conclusions and contributions of the dissertation devoted to the study of mechanical and technological parameters of a rotary crusher - eccentric type.

The development is directed toward a current industrial problem: the need to increase the efficiency of crushing processes through machines that provide a better combination of productivity, quality of the crushed product and specific energy consumption.

In the dissertation, the rotary crusher - eccentric type is considered not only as a structural variety of known crushing solutions, but as an independent object of engineering and scientific-applied research.

Its intermediate but specific position among jaw, roll, rotary and cone crushing machines is substantiated. This gives grounds for considering ERC as a separate structural-technological class that requires its own methodology for analysis, experimental verification and optimization.

The work applies a complex approach that combines literature and classification analysis, theoretical determination of mechanical and technological parameters, 3D CAD modelling, FEM/CAE assessment of loading, experimental studies, grain-size analysis, statistical processing and multi-objective optimization.

Thus, the separate parts of the study are connected in a unified methodological sequence, and the results are not considered in isolation but as mutually complementary evidence.

The theoretical part creates an engineering basis for process assessment by distinguishing productivity, power, energy, specific energy consumption, inertial, peripheral and contact loads. CAD and FEM analysis complement this basis through assessment of structural serviceability and dynamic behavior of the main elements. In this way, a link is made among the geometry of the machine, the operating mode and the expected loading.

The experimental part demonstrates the real behavior of ERC under controlled conditions. Through tests with limestone and diabase, the influence of frequency, working clearance and number of chambers on productivity, grain-size composition, energy indicators and vibration state is established.

Grain-size analysis has particular significance because it shows not only the quantity of processed material, but the quality of the obtained product. It is established that increasing the rotational frequency leads to more intensive size reduction, a decrease in the mean particle size and an increase in the share of fine fractions.

Statistical analysis transforms the experimental results into quantitative dependencies. Through regression models, the influence of the control factors on the main output indicators is described, and model adequacy is evaluated through R^2, adjusted R^2, P-Value and F-criterion. This allows the results to be used not only to describe the performed tests, but also as a basis for an engineering-justified selection of operating modes.

Multi-objective optimization represents the logical conclusion of the study. It accounts for the fact that, in the real process, maximum productivity, minimum energy consumption and the finest product cannot be achieved unconditionally at the same time.

Therefore, a rational compromise operating mode is sought in which the quantitative, qualitative and energy indicators are combined. Thus, ERC is evaluated through an integrated system of criteria, not through a one-sided assessment based on only one output indicator.

The formulated contributions show that the dissertation has scientific-applied and practical value. The scientific-applied value is expressed in distinguishing ERC as an independent object of study; in defining a system of control factors and objective functions; in building a methodology for theoretical, experimental and statistical study; and in obtaining quantitative dependencies for process assessment. The practical value is related to the possibility of using the results in the design, adjustment, testing and improvement of rotary crushers of eccentric type and similar crushing systems.

In conclusion, it can be accepted that the stated aim of the dissertation has been fulfilled. A complete methodology for studying a rotary crusher - eccentric type has been developed and applied, through which relationships among the structural, kinematic, dynamic and technological parameters of the machine have been established.

The obtained results prove that the efficiency of ERC must be evaluated comprehensively - through productivity, grain-size composition, specific energy consumption and stability of the working process.

In this way, the dissertation contributes to the development of the engineering methodology for analysis and assessment of crushing machines by placing the rotary crusher - eccentric type within a clear scientific-applied framework.

The study creates a basis for future improvement of the design, expansion of the experimental base, study of other materials and application of the obtained dependencies in the development and adjustment of more efficient crushing systems.