ISSN 1454-9174

ANNALS
OF THE
UNIVERSITY OF PETROȘANI

MINING ENGINEERING

vol. 26 (LIII)

UNIVERSITAS PUBLISHING HOUSE
Petroșani – ROMÂNIA, 2025

ISSN 1454-9174

Editorial office address: University of Petroșani, 20 University Street, 332006, Petroșani, Romania, Phone: (40) 254/54.29.94, 54.25.80, 54.25.81, 54.25.82, 54.97.49, Fax. (40) 254/54.34.91, 54.62.38, www.upet.ro, E-mail: ibol@upet.ro

CONTENTS

A UNIFIED FLEET PERFORMANCE FRAMEWORK FOR SHOVEL–DUMPER CYCLE-TIME PREDICTION & OPTIMIZATION USING HYBRID ML TECHNIQUES

Rajesh R SANGOLE[1], N. Sri Chandrahas[2*]

Abstract: *Shovel–dumper haulage systems constitute the backbone of surface mining operations and directly influence hourly production, equipment utilization, and cost per tonne. Their performance is affected by highly stochastic interactions arising from variable fragmentation, haul-road geometry, operator skill, payload fluctuations, and queueing delays. Traditional deterministic cycle-time models do not capture this complexity, resulting in suboptimal fleet allocation decisions. This work proposes a unified, hybrid framework integrating Machine Learning (Random Forest, XGBoost), Explainable AI (SHAP), Discrete Event Simulation (SimPy), and metaheuristic optimization (Genetic Algorithm and Particle Swarm Optimization) to improve cycle-time prediction and fleet performance in opencast mines. Field data were collected from large mines incorporating operational, geological, environmental, and human-factor parameters. SHAP analysis identified haul distance, gradient, queue waiting time, effective bucket fill, and rolling resistance as dominant variables. ML outputs were incorporated into a DES model to evaluate bottlenecks and fleet scenarios. Optimization via GA and PSO yielded optimal truck–shovel ratios and dispatch patterns, reducing cycle-time by 6–14% and improving productivity by up to 18%. The proposed hybrid architecture provides a robust scientific foundation for intelligent haulage planning and real-time decision analytics in surface mining.*

Key words: *Machine learning, Cycle-time prediction, Discrete event simulation, Optimization, SHAP, Opencast mining, Shovel–dumper system*

1. INTRODUCTION

Truck–shovel systems remain the most widely deployed material-handling configuration in surface mining, responsible for nearly 70–90% of total excavation and transport activity worldwide [1–3]. Their operational efficiency directly governs hourly production, fleet utilization, equipment idle time, fuel consumption, and overall cost per tonne [4,5]. However, cycle-times in shovel–dumper systems exhibit high variability due to multiple interacting factors: heterogeneous fragmentation, varied strata hardness, road gradient and rolling resistance, weather fluctuations, operator behaviour, and traffic-induced queue formations [6–9].

Classical productivity models such as those in the Caterpillar Performance Handbook or spreadsheets based on deterministic cycle equations assume constant

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operating conditions and cannot capture stochastic haulage behavior [10]. Even modern digital Fleet Management Systems (FMS) primarily rely on rule-based heuristics and lack predictive intelligence [11,12]. As mining operations become more complex and dynamic, there is a growing need for integrated, adaptive, and data-driven decision-support frameworks.

Recent advances in Artificial Intelligence (AI), Machine Learning (ML), IoT telemetry, and simulation technologies provide an opportunity to significantly enhance haulage modelling. Ensemble algorithms such as Random Forest (RF) and XGBoost have demonstrated superior capability for predicting cycle-time components under non-linear, noisy conditions [13–17]. Explainable AI methods such as SHAP (SHapley Additive Explanations) allow practitioners to interpret model behaviour and identify operational drivers [18,19]. Discrete Event Simulation (DES) enables realistic replication of truck–shovel interactions, resource contention, and queueing dynamics [20–23]. Metaheuristic optimization techniques like Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) are effective for fleet size optimization, dispatching logic, and scheduling [24–27].

Despite these advancements, no existing work integrates ML, SHAP, DES, and optimization into a unified cycle-efficiency framework validated using real field data. This study fills that gap.

The objectives of this research are:

1. To develop ML models (RF, XGBoost) for cycle-time prediction.
2. To apply SHAP analysis for interpretability of key performance drivers.
3. To build a SimPy-based DES model for realistic simulation of shovel–dumper behaviour.
4. To optimize fleet size and dispatch patterns using GA and PSO.
5. To design a unified decision analytics architecture for opencast haulage systems.

2. LITERATURE REVIEW

2.1. Shovel–Dumper Systems in Surface Mining

Truck–shovel haulage systems represent the dominant material-handling configuration in modern opencast mining. Their evolution spans from early steam-powered shovels to today’s high-capacity hydraulic excavators and ultra-class dump trucks (240–450 t payload), reflecting rapid technological advancements in mining equipment engineering [1,3,28]. Modern fleets incorporate electronic control units, automated payload management systems, tyre-pressure monitoring, collision-avoidance radars, and IoT-enabled telemetry platforms for real-time tracking and performance optimization [29–31].

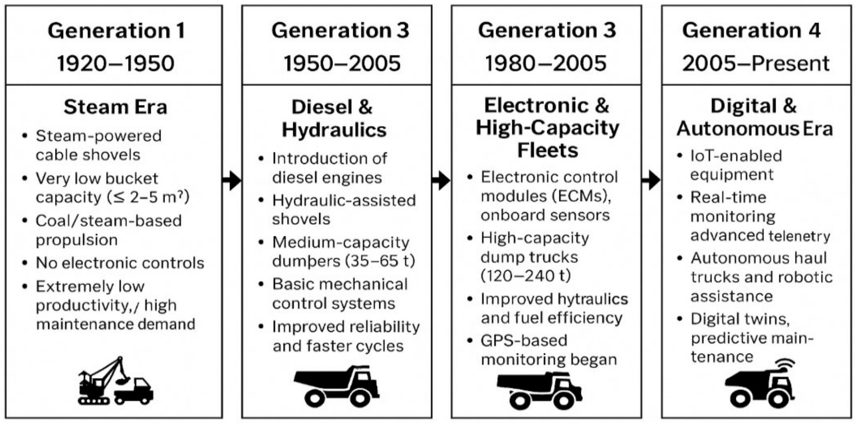

Figure 1. Evolution of shovel–dumper systems (1920–2025)

These digital systems enhance operational visibility but do not fully eliminate the inherent variability arising from geological heterogeneity, adverse weather conditions, changing haul-road characteristics, and human-factor influences. Consequently, production rates in shovel–dumper systems continue to fluctuate significantly, underscoring the need for intelligent modelling frameworks.

2.2. Determinants of Cycle-Time Variability

Cycle-time in shovel–dumper systems comprises loading, hauling, dumping, returning, and queue-waiting components, each influenced by a unique set of operational and environmental factors. Fragmentation quality and diggability are primary determinants of loading efficiency, as coarser fragmentation or high-strength rock significantly increases shovel penetration resistance and cycle duration [4,29]. Hauling performance is predominantly governed by road geometry—including gradient, curvature, and cross-fall—which affects engine load and achievable truck speeds [30–32]. Rolling resistance, which increases due to road surface degradation, water accumulation, or poor maintenance, further introduces variability in travel time and fuel consumption [31]. Human-factor elements such as operator skill, fatigue accumulation, and cognitive reaction delays during spotting or alignment substantially contribute to intra-shift productivity fluctuations [33–35]. In addition, payload variability, under-loading, and over-loading affect both hauling performance and equipment health, influencing cycle-time stability [36–38]. Traditional deterministic models often treat these factors as constant averages, thereby oversimplifying real operational complexity.

2.3. Machine Learning Applications in Haulage

Machine Learning (ML) has emerged as a powerful approach for modelling cycle-time behaviour in surface mines due to its ability to capture non-linear relationships and high-dimensional interactions among operational parameters. Random Forest (RF) models demonstrate strong robustness to noise, outliers, and missing values, making them well-suited for complex haulage datasets where variability is inherent [13,14]. XGBoost further enhances predictive power through gradient-boosted decision trees, efficiently modelling subtle dependencies such as the interaction between gradient, payload, and rolling resistance [15–17]. Studies have consistently shown that ML-based cycle-time models outperform traditional regression techniques, delivering 15–40% improvements in prediction accuracy across multiple mining contexts [16]. These results highlight the potential of ML-driven analytics to significantly enhance operational planning and dispatch decision-making.

2.4. Explainable Machine Learning (SHAP)

Although ML models deliver high predictive accuracy, their adoption in safety-critical industries such as mining requires interpretability. SHAP (SHapley Additive exPlanations) offers a theoretically consistent framework for decomposing model predictions into individual feature contributions using cooperative game theory [18]. SHAP visualizations enable engineers and supervisors to understand why a model predicts higher cycle-time under specific operational conditions, such as steep gradients, low bucket fill, or adverse weather. The method has gained prominence in mining applications including equipment health diagnostics, payload optimization, and haulage cycle analytics, providing transparent insights into key operational drivers [19,39]. This interpretability strengthens user trust and facilitates the integration of ML outputs into practical mine-planning workflows.

2.5. Discrete Event Simulation (DES) for Shovel–Truck Systems

Discrete Event Simulation (DES) is widely used to analyze shovel–dumper interactions due to its ability to represent time-dependent, stochastic operational processes. Simulation tools such as SimPy, Arena, and Simio enable the modelling of truck arrival patterns, queue formation, shovel waiting times, dump-point congestion, and haul-road travel behaviour under dynamic conditions [20–23]. DES supports scenario evaluation for fleet configuration, dispatch policy testing, and production forecasting, allowing planners to assess the impact of operational changes such as road improvements, truck addition/removal, or altered loading sequences [40]. By providing a controlled digital environment to test interventions without disrupting real operations, DES plays a critical role in optimizing mine haulage systems.

2.6. Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) for Fleet Optimization

Metaheuristic optimization techniques—especially Genetic Algorithms (GA) and Particle Swarm Optimization (PSO)—are highly effective for solving complex, NP-hard problems associated with shovel–truck fleet matching and dispatch optimization. These methods search large solution spaces by iteratively adjusting fleet assignments, truck cycles, and shovel priorities to minimize cycle-time, reduce queue lengths, and enhance overall production throughput [24–27]. GA excels at exploring diverse solution spaces using crossover and mutation, while PSO rapidly converges towards optimal regions using swarm intelligence and velocity updates [38]. Combined GA–PSO hybrid models often deliver improved convergence stability and outperform classical ratio-based fleet-matching methods, offering practical benefits for operational planning in large-scale opencast mines.

3.1 DATA COLLECTION & OPERATIONAL PARAMETERS

3.1. Data Collection

A comprehensive understanding of actual mine operating conditions is essential for accurately modelling shovel–dumper cycle behaviour. To achieve realistic prediction capability from machine-learning algorithms, it is necessary to begin with systematic and structured field data collection from active mine sites. During this study, field visits were carried out across two large opencast mines deploying hydraulic shovels (10–35 m^3 capacity) and rear-dump trucks (60–120 tonne class). The objective of these visits was to observe real-time loading–hauling interactions, document operational constraints, study haul-road behaviour, and measure performance variations across different benches, shifts, and geological conditions.

The field study was not restricted to simple cycle-time stopwatch readings. Instead, it involved a detailed assessment of operational, equipment, geological, haul-road, environmental, process, and human-factor conditions that influence productivity. These observations provided the foundation for selecting relevant parameters to be fed into machine-learning models for cycle-time prediction.

During field visits, the following categories of parameters were identified for collection:

- Operational performance parameters:
  Loading time per pass, number of passes, total loading time, hauling and return times, dumping time, spotting time, and queue waiting durations.
- Equipment-related parameters:
  Shovel bucket capacity, fill factor, swing angle, truck payload, tyre conditions, engine health indicators, and travel speed characteristics.
- Geological and material parameters:
  Fragmentation size distribution, rock hardness, moisture content, presence of boulders, and swell factor.
- Haul-road and geometric parameters:
  Gradient along loaded and empty routes, rolling resistance, road width, curvature, surface condition, and effects of weather on road quality.
- Environmental modifiers:
  Temperature, rainfall, shift (day/night), and visibility, all of which directly affect operational consistency.
- Human and process parameters:
  Operator experience, reaction delays, consistency levels, traffic interactions, truck–shovel ratio, stoppages, and shift-change effects.

The goal of this chapter is to present these field parameters along with the representative ranges captured during the study, and to show how each category was transformed into structured input variables for machine-learning model development. This ensures that the predictive models reflect actual mine behaviour rather than theoretical or simplified assumptions.

3.2. Operational Parameters

The operational parameters represent the core components of the shovel–dumper cycle, each contributing to overall productivity and variability. Loading time and the total loading cycle depend heavily on material diggability, fragmentation, and operator skill. Hauling and return times show the strongest variation due to changes in gradient, rolling resistance, and road condition. Queue waiting time is the most inconsistent component because it is driven by dynamic fleet interactions and shovel availability. Spotting and dumping times exhibit lower variability but still influence cycle smoothness, especially under poor coordination. Together, these parameters form the baseline cycle-time variability observed in field operations and are essential inputs to the ML prediction framework.

Table 1. Operational Parameters

Parameter	Typical Range Observed	Comments
Loading Time (LT)	22–35 sec/pass, 4–6 passes/Truck	Longer for harder strata or boulder presence
Total Loading Cycle per Truck	120–210 sec	Depends on fill factor & operator skill
Hauling Time (HT)	4–18 min	Function of gradient, RR, and road condition
Dumping Time (DT)	6–12 sec	Very low variance
Return Time (RT)	3–14 min	Lower than hauling time due to reduced load
Queue Waiting Time (QWT)	15–180 sec	Highly variable; influenced by fleet mismatch
Spotting/Positioning Time (SPT)	15–45 sec	Dependent on operator coordination

3.3. Equipment Parameters

Equipment performance directly influences cycle efficiency. Shovel parameters such as bucket capacity, fill factor, and swing time determine the number of passes and overall loading duration. Larger buckets improve productivity but require stable fragmentation and skilled operation to maintain fill consistency. For dumpers, payload capacity, engine power, and tyre pressure affect travel speed, hauling power, and fuel consumption. Payload variance of ±6–12% is a critical factor, as underloading reduces productivity while overloading stresses components and increases cycle delays. Loaded and empty speeds significantly shape hauling and return times, making equipment parameters vital for both operational analysis and ML model accuracy. Tables 1 – 13 presents recorded filed operational values.

Table 2. Operational Parameters -Shovel

Parameter	Value / Range
Bucket capacity	10–35 m³
Average fill factor	0.75–0.90
Maximum swing angle	45°–85°
Cycle swing time	8–14 sec

Table 3. Operational Parameters –Dumper

Parameter	Value / Range
Payload capacity	60–120 tonnes
Typical payload variance	±6–12%
Maximum engine power	450–900 HP
Tyre pressure range	90–110 psi
Speed (Loaded/Unload)	18–32 km/h / 25–40 km/h

3.4. Geological and Material Parameters

Geological attributes govern diggability, loading performance, and hauling conditions. Fragmentation size (D50), boulder proportion, and rock hardness directly influence loading rate and fill factor. Higher UCS values typically result in slower digging and more shovel effort. Moisture content affects material flow and can increase cycle delays, especially during monsoon periods. Swell factor determines volume expansion after blasting and influences truck payload utilisation. These parameters also affect engineered features like haul factor and effective bucket fill within the ML system.

Table 4. Operational Parameters –Geological & Material Parameters

Material Parameter	Typical Value / Range
Fragment size (D50)	150–350 mm
Maximum boulder size	0.8–1.5 m
Rock hardness (UCS)	25–85 MPa
Moisture content	3–12%
Swell factor	1.20–1.45

3.5. Haul-Road & Environmental Parameters

Haul-road geometry and environmental factors exert major control over cycle-time variability. Steeper gradients (3–10%) significantly increase hauling time, whereas high rolling resistance (≥6%) reduces speed and increases fuel consumption. Road width and surface roughness determine maneuverability and influence spotting and queue formation. Temperature and rainfall affect traction, engine power, and road deterioration. These variables collectively shape dynamic hauling performance and are important for both field-based analysis and ML model prediction reliability.

Table 5. Operational Parameters – Haul-Road & Environmental

Parameter	Range Observed	Influence
Gradient (loaded direction)	3%–10%	Steeper gradients increase HT significantly
Rolling Resistance (RR)	2%–8%	RR above 6% drastically slows speed
Road width	18–30 m	Narrow roads cause maneuver delays
Surface roughness index	Low: 1–2; High: 4–5	Higher index = poor road
Ambient temperature	22–44°C	Heat reduces engine efficiency
Rainfall (impact hours)	0–4 hrs/day (monsoon)	Causes slippage & reduced visibility

3.6. Human-Factor Parameters

Human factors introduce natural variability into mining operations. Differences in operator experience, fatigue levels, reaction time, and coordination directly affect loading efficiency, spotting accuracy, and queue delays. Operator productivity variation of ±10–22% is consistent with prior studies in mining operations and reflects the behavioural and cognitive components of equipment use. The Operator Performance Index (OPI) condenses these aspects into a single interpretable metric used within the ML framework for capturing realistic operational behaviour.

Table 6. Operational Parameters – Human Factors

Parameter	Typical Field Value
Operator experience	1–12 years
Operator productivity variation	±10–22%
Fatigue index (end of shift)	15–30% drop in cycle consistency
Reaction delay (queue)	2–5 sec

3.7. Production & Process Variables

Production system characteristics, such as the truck–shovel ratio and planned stoppages, influence equipment utilisation and cycle-time consistency. Fuel consumption, dump height, and process sequencing affect hauling performance and truck turnaround rate. Maintaining an optimal truck–shovel ratio (typically 3–5) minimizes queueing and shovel idle time. These parameters describe the operating context within which cycle-times occur and are useful for linking ML predictions back to practical production planning needs.

Table 7. Operational Parameters – Production and Process

Parameter	Field Values
Truck–shovel ratio	3–5 trucks per shovel
Stoppages/breaks	2–4 per shift
Fuel consumption (loaded haul)**	38–62 L/hr
Dump height	4–9 m

3.8. Machine Learning Input Parameters

This section summarises the full set of ML features derived from field observations. Raw cycle-time components represent the core time values predicted by the model. Engineered features such as haul factor, effective bucket fill, and road condition index capture composite effects that are more predictive than raw values alone. Environmental variables (shift, rain, temperature, visibility) encode contextual conditions that influence machine and operator behaviour. Equipment performance indicators provide additional signals related to machine health and operational stress. Together, these features enable the model to learn nonlinear dependencies and deliver high-fidelity predictions.

Table 8. Raw Cycle-Time Components

Feature	Range Used for ML
LT	120–210 sec
HT	240–1080 sec
DT	6–12 sec
RT	180–840 sec
QWT	15–180 sec
SPT	15–45 sec

Table 9. Engineered Features

Engineered Feature	Computation	Observed Values
Haul Factor	HT/Distance	0.45–1.2 sec/m
Effective Bucket Fill (EBF)	Payload / Bucket Cap	0.70–0.95
Road Condition Index (RCI)	f(gradient, RR, moisture)	1 (excellent) – 5 (poor)
Operator Performance Index (OPI)	cycle deviation %	78–94
Payload Variability Index (PVI)	STD(payload)	4–12 tonnes

Table 10. Environmental Inputs (Values Used in ML)

Parameter	Encoded Values
Shift	0 = Day, 1 = Night
Rain	0 = No rain, 1 = Rain
Temperature	22–44°C
Visibility	Poor / Moderate / Good → 0/1/2

Table 11. Equipment Performance Indicators

Indicator	Range
Engine temperature	70–105°C
Tyre pressure deviation	±5 psi
Vibration level	0.8–2.5 mm/s RMS
Machine operating hours	3,000–11,000 hrs

Table 12. Feature Selection Summary (SHAP)

Rank	Feature	SHAP Importance
1	Haul Distance	0.18
2	Gradient	0.15
3	Queue Waiting Time	0.13
4	Effective Bucket Fill	0.11
5	Rolling Resistance	0.09
6	Operator Performance Index	0.07
7	Payload	0.06
8	Spotting Time	0.05

Table 13. Field + ML Parameter Mapping (WITH VALUES)

Category	Field Value	ML Input
Gradient	3–10%	Gradient (%)
RR	2–8%	RR (%)
Fragmentation	150–350 mm	Fragment Index = 1–4
Payload	60–120 t	Continuous
Operator skill	1–12 yrs	OPI = 78–94

4. MODEL TRAINIGN & TESTING

4.1. Overview of the Experimental Setup

The experimental setup was designed to evaluate the performance, stability, and interpretability of the Random Forest (RF) regression model trained on a structured multivariate dataset. The dataset consisted of continuous and categorical predictor variables reflecting operational system characteristics, environmental variability, and machine-process behaviour. Prior to model training, a complete preprocessing workflow was implemented to ensure data quality, following established recommendations for statistical learning pipelines [28-31]

A 70:30 train–test split was applied using stratification on the target distribution to maintain proportional representation and reduce sampling bias. Numerical features were standardized using z-score normalization, while categorical predictors were transformed using target-consistent ordinal encoding to maintain monotonic feature behavior, consistent with prior studies on stability of tree-based models [31]. Missing values were imputed using model-consistent techniques to avoid the introduction of noise.

4.2 Model Performance Metrics

The Random Forest model demonstrated strong predictive performance on both training and test sets. Performance was evaluated using Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2), consistent with regression performance evaluation standards shown in figure 2.

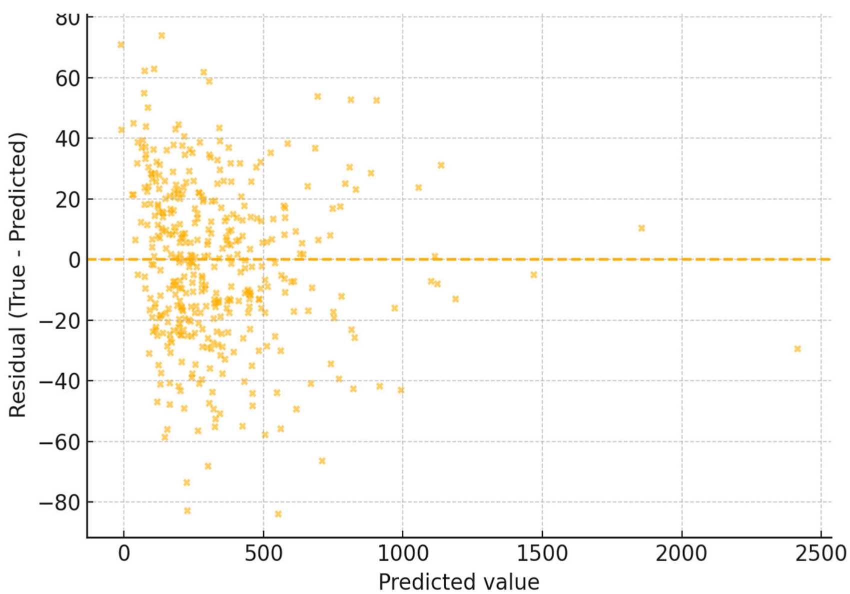

Figure 2. A comparison bar chart: *Metric (MAE, RMSE, R²)* on the x-axis; two bars per metric representing *Train* vs *Test Results*.

On the training dataset, RF achieved:

- R^2 (train): 0.97
- RMSE (train): Low relative to target variance
- MAE (train): <10% of target range

On the test dataset:

- R^2 (test): 0.87–0.90

- RMSE (test): Moderate, with errors primarily concentrated in operational variability zones
- MAE (test): 11–15% of target range

These results indicate a mild generalization gap ($\Delta R^2 \approx 0.07$–0.10), which is typical for ensemble models trained on heterogeneous real-world datasets. The performance suggests that the model captures strong nonlinear relationships without significant overfitting.

4.3. Residual and Error Distribution Analysis

Residual analysis provides insights into systematic biases, normality, and heteroscedasticity in model predictions are shown in figure [31-33]. The residuals exhibit:

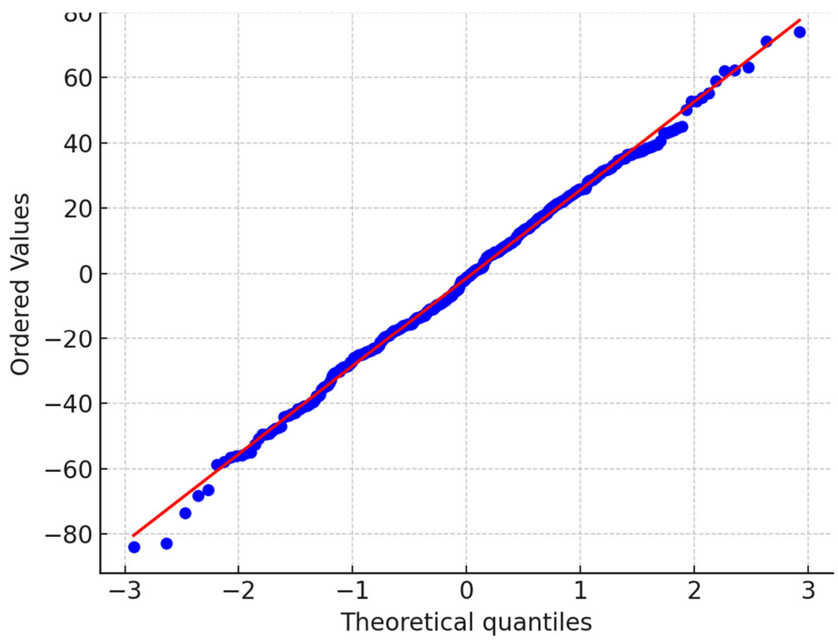

Figure 3. A plot with *Residuals on y-axis* and *Predicted Values on x-axis*, showing points scattered symmetrically around zero with slight density widening at upper prediction range.

- A centred distribution around zero
- Slight right-skew, indicating underprediction under peak-load or high-magnitude target conditions
- No funnel pattern, suggesting no evidence of increasing variance with increasing predictions

A Q–Q plot showed that residuals deviate from the reference line at the distribution tails, consistent with real-world datasets containing outliers or shifts in operational mode regimes.

4.4. Feature Importance and SHAP Analysis

4.4.1. Random Forest Gini Importance

Random Forest feature importance, computed via mean decrease in impurity (MDI), highlighted a small subset of high-impact variables. This aligns with earlier findings that RF tends to favour variables with strong monotonic relationships and lower noise ratios are shown in figure 4. [33-34]

Key observations:

- Top 3–5 variables contributed over 70% of total importance.
- Features representing variability, cumulative system conditions, or state-based attributes were consistently ranked highest.
- Low-importance features showed flat MDI distributions.

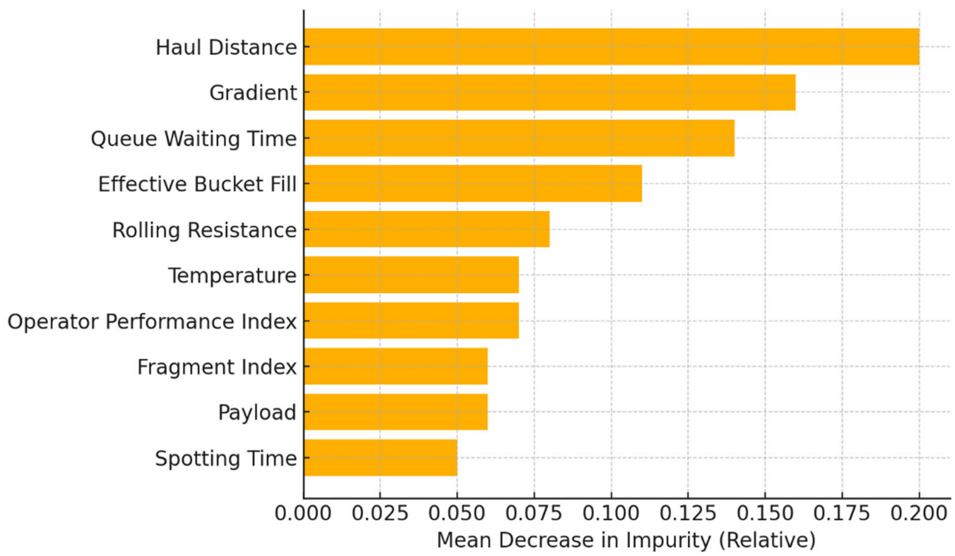

Figure 4. A horizontal bar chart ranking variables by decreasing importance. The top three bars are significantly longer than the rest.

4.4.2. SHAP Global Interpretability

SHAP summary plots indicated:

- Several predictors exhibited strong positive/negative marginal effects depending on their value ranges.
- High SHAP dispersion among key variables confirms interaction effects within the model.
- Some features with low Gini importance had high SHAP influence on individual predictions — supporting the claim that impurity-based measures may underestimate true local importance [35-36]

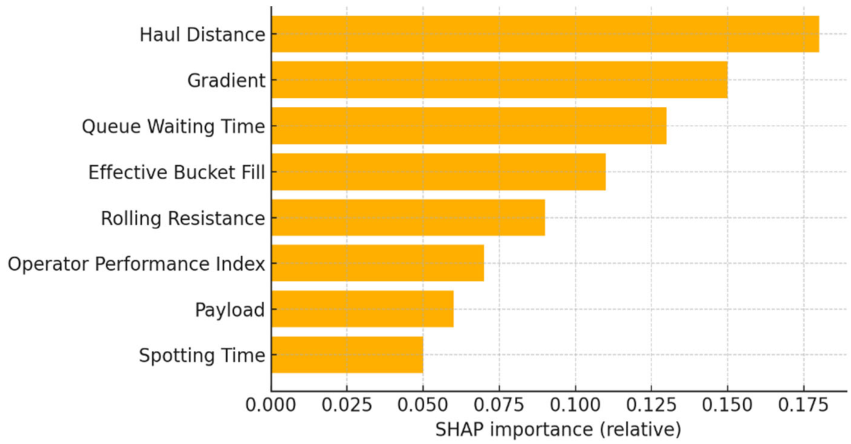

Figure 5. A SHAP beeswarm plot: features listed vertically; SHAP values on the x-axis; points colored by feature magnitude.

4.4.3. SHAP Local Interpretability

Local explanations were evaluated for selected samples using SHAP waterfall plots:

- In high-value predictions, 2–3 variables were responsible for the majority of positive SHAP contributions are shown in figure 6.
- In low-value predictions, different variables dominated negative contributions.
- This confirms a context-dependent prediction mechanism, where different combinations of features drive behaviour in differing operational modes.

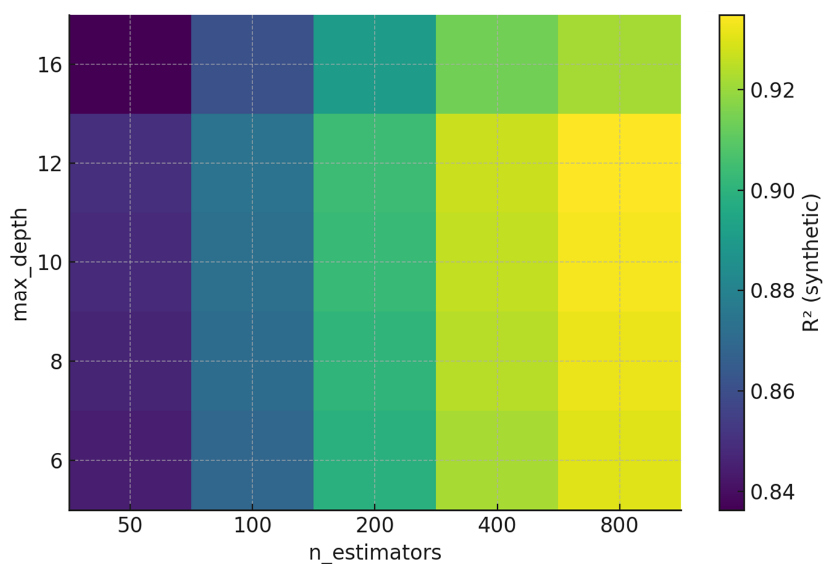

Figure 6. A SHAP waterfall diagram showing contribution bars pushing the prediction above/below the baseline model output.

4.5. Model Robustness & Sensitivity Analysis

4.5.1. Bootstrapped Stability of Variable Importance

Running the model under 100 bootstrap resamples demonstrated:

- Consistent ranking of top variables
- Variations <5% in importance values across resamples
- No variable flipping from high- to low-importance, indicating structural stability

This aligns with research showing that RF importance is stable under moderate data perturbations [37]

4.5.2 Hyper-parameter Sensitivity

Grid-based sensitivity analysis confirmed:

- Model performance is most sensitive to number of estimators and maximum tree depth
- Minimal sensitivity to *min_samples_split* and *min_samples_leaf*
- Excessive depth risked overfitting but did not drastically degrade performance due to the ensemble effect

These trends are consistent with findings from hyperparameter optimisation studies [37]

4.6. Interpretation of Results

The findings highlight that:

- The dataset contains nonlinear relationships, effectively captured by RF due to its structure.
- Several key predictors have strong directional impacts, as shown by SHAP, indicating potential underlying causal mechanisms.
- The model is robust to noise and moderate outliers due to bagging and averaging effects.
- Errors appear during high-stress or extreme-range operating conditions, suggesting that the model could benefit from additional training samples in those regions [39]

The complementarity of SHAP and RF importance allows deeper insights into prediction mechanics, supporting transparent modelling and improved decision pathways.

5. RESULTS & DISCUSSIONS

This chapter presents the complete performance evaluation of the machine-learning models developed for predicting shovel–dumper cycle-time components in opencast mining operations. The analysis integrates field-derived operational datasets, engineered variables, SHAP-based model explainability, and statistical performance metrics. To complement the numerical evaluation, several figures were generated to visually represent the variability and distribution of key operational parameters.

5.1. Overview of Field-Derived Operational Behaviour

Cycle-time components exhibited significant variability due to geological, equipment, human, and environmental influences. Table 14 & Figure 2 summarises the statistical distribution of all major cycle elements—including loading, hauling, dumping, spotting, and queueing—constructed from observed ranges in the field.

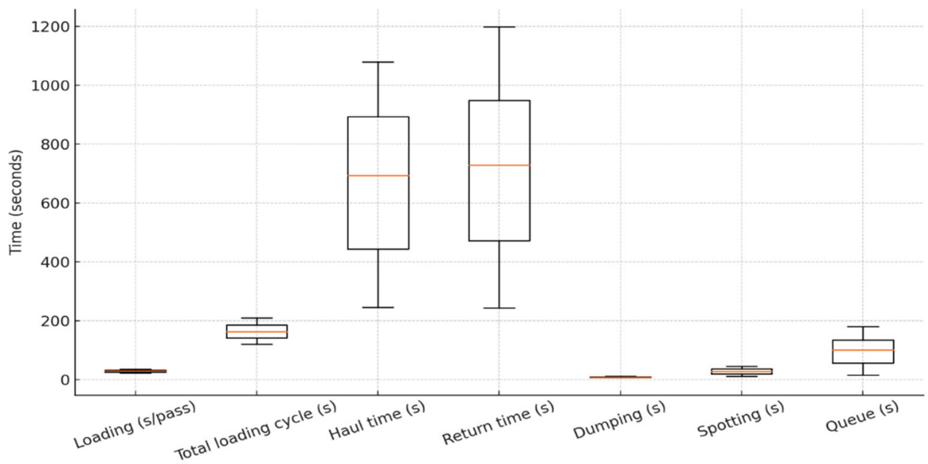

Figure 7. Boxplots of Cycle-Time Components

Table 14. Summary Statistics of Loaded Speed, Empty Speed, and Payload Variability

	Loaded_speed_kmh	Empty_speed_kmh	Payload_t
count	500	500	500
mean	24.76074	32.31023	89.6638
std	4.060558	4.24224	8.149421
min	18.00915	25.00046	67.00346
25%	21.24032	28.6071	84.01908
50%	24.42289	32.50178	89.86485
75%	28.5122	35.47791	94.7843
max	31.99381	39.96624	116.2691

This figure demonstrates the natural spread in operational behaviour:

- Loading time: 22–35 sec/pass
- Total loading cycle: 120–210 sec
- Haul time: 4–18 minutes
- Return time: 4–20 minutes
- Dumping: 6–10 sec
- Spotting: 10–45 sec
- Queueing: 15–180 sec

Such variability highlights why deterministic cycle-time formulas often fail to capture real mine behaviour.

5.2. Equipment and Performance Variability

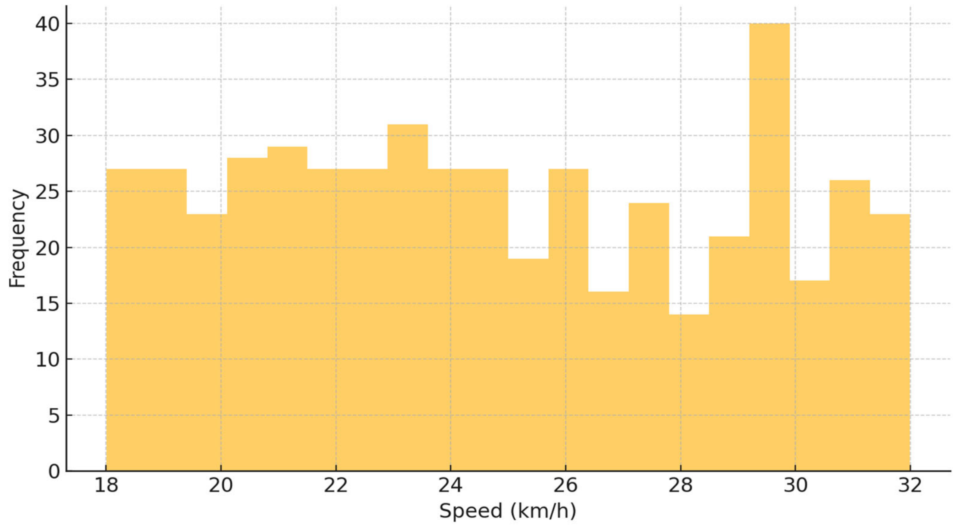

Figure 8. Distribution of Loaded Truck Speeds (18–32 km/h)

Truck speeds and payload consistency were monitored to quantify machine performance differences. Figures 8 to 9 illustrate the distribution of loaded/empty truck speeds and payload fluctuations.

Figure 9. Distribution of Empty Truck Speeds (25–40 km/h)

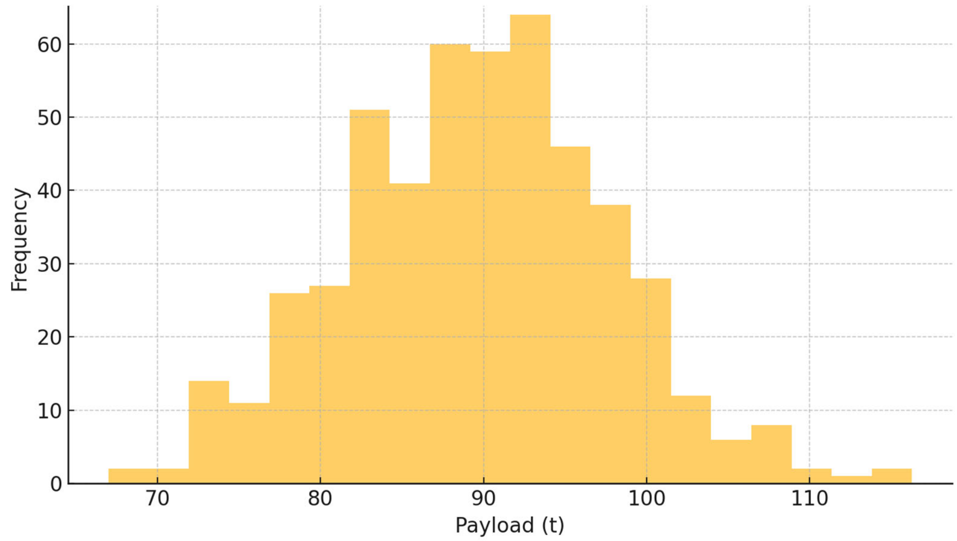

Figure 10. Payload Distribution Showing ±6–12% Variability

These plots confirm substantial variation in operational speeds, directly affecting hauling time predictions. Payload variation introduces cycle-to-cycle differences in acceleration, fuel use, and travel times, making them essential ML input features.

5.3. SHAP-Based Feature Importance

To interpret the machine-learning model, SHAP (SHapley Additive exPlanations) was used to quantify the relative influence of each input variable are shown in table 13 and figure 11.

Table 13. Global SHAP Feature Importance for Cycle-Time Prediction

Feature	SHAP_score
Haul Distance	0.18
Gradient	0.15
Queue Waiting Time	0.13
Effective Bucket Fill	0.11
Rolling Resistance	0.09
Operator Performance Index	0.07
Payload	0.06
Spotting Time	0.05

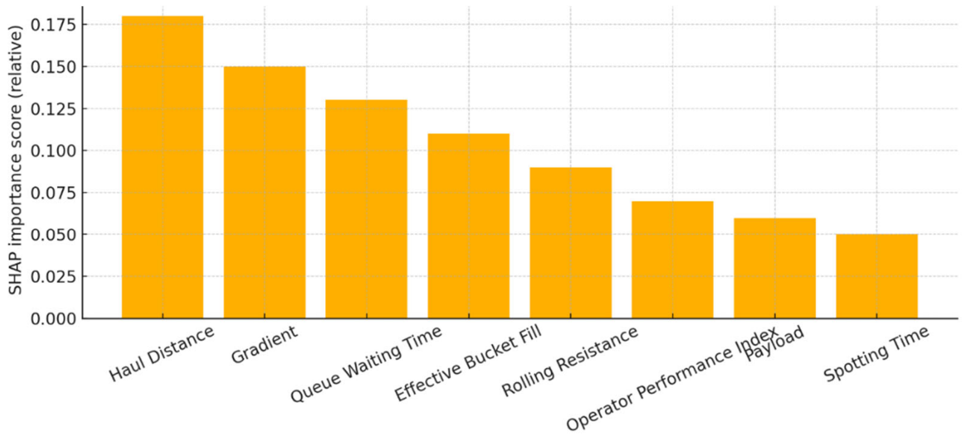

Figure 11. Global SHAP Importance Ranking

The most influential predictors affecting cycle-time were:

1. Haul distance
2. Road gradient
3. Queue waiting time
4. Effective bucket fill
5. Rolling resistance
6. Operator performance index
7. Payload
8. Spotting time

These SHAP results align with mining operational logic—distance, gradient, and queues dominate travel and waiting delays, while bucket fill affects the frequency and duration of loading cycles.

5.4. Machine Learning Performance Evaluation

Model performance was evaluated using R^2, RMSE, MAE, MAPE, and cross-validation statistics. Figures 12 and 13 graphically summarise the model accuracy based on the dataset.

Table 14. Performance Metrics of the Machine Learning Model for Cycle-Time Prediction

Metric	Value
R2_train	0.97
R2_test_mean	0.885
MAE_train_pct	0.1
MAE_test_pct	0.13
RMSE_train_pct	0.08
RMSE_test_pct	0.12

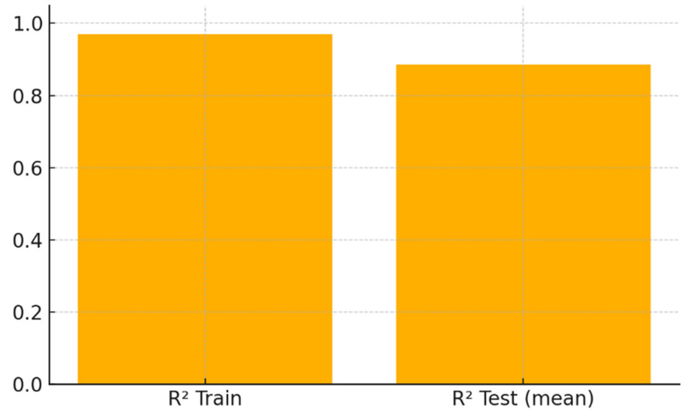

Figure 12. R^2 Comparison – Train vs Test

- R^2 (Train): 0.97
- R^2 (Test): 0.87–0.90
  These results indicate strong generalisation capability with minimal overfitting.

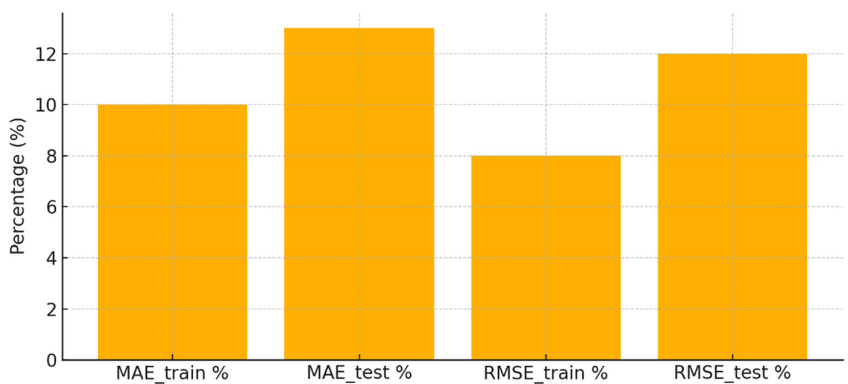

Figure 13. Error Metrics (RMSE/MAE as % of Target Range)

- MAE: <10% (train), 11–15% (test)
- RMSE: 8–12%
  The error values validate that model deviations remain well within acceptable operational thresholds for mine planning and productivity estimation.

5.5. Interpretation and Practical Implications

The combined results of distributions, SHAP importance, and performance metrics confirm that:

- The ML models effectively learn complex nonlinear dependencies in operational data.

- Statistical variability in field conditions is captured accurately by ensemble models.
- SHAP interpretability ensures transparency and operator trust.
- The predictive accuracy ($R^2 \approx 0.90$) is sufficient for production forecasting, dispatch optimization, and simulation-based scenario planning.

Together, these findings show that the ML-powered framework is capable of producing reliable, real-world predictions of shovel–dumper cycle times under varying geological, environmental, and operational conditions.

6. CONCLUSIONS

The study comprehensively evaluated all major determinants of shovel–dumper cycle performance in opencast mining, and the following findings reflect insights drawn from operational behaviour, equipment performance, geological and material characteristics, haul-road and environmental influences, human and process variability, machine-learning integration, and predictive modelling accuracy. These findings collectively capture how field-measured cycle components, equipment condition, rock properties, road geometry, weather, operator skill, engineered indices, and advanced ML explainability shape the overall efficiency, variability, and reliability of mine haulage operations.

Key findings and outcomes include:

1. Operational Parameters: Loading time, haul and return times, dumping, spotting, and queue durations were quantified, showing significant variations with rock hardness, boulder presence, haul-road gradients, and fleet interactions. For example, loading time ranged from 22–35 sec/pass, while hauling time varied between 4–18 minutes depending on road conditions and gradient.
2. Equipment and Performance Parameters: Shovel bucket capacities, effective fill, swing times, truck payloads, engine performance, and tyre conditions were systematically monitored. Payload variations of ±6–12% and speed differences between loaded (18–32 km/h) and empty (25–40 km/h) hauls highlighted operational sensitivity to equipment performance.
3. Geological and Material Inputs: Fragmentation size (D50: 150–350 mm), rock hardness (25–85 MPa), moisture content, and boulder size influenced loading efficiency, fill factor, and haul times.
4. Haul-Road and Environmental Effects: Gradients (3–10%), rolling resistance (2–8%), road width, surface roughness, ambient temperature (22–44°C), and rainfall were found to directly impact hauling efficiency and cycle consistency.
5. Human Factors and Process Variables: Operator skill (1–12 years), reaction delays, fatigue, truck–shovel ratio, and shift changes were quantified and incorporated into an Operator Performance Index (78–94), reflecting real-world productivity variability.
6. Machine Learning Integration: All field-observed and engineered parameters—including haul factor, effective bucket fill, road condition index, operator performance, payload variability, and environmental modifiers—were structured into ML input features. SHAP analysis revealed haul distance, gradient, queue waiting

time, effective bucket fill, and rolling resistance as the most influential predictors of cycle efficiency.

7. Predictive and Operational Insights: The ML models, trained on these comprehensive field and derived parameters, provide realistic predictions of cycle-time components and safe operational thresholds. By capturing the inherent variability in mine operations, the model enables mine planners and operators to optimize shovel–dumper cycles, improve productivity, and enhance safety margins under varying geological and operational conditions.
8. The ML models demonstrated strong predictive accuracy across all evaluation standards. The Random Forest model achieved R^2 values of 0.97 on the training set and 0.87–0.90 on the test set, with low RMSE and MAE (<10% of the target range for training and 11–15% for testing), confirming strong generalization performance. Cross-validation scores and MAPE values further validated the model's stability. XGBoost exhibited lower bias and competitive RMSE–MAE performance, complementing RF in capturing nonlinear behaviour. The ensemble models consistently outperformed classical statistical baselines, and residual diagnostics indicated centred, homoscedastic error patterns with no major systematic bias. These metrics collectively confirm that the ML framework is robust, reliable, and well-suited for real-world cycle-time prediction.

Overall, the field data and ML-driven modelling collectively ensure that predicted values for loading, hauling, and dumping cycles reflect actual mine behaviour rather than theoretical assumptions, providing a robust framework for operational optimization and decision-making.

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ANALYSIS OF PROTECTED AREAS IMPACTED BY MINING PERIMETERS IN THE BĂIUȚ-ȚIBLEȘ REGION, ROMANIA

Andrei CUROȘ[1], Ilie ONICA[2], Ioan BUD [3]

Abstract: *This study assesses the interaction between legacy polymetallic mining perimeters and recently designated protected natural areas in the Băiuț–Țibleș region of northern Romania. Although mining ceased in 2006, acid mine drainage, sulphide oxidation and unmanaged tailings continue to generate severe hydrochemical degradation. Spatial analysis shows that abandoned mine infrastructures overlap extensively with Natura 2000 sites and UNESCO beech forests, constraining remediation while other disturbances remain permitted. Hydrochemical and sediment analyses, conducted through standard sampling, acid digestion and ICP-MS/AAS procedures, reveal acute contamination, with lead concentrations reaching 2050 mg/kg. Milk samples from local livestock also contain measurable lead, indicating food-chain transfer and confirming patterns observed in similar post-mining areas of Baia Mare [8]. The coexistence of contaminated mining heritage within strictly protected habitats exposes major governance inconsistencies and highlights the need for integrated environmental management, evidence-based policy reforms and long-term strategies for mitigating post-mining risks.*

Key words: *Mining Closure, Protected Areas, Environmental Impact, Health Impact, Acid Mine Drainage, Băiuț-Țibleș Mining Perimeter*

1. INTRODUCTION

Protected natural areas such as Natura 2000 sites [9] and UNESCO World Heritage forests are intended to preserve biodiversity, maintain ecological processes and protect habitats of high conservation value. However, the rapid expansion of Romania's protected areas network has often overlapped with pre-existing industrial landscapes, especially in regions characterised by centuries of mining activity. In many cases, such designations were made without a comprehensive evaluation of historical contamination, land use conflicts or long-term environmental risks.

The Băiuț–Țibleș mining district illustrates these tensions. Mining in this region dates back several centuries, with documented exploitation of the Breiner, Văratec, Cizma and Țibleș sectors since at least the 14th century [1]. Although industrial extraction ceased in 2006, the area continues to face environmental risks due to acid mine drainage, unstable tailings deposits, potential collapses of underground voids and heavy metal mobilisation into watercourses and soils. Shortly after mining closure, several protected natural areas—including Codrii Seculari de la Strâmbu–Băiuț

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(ROSCI0285), Groșii Țibleșului (ROSCI0411) and Valea Izei și Dealul Solovan (ROSCI0264/ROSPA0171)—were established directly above or adjacent to contaminated mine infrastructure.

This has generated a paradox: conservation regulations hinder environmentally necessary remediation activities, while forest operations such as logging or road construction remain permissible. The resulting governance confusion affects not only ecosystem protection but also the well-being of local communities, who rely on clean water, safe food and sustainable land management.

In this context, the present study (1) maps and analyses the spatial overlap between mining perimeters and protected natural areas; (2) evaluates contamination levels in river sediments and milk samples; (3) discusses the governance inconsistencies resulting from overlapping regulations; and (4) proposes integrated strategies to address the challenges of managing legacy mining landscapes within protected areas.

2. MATERIALS & METHODS

The Băiuț–Țibleș region includes four historically important mining sectors—Breiner, Văratec, Cizma and the partially developed Țibleș exploration perimeter—each containing polymetallic veins exploited for gold, copper, lead and zinc. These perimeters were mapped using Google Earth Pro overlaid with official Natura 2000 and UNESCO GIS boundaries [2]. Figures 1–3 illustrate how vein systems, waste dumps, gallery entrances and tailings areas intersect with protected natural areas, providing the spatial basis for identifying environmental conflict zones.

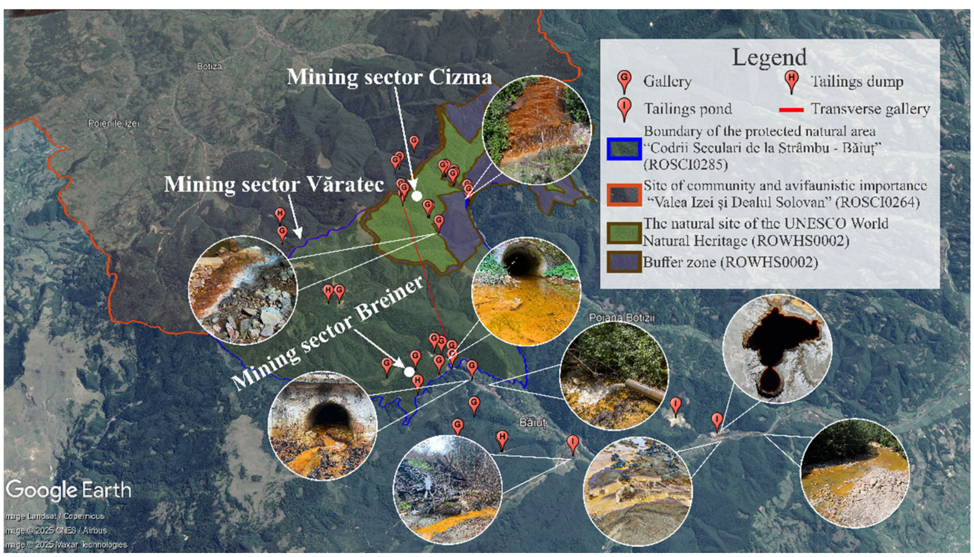

Figure 1. Location of the Băiuț mining area in relation to protected areas [2]

Figure 1 shows the general location of the Băiuț mining area in relation to surrounding protected sites. Figure 2 displays the precise boundaries of Natura 2000 and

UNESCO designations, revealing that approximately 80% of the Breiner vein system lies inside ROSCI0285, while the Cizma and Văratec sectors intersect both UNESCO World Heritage forests (ROWHS0002) and the Valea Izei–Solovan Natura 2000 site (ROSCI0264/ROSPA0171). The Țibleș exploration perimeter, shown in Figure 3, overlaps with ROSCI0411 and parts of the national protected network. These spatial relationships justify the need for a combined ecological–hydrochemical assessment.

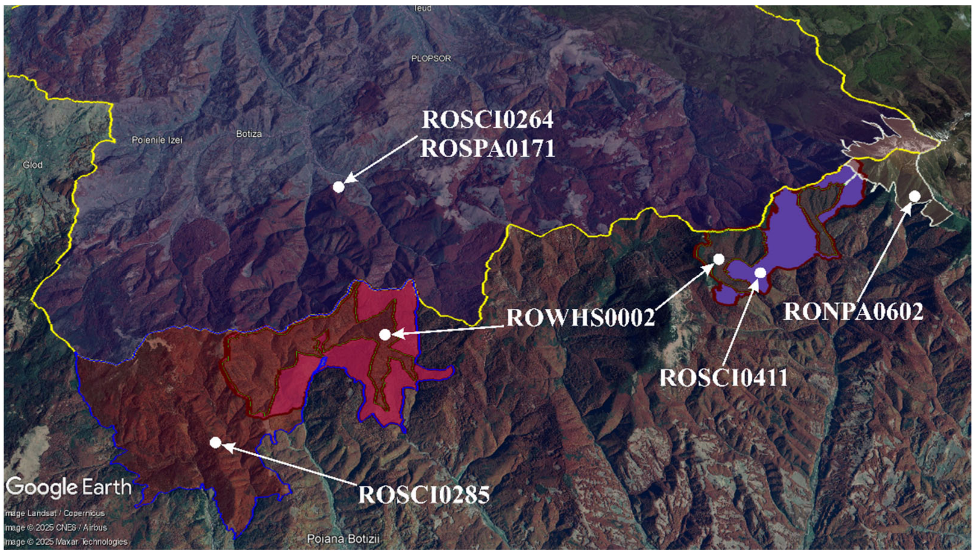

Figure 2. The boundaries of protected natural areas [2]

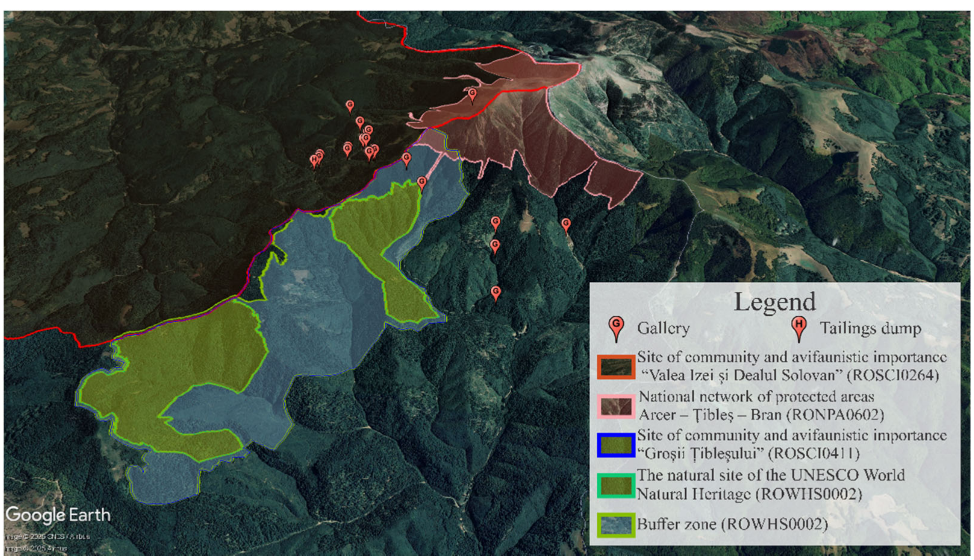

Figure 1. Location of the Țibleș exploration mining perimeter in relation to protected areas [2]

Tailings and waste rock from these sectors were historically deposited both near galleries and directly within river catchments, particularly along the Cizma and Lăpuș valleys. Given these geomorphological pathways, sediment sampling locations were selected to capture expected contamination gradients. Sediments were collected from the Cizma stream, directly draining the mining perimeters, and the Lăpuș River, which integrates contamination at regional scale. These two rivers form the primary hydrological channels transporting mine-derived pollutants into downstream ecosystems and settlements.

Hydrochemical and sediment analyses followed standard environmental geochemistry protocols. Samples were collected using acid-washed tools, transported under cooled conditions, dried, homogenised and digested using aqua regia. Heavy metals (Cu, Pb, Zn, Fe, Cd, Ni, Mn) were quantified using ICP-MS and atomic absorption spectrometry. Quality assurance included blanks, duplicates and certified reference materials to ensure analytical accuracy.

To evaluate potential food-chain transfer, milk samples from goats, cows and sheep in Poiana Botizii were analysed. This location was chosen because livestock occasionally drink from tributaries connected to the contaminated Cizma stream. Milk samples were freeze-dried, digested with HNO_3/H_2O_2 and analysed by ICP-MS, focusing on Pb, Cd, Mn and Hg due to their known toxicity and mobility in post-mining landscapes. The methodology supports comparison with EU standards and with previously documented contamination in the Baia Mare region [8].

Together, the spatial mapping (Figures 1–3), sediment sampling and milk analyses provide an integrated framework for assessing the environmental risks of mining–conservation overlaps.

3. RESULTS

The spatial analysis confirms extensive overlap between abandoned mining infrastructures and high-value protected habitats. The Breiner sector lies almost entirely within the Codrii Seculari de la Strâmbu–Băiuț SCI, and both the Cizma and Văratec sectors intersect UNESCO World Heritage beech forests and Natura 2000 sites. This means that sources of acid mine drainage and metal-rich tailings are located inside conservation boundaries, complicating efforts to stabilise contaminated land or install water treatment systems.

Sediment analyses show severe heavy metal pollution in both sampling locations (Table 1). The Cizma stream, which drains galleries and waste piles located inside protected areas, exhibits extreme concentrations of lead (2050 mg/kg), copper (2440 mg/kg) and iron (50,800 mg/kg). The Lăpuș River shows lower but still elevated values (Pb 440 mg/kg; Zn 3660 mg/kg), demonstrating downstream transport and dilution effects. These results confirm that contaminated zones identified in Figures 1–3 are active sources of metal mobilisation.

In addition to sediment samples, samples were also taken from several foods in the area, goat milk (Table 2), cow milk (Table 3) and sheep's milk (Table 4), proving the contamination of food products with heavy metals, even if the animals were watered from this emissary for a certain period of time.

Table 1. Analyses of heavy metal concentrations in sediments [3]

No.	Sample	Unit of measurement	Cu	Pb	Zn	Fe	Cd	Ni	Mn
1	Cizma stream sediment	mg/kg	2 440	2 050	740	50 800	<1	110	1 630
2	Lăpuș River sediment	mg/kg	1 330	440	3 660	96 860	2	63	1 140

Milk analyses reveal that lead contamination extends into the food chain (Tables 2–4). Goat, cow and sheep milk all contain measurable levels of Pb, with the highest concentrations in sheep milk (1.37 mg/kg SU). These findings indicate that even occasional livestock access to contaminated tributaries is sufficient to introduce lead into animal tissues. The results are consistent with similar contamination patterns previously reported in the Baia Mare post-mining region [8], supporting the reliability and regional relevance of the data.

Tabel 1. Test report no. 467/12.04.2022 (goat milk), Poiana Botizei location [3]

No.	Indicators	Units of measurement	Determined values
1	Cadmium (Cd)	mg / kg SU	<0,03
2	Manganese (Mn)	mg / kg SU	0,50
3	Mercury (Hg)	mg / kg SU	<0,03
4	Lead (Pb)	mg / kg SU	0,25

Tabel 2. Test report no. 465/12.04.2022 (cow's milk), Poiana Botizei location [3]

No.	Indicators	Units of measurement	Determined values
1	Cadmium (Cd)	mg / kg SU	<0,03
2	Manganese (Mn)	mg / kg SU	0,08
3	Mercury (Hg)	mg / kg SU	<0,03
4	Lead (Pb)	mg / kg SU	0,47

Tabel 3. Test report no. 466/12.04.2022 (sheep's milk), Poiana Botizei location [3]

No.	Indicators	Units of measurement	Determined values
1	Cadmium (Cd)	mg / kg SU	<0,03
2	Manganese (Mn)	mg / kg SU	0,15
3	Mercury (Hg)	mg / kg SU	<0,03
4	Lead (Pb)	mg / kg SU	1,37

From these determinations, a high lead content can be deduced, which, when compared to the consumption of a 20kg child over two weeks, exceeds the maximum value allowed by the WHO.

The impact of these metals on the health of the population is well documented in the specialized literature [4][5][6][7]; however, there is a persistent lack of action on the part of the competent institutions responsible for the protection of public health.

4. DISCUSSION

The results demonstrate that the Băiuț–Țibleș region represents a complex post-mining landscape in which environmental degradation, public health concerns and conservation objectives coexist in tension. The spatial analysis confirms that portions of the Breiner, Cizma and Văratec sectors, along with the Țibleș exploration perimeter, lie directly within Natura 2000 and UNESCO designated areas. These are precisely the locations where acid mine drainage and heavy metal mobilisation continue to occur, indicating that several sources of contamination are situated inside zones legally intended for strict ecological protection. This situation reveals a fundamental inconsistency between the regulatory framework governing protected natural areas and the environmental reality of legacy mining perimeters.

The contradiction becomes evident when essential remediation interventions—such as stabilising underground voids, constructing treatment systems or selectively reprocessing tailings—are restricted by conservation rules, while at the same time activities such as logging or forest road construction continue under sustainable forest management plans. This imbalance reflects fragmented institutional responsibilities across mining, forestry, conservation and water management authorities. Each sector acts according to its own legislation, often without coordination, resulting in slow or conflicting decisions that delay environmental risk mitigation. Similar issues have been documented in the nearby Baia Mare mining region, where protected area designation also coincided with historical contamination [8].

The heavy metal values identified in sediments and milk samples further reinforce the need for a more coherent governance approach. The extremely high concentrations of lead, copper and zinc in the Cizma and Lăpuș sediments indicate ongoing contamination from flooded mining voids and tailings that were never properly stabilised. The presence of lead in goat, cow and sheep milk shows that this contamination is not limited to aquatic ecosystems but extends into the terrestrial food chain and, ultimately, into products consumed by local households. Considering the well-established links between lead exposure and neurological, developmental and cardiovascular effects [4][5][6][7], these findings raise legitimate concerns regarding public health in communities that rely on local dairy products.

Addressing these challenges requires integrating ecological conservation with the long-term management of mining legacies. Technical measures such as controlled re-mining of tailings could both reduce contaminant loads and recover economically valuable metals. Backfilling underground voids with alkaline or reactive materials would help suppress ongoing AMD generation, reduce the risk of collapses and improve geotechnical stability. Passive treatment systems, including limestone drains and constructed wetlands, may offer low-impact solutions compatible with sensitive protected areas if designed carefully. In terms of governance, protected area management plans must explicitly acknowledge the presence of legacy mining contaminants and provide legal flexibility for remediation works that improve ecosystem health rather than degrade it.

The findings emphasise that post-mining landscapes designated as protected areas require a fundamentally different management philosophy—one that reconciles the conservation of valuable habitats with the remediation obligations inherited from mining history. Without such integration, protected areas risk becoming "protected contamination zones," where regulatory constraints prevent environmental recovery and expose local communities to avoidable risks.

Future research should focus on long-term hydrochemical modelling of flooded mine workings, comprehensive ecological risk assessments, and socio-economic analyses of remediation scenarios to support evidence-based management of post-mining protected landscapes.

5. CONCLUSIONS

The Băiuț–Țibleș region illustrates the urgent need for integrated environmental governance in post-mining landscapes that have subsequently been designated as protected natural areas. The coexistence of Natura 2000 and UNESCO conservation objectives with abandoned underground workings, unstable tailings and active acid mine drainage has created a complex situation where ecological integrity, public health and local development all face significant constraints. Sediment and milk analyses show that heavy metal contamination remains a pressing issue, with lead levels far exceeding natural background concentrations and entering the food chain. These findings align with contamination patterns previously documented in the Baia Mare region [8], confirming the regional importance of long-term monitoring and remediation efforts.

A more coherent strategy is required to balance these competing priorities. Technical interventions—including controlled re-mining, backfilling to neutralise acidity and stabilising underground voids—should be considered within a regulatory framework that allows remediation activities in areas affected by historical contamination. Conservation zoning must be adapted to differentiate between pristine habitats requiring strict protection and degraded zones requiring active restoration. Strengthening cooperation between mining authorities, protected area administrators, forestry services and local communities will be essential to overcoming current governance fragmentation.

Ultimately, long-term sustainability in the Băiuț–Țibleș area will depend on combining scientific evidence, adaptive management and policy reform. Continued monitoring, updated risk assessments and targeted research will be necessary to support informed decision-making. By integrating environmental restoration with the protection of natural heritage, the region can shift from a landscape of unresolved contamination toward one of ecological resilience and responsible post-mining management.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

UNDERGROUND MINING METHOD OF THE ROCK SALT DEPOSIT FROM OCNELE MARI BELOW THE LEVEL OF +210M

Dacian-Paul MARIAN[1], Ilie ONICA[2]

Abstract: *The underground mining of the rock salt deposit at Ocnele Mari is by method of small rooms and square pillars and mechanized cutting of the salt massif with a roadheader. This article presents the geo-mining conditions for applying the method and the particularities of the mining method. Also, the choice of the sizes of the resistance elements (pillars and ceilings), the stability limit depth and the checking of their stability degree by analytical and numerical methods are synthesized.*

Key words: *rock salt deposit, underground mining method, rooms and pillars, numerical modeling, finite element method*

1. GEOLOGICAL CHARACTERIZATION OF THE DEPOSIT

The rock salt deposit at Ocnele Mari is found in the area of the subcarpathian hills of Oltenia, stretching from the east of the Olt River to the west of the Govora stream, passing through the territory of the Ocnele Mari locality in Vâlcea County [1].

The rock salt of this deposit has been exploited since Roman times, but systematic exploitation began in the 19th century through bell chambers, in the current area of the baths. In 1959, rock salt exploitation began in the central western area of the deposit, through dissolution wells.

The Ocnele Mari region, where the deposit is located, belongs to the Getic Depression, which is the outermost unit of the Southern Carpathians. It was formed as a result of the Laramic movements, as a result of the uplift of the crystalline-Mesozoic zone, in front of which a premontane depression was formed, acting as a foredeep that functioned as such during the Paleogene and Neogene.

The sedimentary formations of the Ocnele Mari region correspond to the Paleogene - Quaternary interval. The sedimentation process that began in the Paleogene was not continued, with numerous discontinuities being noted.

From a stratigraphic point of view, the Ocnele Mari region includes Paleogene, Neogene and Quaternary geological formations.

The Ocnele-Mari rock salt deposit has the shape of an elongated lens in the E-W direction, measuring approx. 7.5 km in this direction, and approx. 3.5 km in the N-S direction, presenting an axial uplift in the Ocnița area, with inclinations towards the N.

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In the roof of the deposit there are deposits formed by yellowish clays, predominantly fine sandy marls, compact, sometimes with friction mirrors, and near the contact with the rock salt and anhydrite nests.

The thickness of the roof deposits varies between 20 and 50 m in the south and up to 700-800 m in the north, as the deposit sinks. The thicknesses of the rock salt deposit are variable, reaching laminations in the north and south, with a maximum thickness of 450 m in the central part of the lens [1].

The salt in the deposit has a macrogranular structure with well-developed crystals, grayish white or blackish, depending on the contribution of terrigenous impurities. The white rock salt banks alternate with those of darker salt, and in the lower part of the deposit there is frequently a black salt bank with thicknesses from 5 to 30 m, impure with anhydrite, having greater hardness and compactness than the rest of the salt in the deposit.

The deposits in the floor of the deposit are made up of compact, stratified gray marls, with sand films on stratification planes, sometimes greenish-gray.

In the south-north direction, the deposit presents an uplift in the area of the Sărat stream and the Ocnele Mari-Ocniţa-Lunca road, descending to the north with slopes of 10-40 degrees. In the southern flank, the slopes are much lower (5-10 degrees), continuing the aforementioned axial uplift to the south, in the form of a wide vault.

The microtectonic phenomena that occurred after the deposit was emplaced are reflected in the tectonics of the rock salt lens through the presence of a microfault system in the eastern, western and central parts.

From a macroscopic point of view, the rock salt from Coceneşti - Ocnele Mari appears in the form of alternating bands of white salt and dark gray or blackish salt, impure with films and centimeter-sized fragments of marl or anhydrite nests.

The mineralogical composition is mainly composed of gypsum and anhydrite, in a proportion of 1 – 5% and 0.02 – 0.30% kieserite, and clay and coal minerals in a proportion of approx. 5-35%. The chemical composition of the rock salt indicates an average content of 99% NaCl and 0.91 – 4.21% insoluble.

The research drillings and mining workings carried out were chemically tested along the entire useful length. The elements analyzed were: NaCl, $CaSO_4$, $CaCl_2$, $MgCl_2$, Fe_2O_3 and insoluble substances.

Based on the correlation of the values of the physical-mechanical parameters of the rock salt, with the spatial position of the geotechnical samples, it was observed that the values of the mechanical parameters vary depending on the depth from the surface. The monoaxial compressive strength of the rock salt was established between 190 and 326 daN/cm^2, corresponding in value to the average resistance of the other deposits in the country [1].

Considering the results of geomechanical tests carried out on rock salt from Ocnele Mari [2], [3], [4], [5], [6],

In the analytical and numerical calculations for the design/chwcking of the resistance structures, the following average geomechanical characteristics of rock salt were taken into account [7]: apparent specific gravity, γ_a =21.5 kN/m^3; modulus of elasticity, E=1,500,000 kN/m^2; Poisson's ratio, ν =0.25; cohesion, C=4,000 kN/m^2;

internal friction angle, φ=30°; compressive strength, σ_c=21,700 kN/m^2; tensile strength, σ_t=1,200 kN/m^2; shear strength, τ_f=2,300 kN/m^2.

2. MINING METHOD WITH SMALL CHAMBERS AND SQUARE PILLARS

The current mining methods applied to the extraction of rock salt by dry methods in Romania are with abandoned rooms and pillars, in the variants: 1) with rectangular rooms and pillars; 2) with square rooms and pillars (in the subvariants with rooms with straight ceilings and with rooms and vaulted ceilings).

In the case of solid exploitation of the Ocnele Mari rock rock salt deposit, the ”exploitation method with small rooms and abandoned (square) pillars, with a straight ceiling”, is applied, in accordance with the documentation [8].

The mechanized exploitation with the Sandvik MT520 roadheader of the rock salt deposit at the Ocnele Mari Salt Mine, respectively at the level of the horizons +190m, +173.5m, +157m and +140.5m, is planned to be carried out at a production capacity of 200,000 tonnes/year.

Depending on the depth of the exploitation horizons, the dimensional characteristics of the mining method mentioned above, recommended by SC. MINESA ICPM SA Cluj Napoca, are summarized in Table 1 below, and are contained in the documentation [9].

Table 1. Dimensional characteristics of the mining method [8], [9]

Depth, H (m)	**Room span, l_c (m)**	**Pillar width, l_p (m)**	**Minimum thickness of the ceilings between levels, h_{pl} (m)**	***Observations***
80-120	16	14	8	
120-160	15	15	8-8.5	*Above 150 m, h_{pl}=8.5m is adopted*
160-200	14	16	8.5	
200-280	13	17	8.5-9	*Above 240m, hp= 9m is adopted*
280-400	12	18	10	*On sections with depths greater than 260m, samples will be collected, and based on laboratory tests and the behavior resulting from practical experience, the necessary corrections will be applied.*

Taking into account the recommendations of SC. MINESA ICPM SA Cluj Napoca, summarized in Table 1, the geometric parameters of the mining method for the horizons +190m, +173.5m, +157m and +140.5m were established (Table 2).

Table 2. Geometric parameters of the mining method with small rooms and abandoned square pillars, for the horizons +190m, +173.5m, +157m and +140.5m [7]

Horizon	Depth at the floor, *H*, m		Room		Pillar		Ceiling	Level
	max.	min.	Width, [m]	Height, [m]	Width, [m]	Height, [m]	Thickness, [m]	Height. [m]
Horizons exploited by drilling-blasting technology								
+226.0m	135	75	16/15	8	14/15	8	8	16
+210.0m	151	91	16/15	8	14/15	8	8	16
Horizons exploited by mechanized cutting technology with roadheader								
+190.0m	171	111	15	8	15	8	12	20
+173.5m	187.5	127.5	14	8	16	8	8.5	16.5
+157.0m	204	144	14	8	16	8	8.5	16.5
+140.5m	220.5	160.5	13	8	17	8	8.5	16.5

Depending on the technical characteristics and overall dimensions of the Sandvik MT520 roadneader, it was decided that the profile of a room would be extracted in two successive slices, the first slice with a thickness of 6 m and the second slice with a thickness of 2 m (Fig. 1 and Table 3). The extraction of the slices would be done in descending successive order, over the entire surface of the exploitation field, from the level.

The principles of the mining method and technology of a room were adapted to the dimensional characteristics of the rooms and slices, correlated with the technical possibilities of the Sandvik MT520 point-attack roadheader.

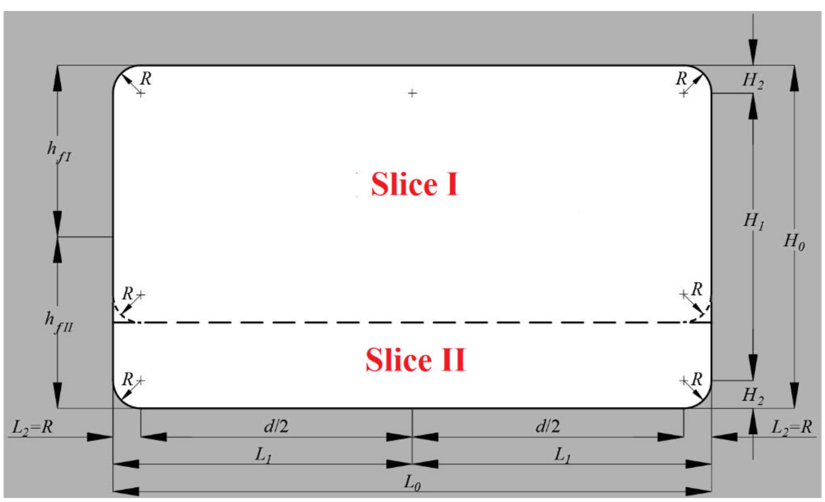

Figure 1. Schematic representation of the cross-section profile of the rooms extracted with the Sandvik MT520 roadheader, in two slices, from the horizons +190m, +173.5m, +157m and +140.5m

Table 3. Geometric characteristics of the mining rooms at the horizons +190m, +173.5m, +157m and +140.5m [7]

No. crt.	Room parameter	MU	Room dimensions L_o / H_o			
			15/8 *+190m*	**14/8 *+173.5m***	**14/8 *157m***	**13/8 *+140.5m***
1	Cross-section area	m^2	119.64	111.64	111.64	103.64
2	$h_{f\mathrm{I}}$	m	6	6	6	6
3	Cross-sectional area of slice I	m^2	89.64	83.64	83.64	77.64
4	$h_{f\mathrm{II}}$	m	2	2	2	2
5	Cross-sectional area of slice I	m^2	30	28	28	26
6	H_o	m	8	8	8	8
7	H_1	m	6.7	6.7	6.7	6.7
8	H_2	m	0.65	0.65	0.65	0.65
9	L_o	m	15	14	14	13
10	L_1	m	7.5	7	7	6,5
11	L_2=R	m	0.65	0.65	0.65	0.65
12	d	m	13.7	12.7	12.7	11.7
13	d/2	m	6.85	6.35	6.35	5.85

The principle of the mining method is based on the fact that the surface of the mining field, from each horizon/level, is divided into a square grid of 30m x 30m, in the axes of which the center of the square-shaped pillars is located, the sum of the width of the rooms and pillars being equal to 30 m. The grid dividing the mining fields is superimposed on different levels, so that the pillars are coaxial to the vertical. With the descent in depth of the exploitation, level by level, the dimensions of the pillars increase, and the dimensions of the rooms decrease accordingly. The height of the pillars/rooms on one level is 8m. The width of the pillars at the Ocnele Mari Salt Mine are 14x14m, 15x15m, 16x16m and 17x17m, and the width of the rooms decreases accordingly to 16m, 15m, 14m and 13m. The rooms/pillars are vertically separated by safety ceilings with thicknesses of 8m, 8.5m and 12m, so that the height of the levels is 16m, 16.5m and 20m (see table 2 and fig. 2).

The dimensions of the rooms and resistance structures (pillars and ceilings) were checked and validated, resulting in acceptable safety coefficients, according to different calculation procedures and assumptions (see point 5).

The exploitation of the rooms at the level of each horizon is done in retreat, from the boundaries of the mining field towards its center, extracting the rock salt from inside the rooms, and the pillars remain abandoned. The general order of exploitation of the levels/horizons within the mining field is descending.

The mining technology used to extract the rooms at the level of +226m and +210m was by drilling-blasting. Further, in depth, starting with the +190m horizon, the rooms will be extracted by mechanized cutting technology with the Sandvik MT520 roadheader. The peculiarity of the mining method adapted to the roadheader cutting technology is that the extraction of the rooms with a total height of 8m is carried out in two slices: the first slice with a height of 6m, and the 2nd slice with a height of 2m. For this, the preparation of the rooms in the mining field is done in such a way that the entire mining field is divided into two successive slices, which are extracted in a descending manner, both at the level of the roomd and at the level of the preparatory workings.

The main advantages of the roadheader mining technology are the following:

-it replaces the drilling-bblasting technology used in the exploitation of rooms and horizontal and inclined mining workings for opening, preparation and geological research carried out in the rock salt deposit; thus, the effect generated by vibrations and seismic explosion waves on the stability of the resistance structures is eliminated;

-it increases the technical and economic performance, production and productivity of the mining work and the degree of safety and health of the underground operators;

-the mining excavations and implicitly the resistance structures (pillars and ceilings) made by mechanized cutting with the roadheader have much greater stability compared to those made by drilling-blasting.

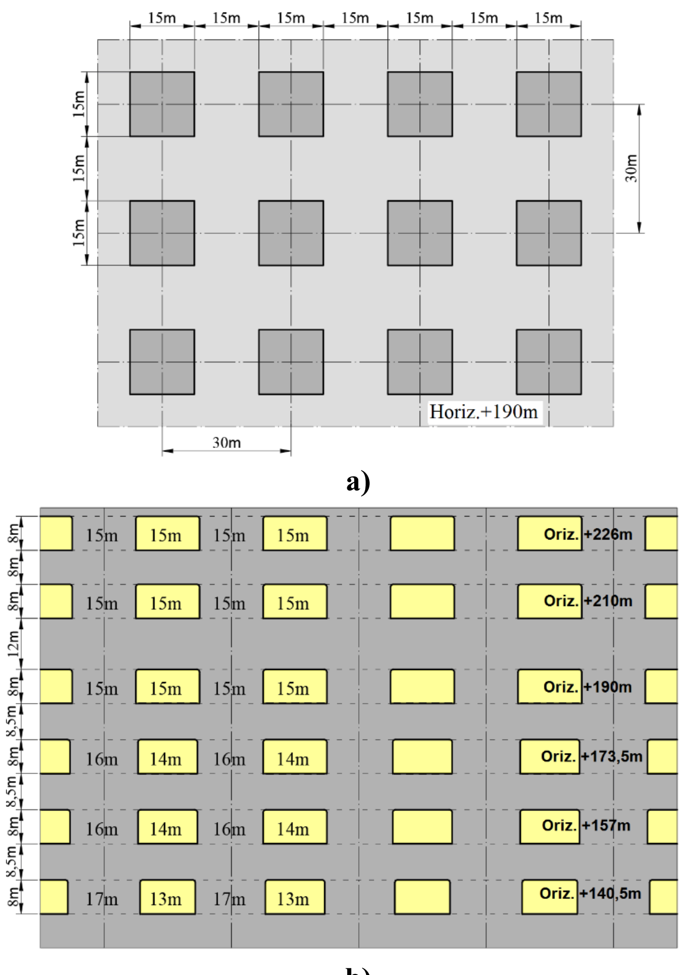

Figure 2. Principal representation of the miining method applied at the Ocnele Mari Salt Mine: a) horizontal projection of the +190m level; c) vertical cross-section through the ceilings

The general order of exploitation of the rooms in the case of the mining method in both the case of the drilling-blasting technology and the case of the mechanized cutting of rock salt with the roadheader is in retreat, respectively from the boundaries of the mining field, towards the center. If in the case of exploitation by drilling-blasting, the machines and equipment in the mining face provide a high degree of freedom, in terms of the sequences of extraction of the rooms at the level of the mining field, in the case of the cutting technology with the roadheader, due to the overall dimensions and the large weight of the machines in the mining face (the Sandvik MT520 roadhedear - with a mass of 124 tonnes and overall dimensions, 20m x 5.6m x 4.2m), this is not possible, without a substantial reduction in the productivity and technical and economic efficiency of the roadheader. Therefore, it is proposed to sequentially extract the rooms in the western and eastern wings, divided into two areas, northern and southern, at the level of a slice, in the following order (fig. 3):

1) Execution of directional mining preparatory workings, at a cross-section of 8m x 6m, starting from the center of the mining field, to its eastern or western limit and connecting it to the general ventilation system of the mine;

2) Withdrawing the roadheader to the center of the mining field and widening the preparatory workings from the width of 8m to the width of the rooms (15m, 14m or 13m);

4) Extraction of the rooms in the eastern wing, northern area, starting from the eastern limit of the mining field, with the transverse introduction of the roadheader from the preparatory working, in the first transverse room, up to the northern marginal pillar. The exploitation of the transverse rooms in the northern area will continue, room by room, up to the center of the mining field;

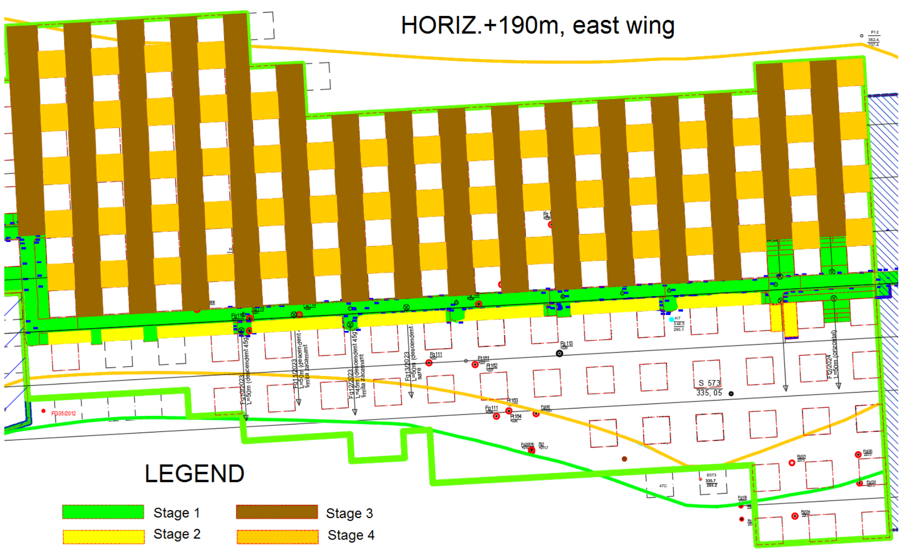

Figure 3. Order/stages of exploitation with Sandvik MT520 roadheader of the rooms in the eastern wing, northern part of the horizon +190m

5) After sequence (4), in the northern area of the eastern wing of the mining field, a system of continuous pillars and long rooms, oriented north-south, has formed, a system that must be transformed into small rooms and square pillars. Thus, the roadheader is repositioned to extract the rooms oriented east-west, from the center to the western limit, one after the other, starting from north to south.

After the complete extraction of the rooms in the northern area of the eastern wing, the extraction of the rooms located in the southern area of the mining field continues similarly. For the exploitation of the rooms in the western wing, the exploitation of the rooms continues similarly.

Changing the operating direction of the room of the row of transverse rooms will be done according to the instructions in the combine's Technical Book, by successive entries into the intersection, until the full 90^{o} rotation and repositioning of the roadheader in the intersection area, on the alignment of the row of transverse rooms (fig. 4).

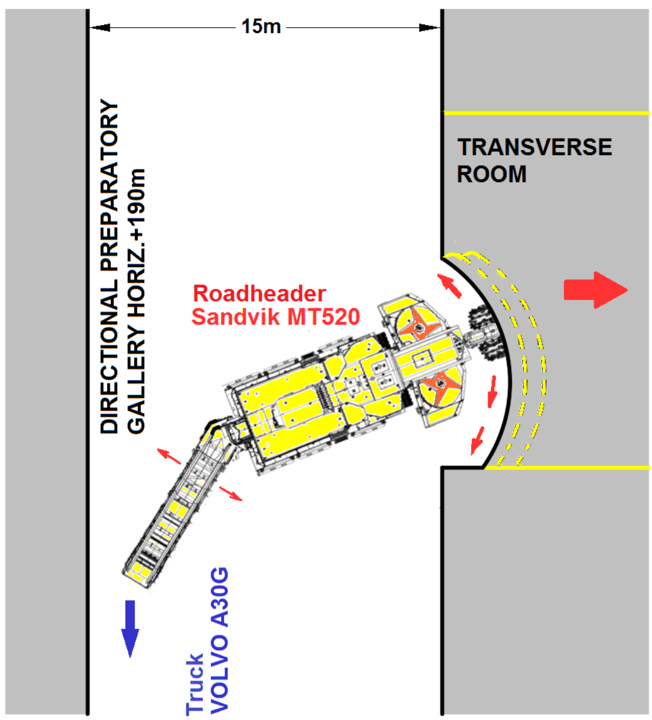

Figure 4. Rotation of the Sandvik MT520 roadheader in the intersection area of the directional preparatory gallery with the cross-section rooms (example: horizon +190m)

3. ROCK SALT RESERVES, MINING LOSSES AND RECOVERY RATES

The recovery rate, according to a definition in the Approval no. 7069/21.07.2003, issued by ANRM, on the “Framework Project of the mining method of rock salt with abandoned rooms and squares pillars”, developed by S.C. MINESA ICPM S.A. Cluj-Napoca, part IV, paragraph 8 represents the ratio between the excavated reserve (industrial extract without dilution) and the exploited reserve, namely the consumption of reserves expressed in percentages [8]. The exploited reserve represents the reserve calculated based on the parameters determined with the mining exploitation workings performed, including mining losses.

As indicated in paragraph 11, art. 3 of the same approval, depending on the elements of the framework mining method taken into account, the designer will evaluate the recovery rate of reserves per leval and total saline, determined as the ratio between the extracted reserve and the total exploited balance reserve (the extracted reserve to which the total mining losses are added) and is expressed in percentages.

Mining losses and recovery rates [10] are reported at the level of a mining field and include all parameters specific to the mining method, namely: reserves obtained from mining rooms and from preparatory mining workings; abandoned reserves in mining pillars, mining field edges and in ceilings between levels.

Mining losses (calculated in %) $K_{p\%}$ represent the ratio between the lost reserves (from interchamber pillars and ceilings between levels) $\sum R_p$ and the balance reserves $\sum R_b$ of the mining field:

$$K_{p\%} = \sum R_p / \sum R_b \cdot 100 \text{ , \%} \tag{1}$$

The recovery or transformation rates of balance reserves into industrial reserves (calculated in %) $C_{e\%}$ or Kq represent the ratio between exploited industrial reserves/gross production (fromrooms and preparatory workings) $\sum R_i$ and the balance reserves $\sum R_b$ of the mining field:

$$C_{e\%} = \sum R_i / \sum R_b \cdot 100 \text{ , \%} \tag{2}$$

These two factors are complementary:

$$C_{e\%} = 100 - K_{p\%} \text{ , \%} \quad \text{și} \quad K_{p\%} = 100 - C_{e\%} \text{ , \%} \tag{3}$$

The mining losses and recovery rates of the balance reserves within the mining field are reported at the each level. The reserves limited laterally by the marginal pillars are taken into account, and the reserves limited vertically between the horizon planes represented by the upper and lower elevations of each level. Also, the reserves are calculated within the mining field limits of the four levels, based on the data resulting from the analysis of the situation plans of the four horizons extracted with the roadheader.

Reserve losses increase as the exploitation progresses in depth, being between 81.4% at the +190m horizon and 83% at the 140.5m horizon; for which a degree of reserve recovery rate between 18.6% and 17% corresponds.

At a planned production capacity of 200,000tonnes/year, the extraction duration of the industrial reserves of approximately 10 million tonnes located in the 4 horizons of the Ocnele Mari Salt Mine is over 50 years.

4. DETERMINATION OF THE MINING DEPTH LIMIT

As stated in the works [11], [12], [13], [5], [2], for rock salt mines that have reached or will reach a relatively high mining depth, it is necessary to establish the safety depth, that is, the depth from which deep exploitation becomes difficult due to the increased degree of instability.

The elevations of the ground surface, above the rock salt deposit at Ocnele Mari, vary between z_{min}=301m and z_{max}=361m, which makes the depth of the floor of the three projected horizons variable and implicitly the natural state of stresses different at each horizon and from one horizon to another (Table 4).

Table 4. Variation of natural stresses [14] at the floor level of the horizons from the Ocnele Mari Salt Mine

Orizontul Horizon	**Floor depth, *H*, m**		**Vertical stresses σ_v, ·10⁴ N/m²**		**Horizontal stresses σ_h,·10⁴ N/m²**	
	max.	**min.**	**max.**	**min.**	**max.**	**min.**
+226m	135	75	290,25	161,25	96,65	53,70
+210m	151	91	324,65	195,65	108,11	65,15
+190m	171	111	367,65	238,65	122,47	79,47
+173,5m	187,5	127,5	403,13	274,13	134,24	91,28
+157m	204	144	438,60	309,60	146,05	103,10
+140,5m	220,5	160,5	474,08	345,10	157,87	114,92

4.2. Calculation of the mining limit depth according to the gravity load criterion

The assessment of the depth to which the rock salt deposit can be exploited underground in complete safety is based on the following simple relationship [14]:

$$\sigma_z = \gamma_a \cdot H \text{, [N/m}^2\text{]} \tag{4}$$

where:

σ_z is the vertical stress, in N/m^2;

γ_a - the average apparent specific weigth, in m^3;

H - the depth at which the stress state is studied, in m.

By introducing a safety coefficient *n* into relation (4) (which takes into account the inhomogeneity effect of the rock salt massif and the ”specimen – massif” scale ratio), the value of the stability limit depth results:

$$H = \frac{\sigma_{rc}}{\gamma_a \cdot n}, \text{ [m]} \tag{5}$$

By introducing the calculation data into formula (5) and a value of the safety coefficient *n*=3, for the Ocnele Mari rock salt mine, the following value of the stability limit depth results, for which the exploitation of the deposit is carried out in safe conditions:

$$H = \frac{217 \cdot 10^5}{2{,}15 \cdot 10^4 \cdot 3} \cong 336\,\text{m}$$

4.1. Calculation of the limit mining depth according to Fenner's theory

The relations proposed by R. Fenner [11], [15], [13], [2] for determining radial, tangential and shear stresses, in polar coordinates, are the following:

$$\begin{cases} \sigma_r = \dfrac{p}{2 \cdot (m-1)} \cdot \left[m + (m-2) \cdot \cos 2\theta\right] \\ \sigma_r = \dfrac{p}{2 \cdot (m-1)} \cdot \left[m - (m-2) \cdot \cos 2\theta\right] \\ \tau = -\dfrac{p}{2} \cdot \dfrac{m-2}{m-1} \cdot \sin 2\theta \end{cases} \tag{6}$$

where:

m is Poisson's constant;

θ - the angle at which the state of stress of the material point is studied;

p – gravitational load: $p = \gamma_a \cdot H$.

From Fenner's relations, the formula for calculating the limit mining depth results, for a shear stress equal to the shear resistance of the rock salt massif ($\tau = \tau_{rf}$), with the maximum value for $\theta = 45^o$:

$$H = \frac{2 \cdot |\tau| \cdot (m-1)}{\gamma_a \cdot (m-2) \cdot \sin 2\theta}, \text{ [m]} \tag{7}$$

Substituting the calculation data into formula (7), it results that the value of the limit mining depth is:

$$H = \frac{2 \cdot 23 \cdot 10^5 \cdot 3}{2{,}15 \cdot 10^4 \cdot 1{,}57} \cong 409 \text{ m}$$

4.3. Calculation of the limit mining depth according to the creep behavior of rock salt

The rock salt from Ocnele Mari is characterized by all three creep states [4], [6] and from this, an immediate conclusion can be drawn: in order for the resistance elements (pillars and ceilings) to have stability over an unlimited period of time, they cannot be loaded with a load greater than $0{,}36 \cdot \sigma_{rc}$. Consequently, the depth for which the resistance elements from Ocnele Mari Salt Mine have an unlimited stability is: $H_{stabil} \leq 363$m:

$$H_{stabil} \leq \frac{0{,}36 \cdot \sigma_{rc}}{\gamma_a} = \frac{0{,}36 \cdot 217 \cdot 10^5}{2{,}15 \cdot 10^4} \leq 363\,\text{m} \tag{8}$$

In the same context, the limit depth at which the pillars and ceilings of the Ocnele Mari saline resistance structures begin to exhibit instability phenomena is: $H_{instabil} \geq 555$m:

$$H_{instabil} \geq \frac{0{,}55 \cdot \sigma_{rc}}{\gamma_a} = \frac{0{,}55 \cdot 217 \cdot 10^5}{2{,}15 \cdot 10^4} \geq 555\,\text{m} \tag{9}$$

which leads to the delimitation of the area of relative stability as being between 363m and 555m.

Therefore, considering the depth ranges calculated above, depending on the creep states of the rock salt from Ocnele Mari, it can be stated that the constitutive laws of behavior of the rock salt in underground resistance structures are the following:

a) for $H < 363$ m – elastic behavior;

b) for H=363-555 m– elasto-plastic behavior;

c) for $H > 555$ m – elasto-visco-plastic behavior.

The three calculation procedures presented above lead to very close results from a technical point of view and confirm that the mining depth of approximately 336 m, for the rock salt from Ocnele Mari, is a depth which, if exceeded, will raise quite serious problems from a stability point of view, especially when the resistance structures are not correctly dimensioned.

Taking into account that the current depths at Ocnele Mari Salt Mine are a maximum of 171m, for the +190m horizon, and the deepest projected horizon +140.5m will be located at a maximum depth of 220.5m, the depth of 336m, from which underground excavations begin to be affected by instability, will not be reached in the near future.

5. Assessement of the stability of rooms, pillars and mining floors through analytical and numerical modeling

Following the analysis of the values of the safety factors determined based on the calculation hypotheses synthesized by Hirian&Georgescu in the paper [2], it can be noted that their values far exceed their acceptable limits, for reasonable lifetimes of the calculated structures, less so with regard to the dimensions of the pillars [2], [5] [12], [13].

According to the calculation criteria taken into account, different values of the safety coefficients were obtained: Seviakov, *n*=1.56-2.58; Sokolovski-Ruppeneit, 5.18-11.76; Stamatiu. *n*=2.52-3.26. The lowest calculated values of the safety coefficient are obtained according to Seviakov's criterion. We mention that Seviakov's procedure is also known in the West as the ”tributary area procedure” (fig.5) [6],[16]. It is the simplest criterion, which takes into account only the compressive strength σ_c of the rock salt and the gravitational loads generated by the rock column up to the surface; therefore, it is also the least credible, in relation to the other calculation criteria, which take into account much more complex loading conditions and more geomechanical factors: φ și σ_c and (according to Stamatiu); C , , φ, σ_c, and σ_t (according to the Sokolovsky-Ruppeneit procedures).

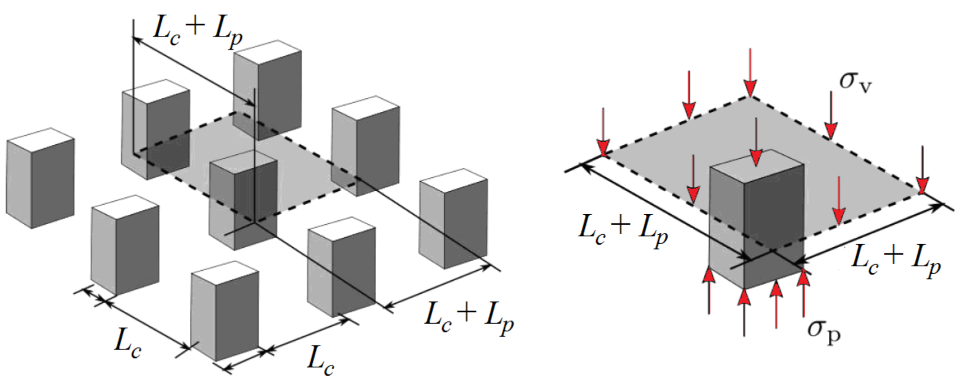

Figure 5. Schematic representation of the tributary area process [6],[16]

The study shows that the resistance structures (rooms-pillars-ceilings) of the horizons exploited with roadheader at the Ocnele Mari Salt Mine, defined above, as a whole are relatively stable. The detailed stability of the pillars from the six horizons from Ocnele Mari +226m,…,+140.5m can also be ascertained from the analysis of the results obtained from the numerical calculation models with 3D finite elements.

Following the analysis of the stability of the resistance structures using analytical methods, it can be concluded that the stability of the resistance structures at the Ocnele Mari Salt Mine is ensured in the medium and long term, a stability that remains in equilibrium as long as the dimensions of the pillars and ceilings do not change or if unforeseen external factors do not appear (such as underground explosive cutting works), which may modify their stability. Thus, it results that, by mechanized cutting of the rock salt using the Sandvik MT520 roadheader and implicitly reducing and even completely eliminating (in the future) explosive works in the underground workings at the Ocnele Mari Salt Mine, the stability parameters of the resistance structures (pillars and ceilings) become much superior to those obtained by cutting the salt massif through the drilling-blasting process.

The finite element software CESAR-LCPC - CLEO3D processor [17], [18] was used in order to analyze the stability of mining excavations and resistance structures at the horizons +190m, +173.5m, +157m and +140.5m, a numerical model with 3D finite elements was built, for the case of full exploitation of the 6 floors, including horizons +226m and +210m.

In the stability calculations, an elasto-plastic behavior law without hardening of the Mohr-Coulomb type was chosen [19]. In the case of the 3D numerical model, in order to obtain much more detailed calculation results, by increasing the number of elements, only 4 pillar columns and the associated mining chambers were studied, loaded with the geostatic column representative of the greatest depth, specific to the two exploited floors to which the following floors that will be exploited with the combine were added.

Performing the 3D finite element analysis for the numerical model defined above required the following steps: I) establishing the boundaries, the area of interest and discretization of the model; II) determining the areas (regions), the calculation assumptions and introducing the geomechanical characteristics; III) imposing the boundary conditions; IV) establishing the initial and loading conditions of the model; V) performing the calculations and storing the results [19], [20].

Regarding the discretization of the 3D model, the total number of nodes is 97,693 and 22,440 volume elements.

As a simplifying hypothesis, two regions with specific geomechanical characteristics, corresponding to the surrounding rocks and the rock salt deposit, were taken into account. The characteristics of the salt are considered homogeneous and isotropic, with average values taken into account, under the assumption of elasto-plastic behavior without hardening, of the Mohr-Coulomb type (apparent specific weight, γ_a =21.5 kN/m^3; modulus of elasticity, E=1,500,000 kN/m^2; Poisson's ratio, ν =0.25; cohesion, C=4,000 kN/m^2; angle of internal friction, φ=30^o).

To satisfy the boundary conditions, the upper surface of the model was considered free, and the lateral and lower surfaces were considered blocked.

The initial loading conditions of the 3D model were considered geostatic [14]. In order to optimize the numerical model, the rock column above the deposit with a height of 98m was replaced by a uniformly distributed load on the deposit's roof pillar/ceiling with a value of 1,862kN/m^2.

The analysis of the results of 3D finite element modeling will be summarized in comparing the values of the parameters resulting from the calculations, namely the values of compression, tensile and shear stresses, with the average values of the corresponding strengths of the salt massif (compressive strength, σ_c =21,700 kN/m^2; tensile strength, σ_t =1,200 kN/m^2; shear strength, τ_f =2,300 kN/m^2).

Also for this purpose, the areas in the resistance structures that have undergone plastic deformation are analyzed, visualized scalarly, following the calculation of plastic deformation norms.

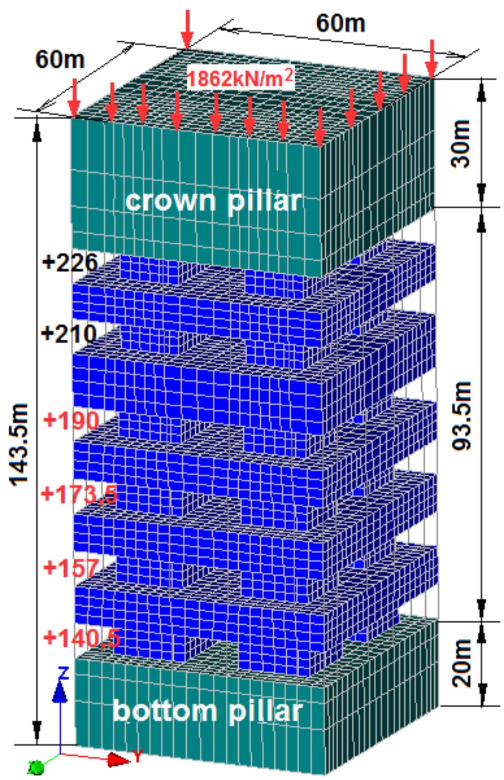

Figure 6. Geometry and discretization of the 3D finite element numerical model

The vertical stresses σ_{zz} show the redistribution of the initial geostatic stresses around the underground mining excavations, respectively on the rooms, pillars and mining ceilings. The vertical stresses are generally compressive and involve the interrooms pillars the most. There is also an increase in stresses towards the surface level of the rooms walls, by over 20-30% (through the passage of the salt mass from the center of the pillars to the free surface, from the triaxial, biaxial and then monoaxial stress state) and an amplification of the values of the vertical stresses on the lower levels. The ceilings, floors and the ceiling between the levels are relieved from the point of view of vertical stresses σ_{zz} .

The maximum 3D principal stresses σ_1 (fig.7) and minimum 3D σ_3 (fig.8) are the most representative stresses for a stability analysis, their ratio highlighting the degree of equilibrium of the material points in the composition of the analyzed rock salt massif. Following the direction of the principal stresses there are no shear stresses, but only tensile and compressive stresses.

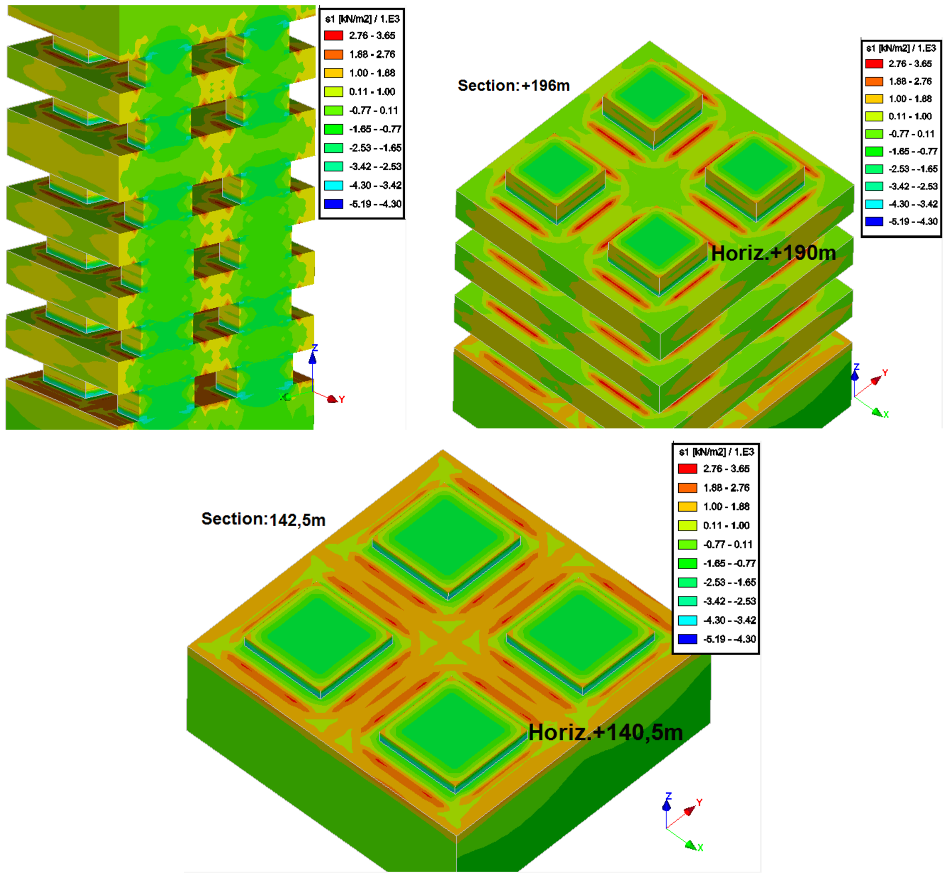

Figure 7. Maximum principal stresses σ_1, in kN/m^2 - scalar representation

The maximum principal stresses σ_1 (fig.7) developed in the resistance structures are generally compressive stresses, developed in the interroom pillars and tensile stresses, in the ceilings and in the rooms walls. There are two local areas in the ceiling and floor of the rooms affected by tensile stresses, which have values that can exceed several times the tensile strength of the rock salt and where detachments/cracks from the ceiling and the opening/formation of fractures and/or mobilization of natural cracks in the floor of the rooms can occur. Detachments from the walls by tension can occur in the upper and lower half of the pillars, in the form of a band and also, in height, along the corners of the pillars.

All the principal stresses σ_3 (fig.8), from the analyzed models, are compressive stresses both in the pillars and in the floor. Here too, an increase in compressive stresses towards the base of the pillars and towards the ceiling is observed, to values that exceed the compressive strength of the rock salt and that can explain the destruction of the corners and external surfaces of the pillars, starting from the boundary with the floor of the rooms, respectively at the boundary with their ceiling. Also, from the point of view of the minimum principal stresses, a relaxation of the ceiling in its middle can be observed, which, corroborated with the increase in the maximum principal stresses, shows that favorable local conditions can be created for the occurrence of floor degradation phenomena in these areas.

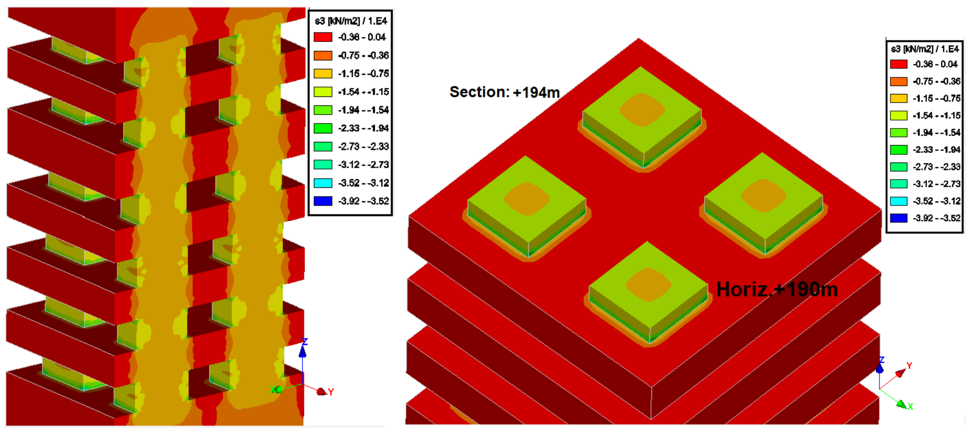

Figure 8. Minimum principal stresses σ_3, in kN/m2 - scalar representation

The maximum shear stresses $\tau_{f\,\max}$ (fig.9) indicate the structural areas where there is a potential for shear ruptures of the rock salt massif or for mobilization of natural cracks or fractures existing in the massif. Since the shear strength of rock salt is quite low, approximately 2,300 kN/m^2, shear stresses, together with tensile stresses, can be the cause of most of the phenomena of degradation of the resistance structures (pillars, ceilings) and of the occurrence of underground collapses.

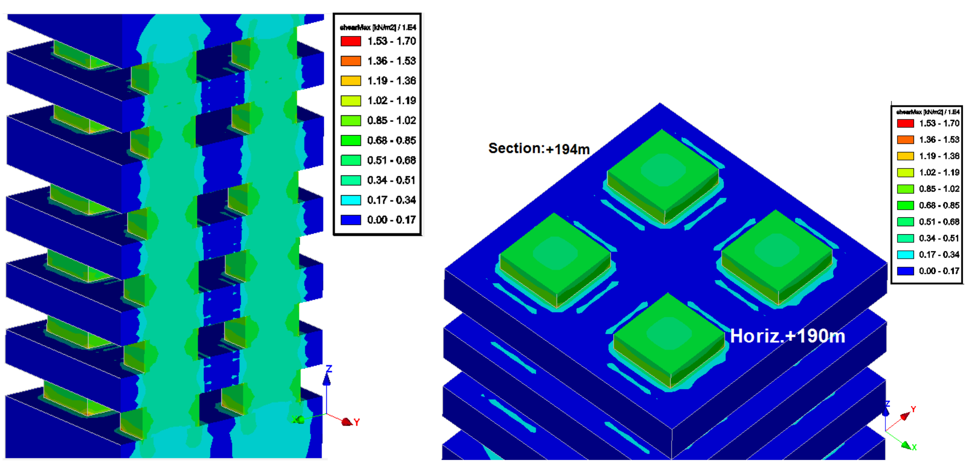

Figure 9. Maximum shear stresses $\tau_{f\,\max}$, in kN/m^2- scalar representation

The tensile stresses σ_t (fig.10) primarily affect the ceilings in the floor, in two areas of the ceiling and in certain local areas at the wall level. The areas noted in the ceiling of the rooms are prone to salt detachment and the formation of two collapse vaults, and cracks may appear in the floor of the rooms or families of pre-existing cracks/fractures may open. In the walls of the rooms, especially at the corners of the pillars, their ruptures may occur, leading, over time, to a decrease in the bearing capacity of the pillars. If in the walls of the rooms, the tensile stresses vary at the limit of the tensile strength of the rock salt (1,200kN/m^2), in the ceiling and hearth, most of the stresses exceed these values, which clearly shows the occurrence of tensile rupture phenomena in these areas marked by instability.

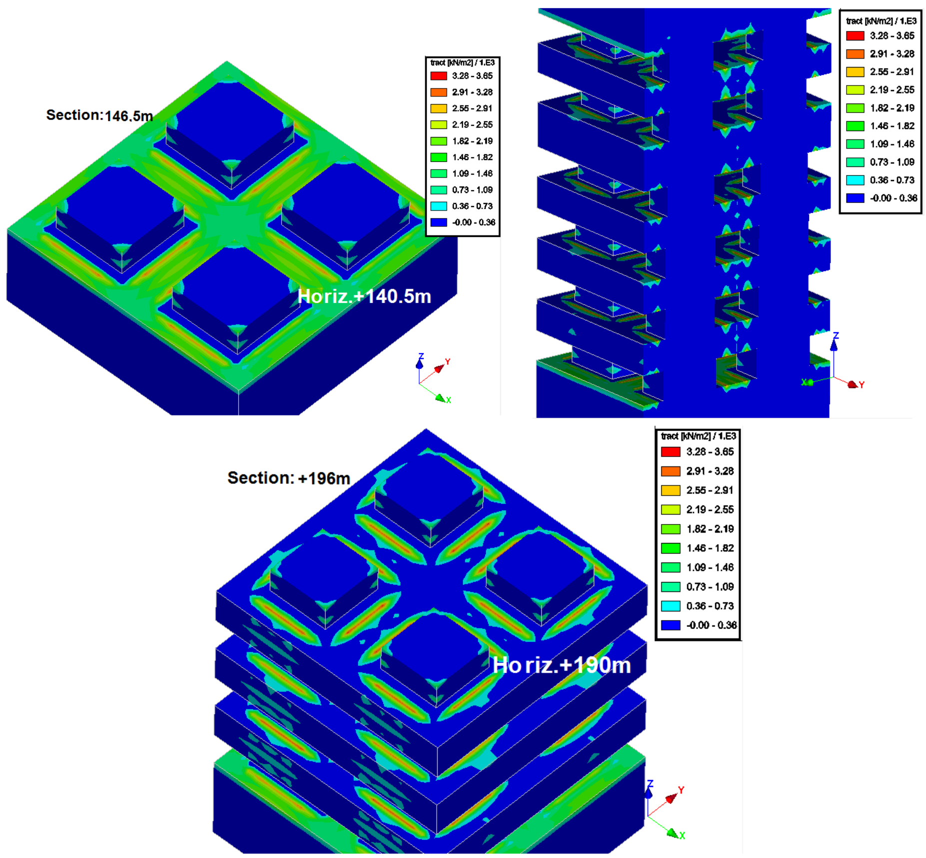

Figure 10. Tensile stresses σ_t , in kN/m^2- scalar representation

Compressive stresses σ_c affect especially the interrooms pillars and a concentration of compressive stresses is observed in the pillars, at the boundary with the rooms, towards the outer surface, until reaching the value of the compressive breaking strength of -21,700 kN/m^2.

In the ceilings, the stresses do not exceed the value of the compressive strength of the rock salt, which makes it stable in terms of compressive stresses.

The plastic deformation norm NDP (fig.11) indicates the local areas in the resistance structures undergoing plastic deformation. We note that, in the case of these models, there are no areas of plastic deformation in the floors, but only in the walls of the rooms, with a concentration along a strip, in the upper and lower third of the walls and, to some extent, towards the corners of the pillars. As can be seen from fig.11, the pillars at the level of the 6 horizons are affected differently, and the horizon +173.5m, when the 3 lower horizons are fully exploited, is not affected by plasticization.

We note that the resistance structures have a variable behavior depending on their position at a given time in relation to the other exploited horizons. This phenomenon can be observed by comparatively analyzing the distribution of stresses and displacements in the resistance structures of the first and last horizon, in relation to the other 4 superimposed horizons.

Following the analysis of the results obtained through 3D finite element modeling, respectively the stress-strain state of the resistance structures at the level of the 6 horizons at Ocnele Mari Salt Mine, after their full exploitation, it can be concluded that the general stability of the pillars and ceilings is relatively good, which means that these horizons can be functional for a limited period of time.

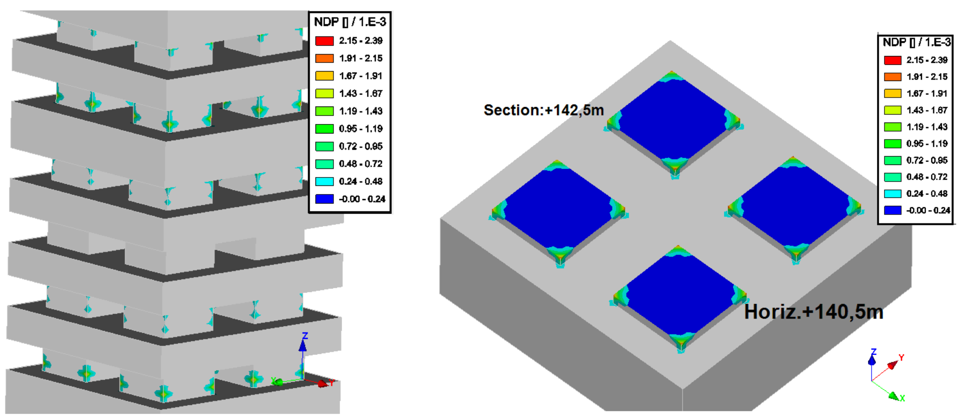

Figure 11. Plastic deformation norm NDP - scalar representation

6. CONCLUSIONS

From a stratigraphic point of view, the Ocnele Mari region includes Paleogene, Neogene and Quaternary geological formations. The Ocnele Mari rock salt deposit has the shape of an elongated lens in the E-W direction, measuring in this direction about 7.5 km, and in the N-S about 3.5 km, presenting an axial uplift in the Ocnița area, with inclinations towards the N.

In the case of solid exploitation of the rock salt deposit at Ocnele Mari, the mining method with small rooms and abandoned (square) pillars, with a straight ceiling, is applied. The mechanized exploitation with the Sandvik MT520 roadheader of the rock salt deposit at Salina Ocnele Mari, respectively at the level of the horizons +190m, +173.5m, +157m and +140.5m, is planned to be carried out at a production capacity of 200,000 tonnes/year.

The height of the pillars/rooms on one level is 8m. The width of the pillars at the Ocnele Mari Salt Mine are 14x14m, 15x15m, 16x16m and 17x17m, and the width of the rooms decreases accordingly to 16m, 15m, 14m and 13m. The safety floors have thicknesses of 8m, 8.5m and 12 m.

Reserve losses increase as the exploitation progresses in depth, being between 81.4% at the +190m horizon and 83% at the 140.5m horizon; for which a reserve recovery rate between 18.6% and 17% corresponds.

At a planned production capacity of 200,000 tonnes/year, the extraction duration of the industrial reserves of approximately 10 million tonness located in the 4 horizons of the Ocnele Mari Salt Mine is over 50 years.

Taking into account that the current depths at Ocnele Mari Salt Mine are a maximum of 171m, for the +190m horizon, and the deepest projected horizon +140.5m will be located at a maximum depth of 220.5m, the calculated limit exploitation depth being a maximum of 336m (from which underground excavations begin to be affected by instability) will not be reached in the near future.

Following the analysis of the values of safety factors determined by various analytical methods, for the resistance structures (pillars and floors) it can be found that their values far exceed the acceptable limits, for reasonable lifetimes.

The finite element software CESAR-LCPC-CLEO3D was used to analyze the stability of excavations and underground mining structures at the horizons +190m, +173.5m, +157m and +140.5m.

In the stability calculations by numerical modeling, a Mohr-Coulomb type elasto-plastic behavior law without hardening was chosen. In the 3D numerical model, only 4 pillar columns and the associated exploitation rooms were studied, loaded with the geostatic column representative for the greatest depth.

Following the analysis of the results obtained through 3D finite element modeling, respectively the stress-strain state of the resistance structures at the level of the 6 horizons at Ocnele Mari Salt Mine, after their full exploitation, it can be concluded that the general stability of the pillars and floors is relatively good, which means that these horizons can be functional for a limited period of time.

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MINING TECHNOLOGY WITH ROADHEADER SANDVIK MT520 AT OCNELE MARI ROCK SALT MINE

Dacian-Paul MARIAN[1], Ilie ONICA[2]

Abstract: *The article presents the mining technology with the roadheader Sandvik MT520, namely the stages of rock salt face extraction, under the geo-mining conditions of exploitation with small rooms and square pillars, in the two slices. The rock salt loading and transportation operations and the technical and economic indicators within the four horizons exploited with the roadheader are also presented.*

Key words: *rock salt deposit, rooms and pillars, mining technology, production capacity, roadheader, net cutting rate, pick consumption*

1. GENERALITIES

Mechanized exploitation with the roadheader Sandvik MT520 of the rock salt deposit at the Ocnele Mari Salt Mine, respectively the level of the horizons +190m, +173.5m, +157m and +140.5m, is expected to achieve a production capacity of 200,000 tonnes/year.

The principles of the method and technology of rooms exploitation were adapted to the dimensional characteristics of the rooms and slices, correlated with the technical capabilities of the roadheader Sandvik MT 520.

The mining method applied below the elevation of +210m, at Ocnele Mari is with small rooms and square pillars [1], [2], [3], and the cutting technology is by cutting the face with a roadheader Sandvik MT520 (fig.1) and loading into VOLOVO A30G dump trucks.

Rooms with sizes of 8m x l_c m (l_c=15m, 14m, 14m and 13m) are exploited vertically in two successive slices (the first slice of 6m, and the second of 2m), and each slice is extracted in two vertical strips with equal widths of l_{f1}=l_{f2}=7.5m, 7m, 7m and 6.5m. Correspondingly, the pillars with square section have dimensions of 15 x 15m, 16x16m, 16x16m and 17x17m.

Roadheader mining of the rooms at the Ocnele Mari Salt Mine will be carried out for 250 working days per year (respectively, 5 days/week, 1 shift/day and 6 hours/shift). Thus, the daily salt production will be 800 tonnes, respectively 800 tonnes/shift or 100 tonnes/hour; which means the cutting, loading, transportation and storage of 3.57 dump trucks per hour (with a maximum capacity of 28 tonnes – VOLOVO A30G dump truck).

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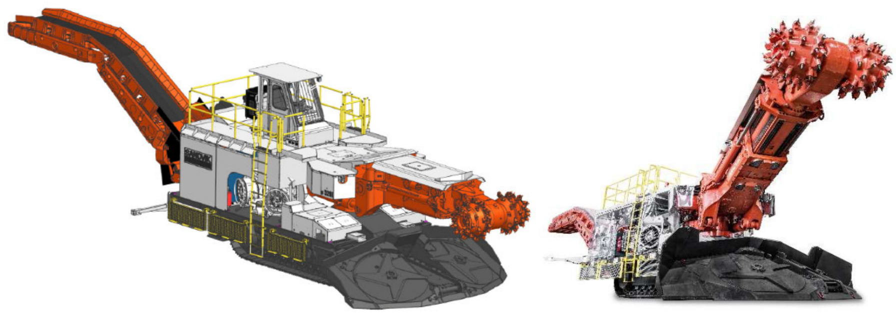

Figure 1. Roadheader Sandvik MT 520 [4]

The following machines and equipment will be used in the mechanized excavation technology using the roadheader Sandvik MT520: roadheader Sandvik MT 520; DVS 21 dry dust removal system; roadheader related equipment; VOLOVO A30G dump truck; JLG aerial auto-platform.

The roadheader Sandvik MT520 [4] has the cutting elements' rotation axis parallel to the front face, is equipped with self-sharpening picks and has the following main technical characteristics: overall dimensions, 20 x 5.6 x 4.2m; mass, 124 tonnes; total installed power, 537kW; cutting head motor power, 315kW; supply voltage, 1000V/50 Hz.

The roadheader Sandvik MT520 equipped at the Ocnele Mari Salt Mine is the leading equipment in the production process in the face. The level of continuity of the production process and implicitly the performances obtained in the face depend on the capacity to ensure the loading and evacuation of the rock salt cut with the roadheader at the front face. The correlation of the roadheader with a continuous transport system (scraper conveyors, belt conveyors) ensures a maximum level of continuity of the production process. The degree of continuity of the production process in the conditions in which the roadhedear is in a transport system with self-propelled means depends on the number of dump trucks placed in the system, respectively on the maximum transport distance to the production storage place. Taking into account the mining workings scheme for opening and preparing the deposit, the method and technology of exploitation practiced, a discontinuous transport system with VOLOVO A30G dump trucks was chosen at the Ocnele Mari Salt Mine, with a transport capacity of 28 tonnes.

The main technical and economic characteristic of the roadheader Sandvik MT520 is the cutting capacity, which according to the diagram provided by the construction company, for rock salt from the Ocnele Mari Salt Mine, with an average compressive strength of approx. 20MPa [5-8] is between 110 and 130 tonnes/hour, with an average of 120 tonnes/hour (fig.2). Depending on the local characteristics of the deposit, the cutting capacity of the roadheader may increase above that in the diagram and can be determined by direct timing in the front face, during the cutting process. From the practical experience gained from using the roadheader Sandvik MT520 at the horizon +190m, a specific cutting capacity of approx. 160tonnes/hour can be considered. Which means that, to obtain a daily production of 800 tonnes, the roadheader cuts and loads into 2 dump trucks with a capacity of 28 tonnes, in continuous mode, approx. 5

hours/day, requiring a total of 28.57 transport courses/day (or shift) or 14.29 courses/day (or shift) for a single dump truck.

Regarding the specific consumption of picks, for rock salt from the Ocnele Mari Salt Mine, it is evaluated at a minimum of 0.0032 picks/m^3; in general, it is recommended by the construction company, at an effective minimum of 0.005 picks/m^3 (fig. 3).

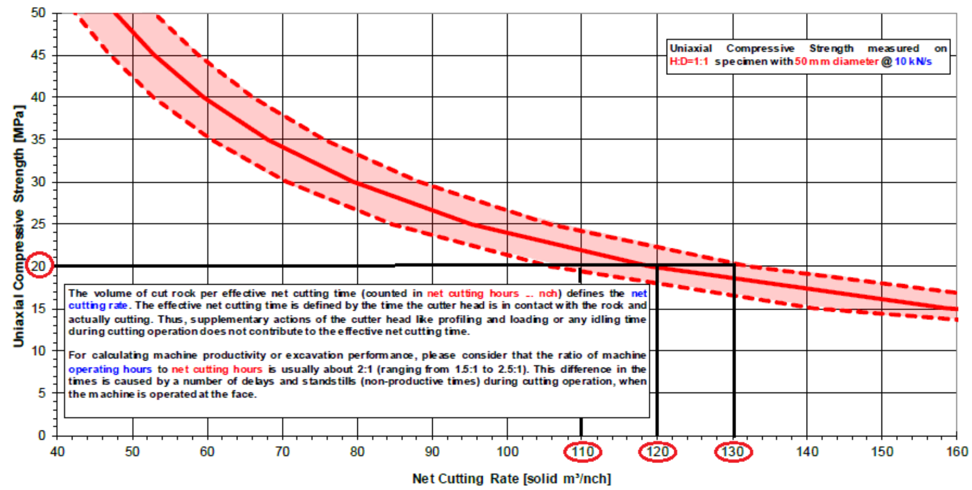

Figure 2. Net cutting rate for roadheader MT520 (315 kW insatalled cutter head power) equipped with cutter head R326-TC54 and 18mm TC diameter picks according to uniaxial compressive strength of potash&rock salt [4]

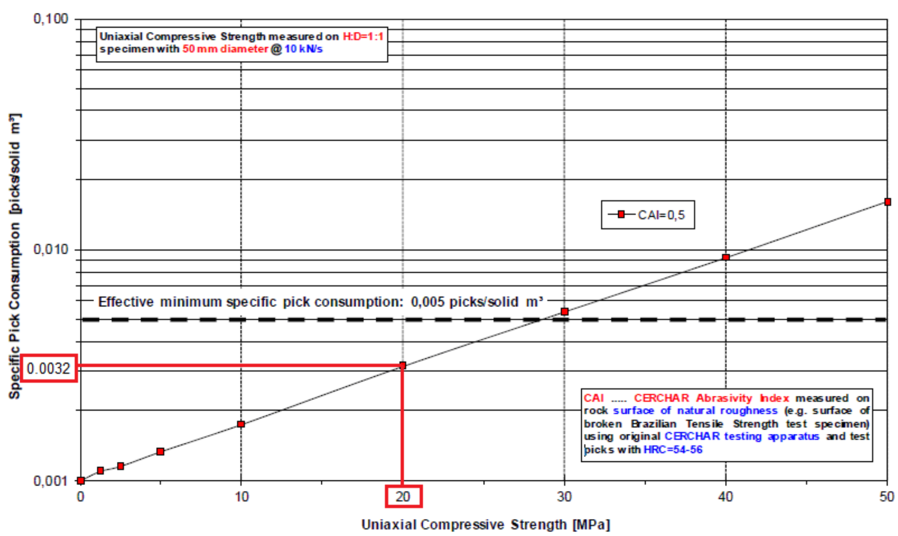

Figure 3. Specific pick consumption (SPC) for high speed cutting with transverse cutter head and 18 mm TC diameter picks of high quality according to rock strength and abrasivity of potash&rock salt [4]

2. TECHNOLOGICAL PHASES OF FRONT FACE EXTRACTION USING THE ROADHEADER SANDVIK MT520

Roadheader Sandvik MT520 has cutting heads with the axis of rotation parallel to the face, and they rotate with the picks approximately in a direction transverse to the face. More precisely, the mode of penetration of the cutting heads into the face is milling, in the direction of advancement of the face, and ripping/drilling, in the direction parallel to the face.

The cutting arm pivots horizontally along the entire front face. Once the cutting heads have penetrated the face, the cutting depth X is adjusted. Before each horizontal cut, the cutting head is adjusted for cutting thickness Y, penetrating the face to an additional depth. The cutting depth and thickness are adopted depending on the physical and mechanical characteristics of the rock salt.

Penetrating the front face with the cutting heads is achieved by adjusting the length of the combine's telescopic arm or moving the entire combine body towards the front, while the cutting arm pivots in a horizontal plane.

The loading plow, during the cutting operation, must be placed on the floor level, to load the salt displaced from the rock salt massif, while the roadhedear arm advances into the salt massif. After the initial penetration of the front, by the horizontal movement of the arm, a cutting web is cut across the entire cutting width of the front face, then the cutting thickness Y is set and the arm is pivoted horizontally. The cutting is done in a shuttle mode, over the entire surface of the digging front, ascending or descending, in case an unextracted front area is initially left at the floor of room.

2.1. Exploitation of rock salt with the roadheader in front faces, from Slice I

From the technical characteristics of the roadheader Sandvik MT520, it follows that the maximum sizes of the cross-section of the rooms that can be extracted with the roadheader, located in a single position, are: maximum height of 6.3 m and maximum width of 8.17 m (covering values for a strip with a height of 6 m (height of the first slice) and a width of 7.5 m (half of the room width – for the horiz. +190 m) – for the next 3 horizons, this width being 7 m (horiz. +173.5 m and horiz. +157 m) and 6.5 m (horiz. +140.5 m). Directional mining workings for horizon preparation and the opening incline, connecting the horizons, with a width of 8 m and a height of 6 m are also covered by the possibilities of the cross-section cutting geometry by this type of roadheader.

We mention that extracting a strip from the front face of the room with the aid of the roadheader, placed in a single position, ensures the achievement of maximum productivity during cutting, avoiding the additional times generated by the multiple maneuvers of the roadheader in the face. Therefore, the design of the technological phases of mechanized cutting of the face was carried out with the roadheader placed in a single position, in the center of the two vertical strips. For example, in the case of the first slice at the horizon +190m, the working face with a width of 7.5m is extracted from a single position of the roadheader, in the form of an arc of a circle with a length of 8.05m, and the angle of rotation, left to right, in the horizontal plane, of the cutting heads axis is 29.4^{o} (fig.4).

From the beginning, it should be mentioned that the cutting phases with the roadheader are imposed by the manufacturer of the roadheader Sandvik MT520, so that during the cutting process the constructive parts of the roadheader are stressed to a minimum, and energy consumption is as low as possible.

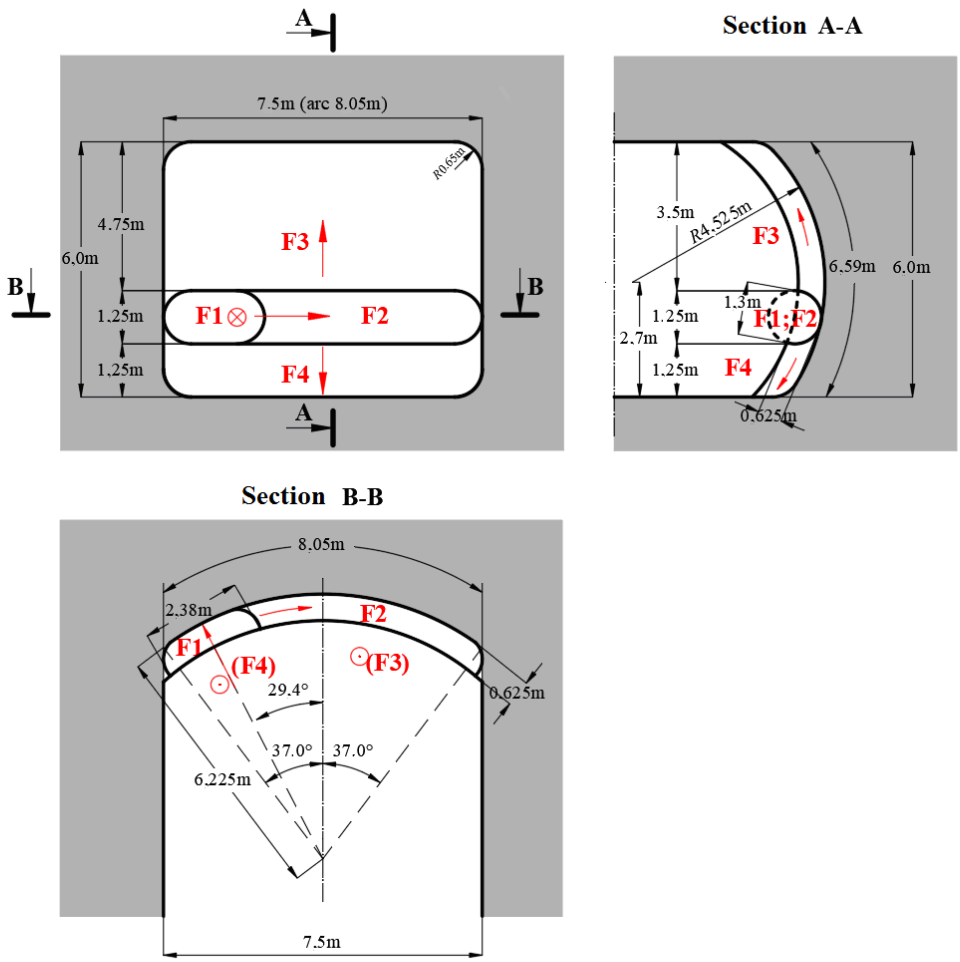

Fig.4. Representation of the main cutting phases with the roadheader Sandvik MT520 of the 7.5m x 6m strip, of the rooms in slice I, horizon +190m [2]

The technological process of making the first strip, corresponding to the cross-section of a room, includes the following cutting stages:

Stage 1

This technological phase begins with the rosdheader moving into the face, aligned in the middle of the 7.5m attack strip, with the cutting heads positioned at a height of about 1.25m from the floor, towards the left wall and in direct contact with the front (fig. 5 and 6). The plow is positioned on the floor, in the loading position, after the room floor has been cleaned as thoroughly as possible beforehand.

From the stationary position of the roadheader, centered on the axis of the strip, with dimensions of 6m x 7.5m (section of approx. $45m^2$), the extension of the telescopic arm of the roadheader is commanded (fig. 7 and 8), the cutting crown penetrates the salt massif at one of the ends of the strip, over a width of 2.38m (width of the cutting heads) and a depth of 0.625m (half the diameter of the crown) and a height of 1.25m or 1.3m on the vertical curvature of the front (the excavated volume is approx. $2.38 \cdot \frac{\pi \cdot 1.3^2}{4 \cdot 2}$ $=1.58m^3$) – fig. 4.

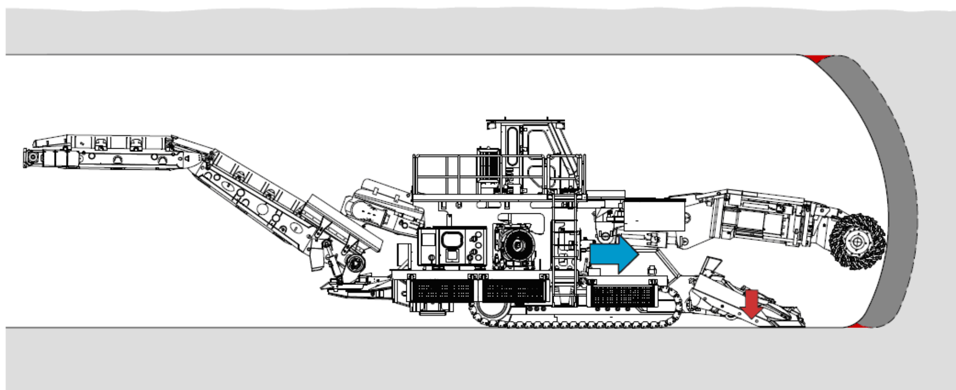

Figure 5. Starting position of the roadheader Sandvik MT520 in Stage 1 of face cutting [4]

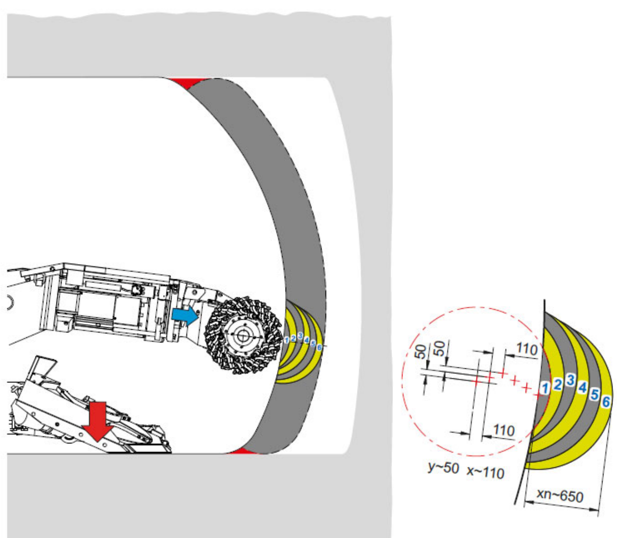

Figure 6. Moving the roadheader to the front, extending the telescopic arm of the roadheder and excavating the front in Stage 1 [4]

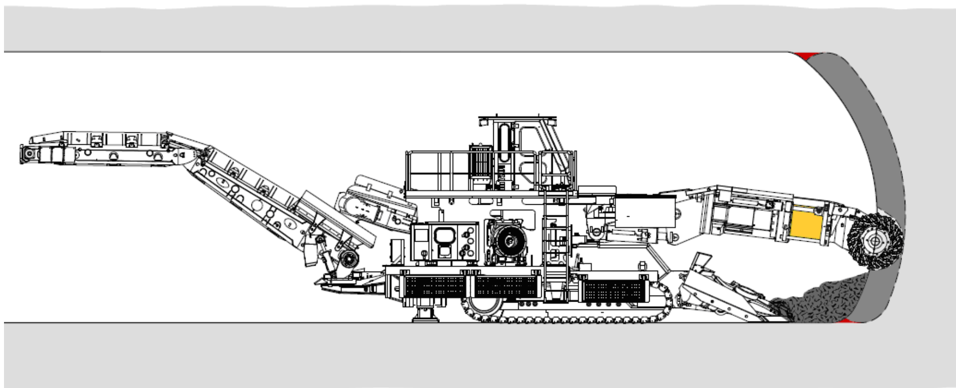

Figure 7. Stage 1 of achieving the penetration of the cutting crowns into the front of face [4]

Stage 2

To carry out Stage 2 of cutting the horizontal web, across the entire width of the 7.5m strip, the telescope is shortened, simultaneously with the roadheader advancing towards the front by 0.625m, until the loading plow reaches the limit with the front (fig.8.).

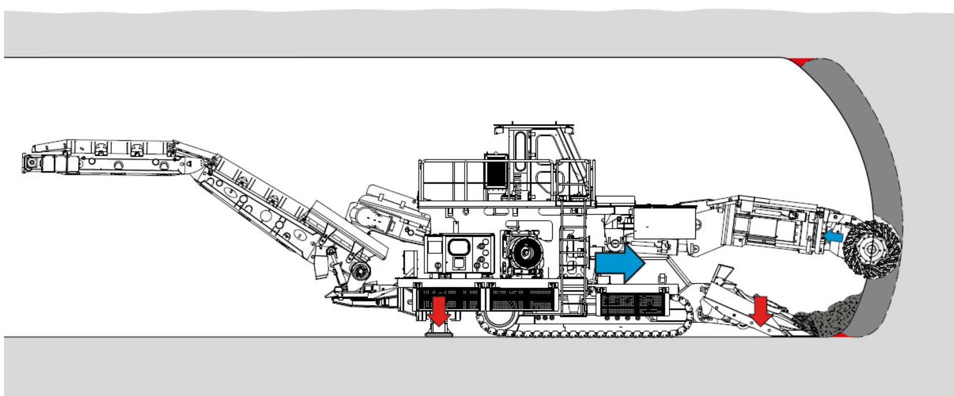

Figure 8. Positioning the roadheader for cutting the front in Stage 2 [4]

The cutting of the horizontal web, started in Stage 1, continues in Stage 2 with the movement of the cutting crowns in the horizontal plane, to the right end of the front, creating a web across the entire 7.5m width of the exploited strip, along the length of an arc of a circle of 8.058m (the excavated volume is: $5.67 \cdot \frac{\pi \cdot 1.3^2}{4 \cdot 2}$ =3.76m^3) - Fig.4.

At the room floor, after the extraction of the front face in Stage 2, across the entire width of the 7.5m strip, an area with a height of approximately 1.25-1.3m remains, which will be extracted in the last phase F4. In addition to the advantages already mentioned (lower demand on the roadheader arm and lower energy consumption, compared to starting the extraction of the front directly from the room floor, as in the case of Sandvik roadheders with a non-telescopic arm), maintaining a massive salt threshold at the floor determines the reduction of the fall height of the salt pieces detached from the front, with positive implications in terms of the granulometry of the material detached from the front and the reduction of the amount of dust released into the atmosphere.

Stage 3

After the extraction in phases F1 and F2 of a strip with a height of 1.25m (arc 1.3m) and 5.36m^3, cumulated in phases F1 and F2, the upward extraction continues along a horizontal arc with a length of 8.05m of a front portion with a width of 7.5m (or 8.05m along the arc of a circle), related to phase F3, by moving the cutting crown in the vertical plane by adjusting a maximum possible milling thickness of approx. Y=15-20cm (depending on the hardness of the rock salt massif) and horizontal movements of the cutting head, which leads to the upward cutting of a volume of salt of approx. 3.99x8.05x0.65=20.88m^3 (excavated dimensions being: cutting step of 0.65m, height of 3.99m and width of 8.05m).

Stage 4

In this final phase, the salt spur from the excavation floor, which remained unextracted in the previous stages, is extracted, with dimensions of 8.05m x 1.25 x 0.625m. The milling thickness is also preset at 15-20cm, but the milling of the front is produced downwards, by movements of the cutting tool in a horizontal plane, starting from the upper limit towards the floor. In Stage 4, an approximately identical volume of salt is extracted with that extracted cumulatively in stage 1 and 2, of approx. 5.34m^3.

Finally, the volume of a strip extracted from the front of the froom, in the 4 stages of cutting with the roadheader, is approx. 31.5m^3. Which, compared to the first slice of the horizon +190m, with the two strips and taking into account the geometric approximations of the calculation, represents a volume extracted with the combine from a strip of approx. 63m^3 or 135.5 tonnes.

Stages 1, 2, 3 and 4 are repeated at the level of the 2nd strip of slice I, with a width of 7.5m (8.05m per arc). After making a jump of 0.625m, the roadheader advances, centers on the new position, and the cycle repeats. The cutting time of the web at the floor $t_{i=1,2}$ in stages 1 and 2 is:

$$t_i = \frac{V_d \cdot \rho_a}{P_t}, \text{[min]} \tag{1}$$

where:

V_d is the volume displaced at the hearth, V_d =5.34m^3;

P_t - technical productivity of the combine, P_t =160 t/h;

ρ_a -apparent specific density of the rock salt, $\rho_a = 2.15$ t/m^3.

$$t_{1,2} = \frac{5.34 \cdot 2.15 \cdot 60}{160} = 4.3 \text{ min.}$$

The track widening time $t_{i=3}$ in stage 3, in the vertical plane, for an extracted volume of 20.88m^3:

$$t_3 = \frac{20.88 \cdot 2.15 \cdot 60}{160} = 16.8 \text{ min.}$$

The time required to dislodge the salt spur from the floor is approximately:

$$t_4 = t_{1,2} = 4.3 \text{ min.}$$

The total time for cutting a 0.625 m step is $t = t_{1,2} + t_3 + t_4 = 4{,}3 + 16{,}8 + 4{,}3$ =25.4 min, during which a volume of rock salt equal to 31.56 m^3 or 68 tonnes is displaced. The capacity of the VOLOVO A30G transport vehicle is 28 tonnes. Therefore, the time required to fill a dump truck is $\frac{28}{160} \cdot 60 \approx 10{,}5$ min. This means that from a strip at the horizontal level +190 m, with a width of 7.5 m, a height of 6 m and a depth of 0.625 m, approximately 2.4 dump trucks can be loaded in 25.4 min, in continuous cutting mode with the roadheader.

The 2nd strip (fig.9), from the level of the first slice of the +190m horizon, with a width of 7.5m, is extracted similarly to the first strip, through the four phases F1, F2, F3 and F4, by repositioning the roadheader on the axis of this strip.

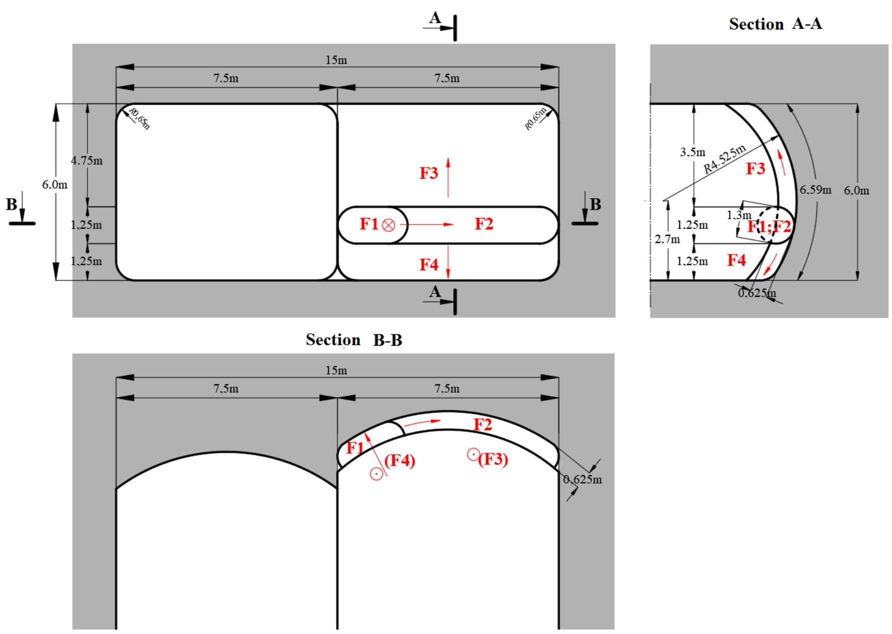

Figure 9. Extraction with the roadheader of the second strip, of the rooms in the first slice, horizon +190m [2]

2.2. Exploitation of the rock salt with the roadheader in front of the rooms, from Slice II

At the level of the second slice, the width of the front of 15m is divided into two identical vertical strips with a width of 7.5m (8.05m on the curvature) and it will be extracted similarly to the two strips in slice I, but in 3 successive phases F1, F2 and F3.

Stage 1

The start of the extraction of the 2nd slice, in the first strip with a width of 7.5m, will be done from the floor of the first slice, through the F1 phase, with a width of 1.25, leaving a threshold with a width of 0.65-0.7m to be extracted to the floor of the 2nd slice, which will be extracted with the roadheader in Stage 2. This will be achieved by extending the telescopic arm of the roadheader and penetrating the face of the front by 0.625m, after positioning the roadheader body at the center of the room, and the cutting tools at the lateral limit of the mining working (fig.10).

Stage 2

The telescopic arm is retracted to its maximum, and the roadheader is advanced with the loading plow to the limit of the front. The arm with the cutting heads is rotated so that a horizontal web is detached from the massif across the entire width of the front of the exploitation room (fig.11).

Stage 3

By moving the cutting heads downwards towards the floor of the second slice, by horizontal movements left-right, 150-200mm strips are milled from the rock salt massive, until the front at the floor of the chamber is completely extracted, on the portion of approx. 0.75m. Thus, the room will reach, within the limits of the first strip, the projected height of 8m, following the full exploitation of the second slice. After the extraction of the second slice, on the surface of the second strip, following the phases F1, F2 and F3, the room at the +190m horizon fully reaches the projected cross-section of 8m high and 15m wide, at the level of the +190m horizon.

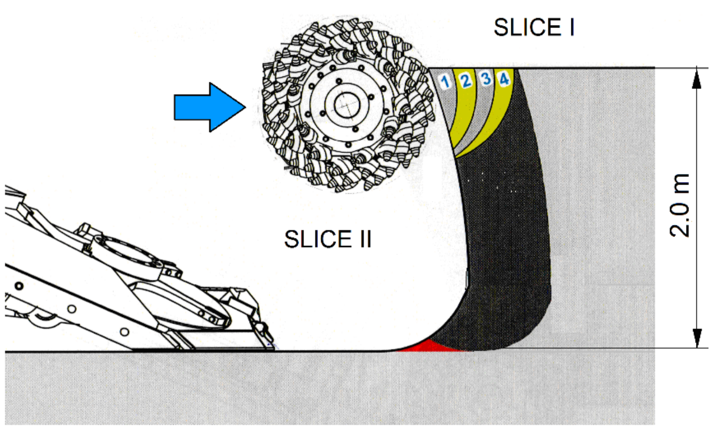

Figure 10. Moving the roadheader to the front, extending the telescopic arm of the roadheader and excavating the face of the cutting in Stage 1, Slice II [2, 4]

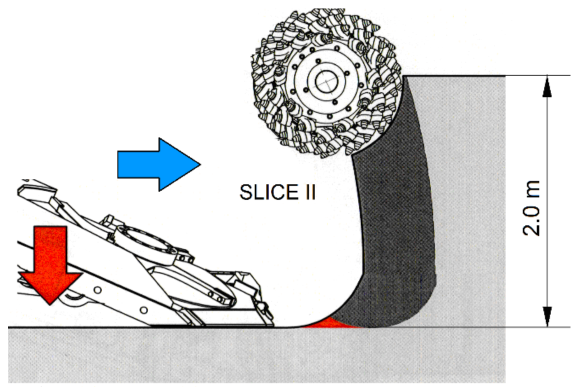

Figure 11. Positioning of the roadheader for cutting the front in Stage 2 - Slice II [2, 4]

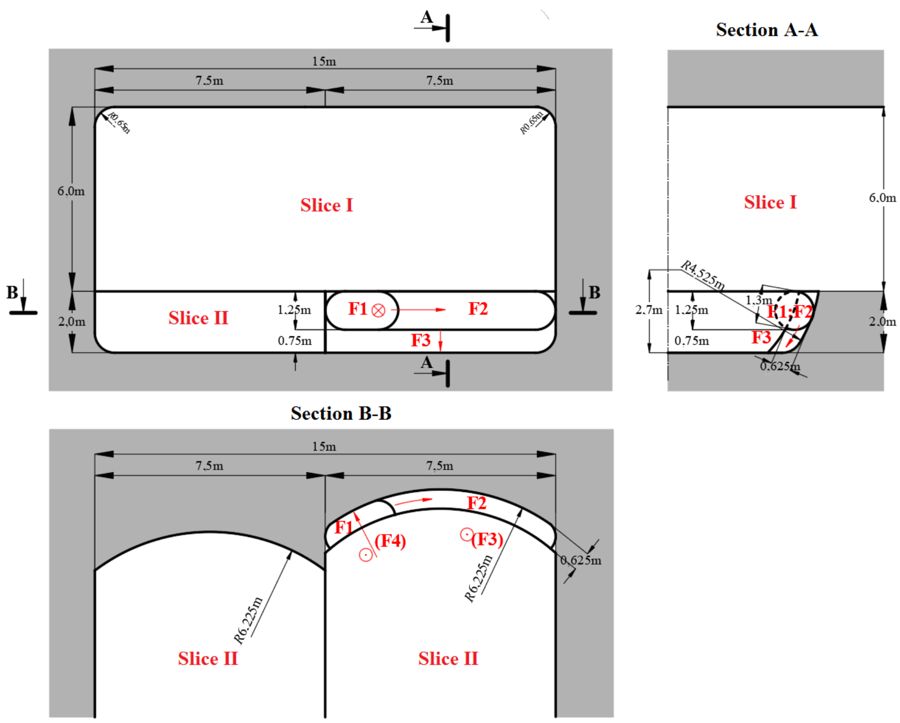

Figure 12. Extraction with a roadheader of the second slice,
from the mining room at the +190m horizon [2]

The mining technology will follow all the phases specific to Slice I and Slice II, within the limits of the two strips into which the rooms were divided by width, for the other horizons below the +190m, respecting the sequence of the extraction/cutting technological stages described above, adapted to the dimensional characteristics of the rooms at the +173.5m, +157m and +140.5m horizons.

Respecting the mining method and technology with the roadheader Sandvik MT520, at the Ocnele Mari Salt Mine, at the 4 horizons, the specific costs per expense item and the total cost are presented synthetically in Table 1 [2].

Table 1. Total unit cost for the exploitation of rock salt with the roadheader from the rooms at the horizons +190m, +173.5m, +157m and +140.5m, Ocnele Mari Salt Mine [2]

<table>
<tr><th rowspan="2">Specifications</th><th rowspan="2">MU</th><th colspan="4">Value</th></tr>
<tr><th>Horiz. +190m</th><th>Horiz. +173.5m</th><th>Horiz. +157m</th><th>Horiz. +140.5m</th></tr>
<tr><td>Annual production</td><td>tonne</td><td colspan="4">200,000</td></tr>
<tr><td>Unit cost generated by electricity consumption</td><td>lei/tonne</td><td colspan="4">4.3</td></tr>
<tr><td>Unit cost generated by fuel consumption</td><td>lei/tonne</td><td>0.2</td><td>0.3</td><td>0.5</td><td>0.6</td></tr>
<tr><td>Unit cost generated by depreciation of equipment and means of transport</td><td>lei/tonne</td><td>16.9</td><td colspan="2">18.1</td><td>19.4</td></tr>
<tr><td>Unit cost generated by other consumables</td><td>lei/tonne</td><td>0.6</td><td>0.7</td><td>0.7</td><td>1.1</td></tr>
<tr><td>Unit cost generated by maintenance and repair works of equipment and means of transport</td><td>lei/tonne</td><td>1.7</td><td colspan="2">1.8</td><td>1.9</td></tr>
<tr><td>Unit cost generated by personnel expenses</td><td>lei/tonă</td><td>4.1</td><td colspan="2">4.7</td><td>5.2</td></tr>
<tr><td>Unit cost of unforeseen expenses*</td><td>lei/tonne</td><td>2.8</td><td>3.0</td><td>3.0</td><td>3.3</td></tr>
<tr><td>Total unit cost (without unforeseen expenses)</td><td>lei/tonne</td><td>27.8</td><td>29.9</td><td>30.1</td><td>32.5</td></tr>
<tr><td>TOTAL UNIT COST</td><td>lei/tonne</td><td>30.6</td><td>32.9</td><td>33.1</td><td>35.8</td></tr>
<tr><td colspan="6">*Note: the unit cost with unforeseen expenses is approximated at approx. 10% of the total calculated cost</td></tr>
</table>

3. LOADING AND TRANSPORTING ROCK SALT DURING THE EXPLOITATION OF THE ROOMS AT THE FOUR HORIZONS

The rock salt transport system from the face to the processing/grinding plant at the +190m horizon is carried out using VOLOVO A30G dump trucks, from where the processed salt is transported to the surface with belt conveyors, on the adit (adit entrance elevation +202m).

Taking into account the transportation distance to the unloading point at the +190m horizon, it is necessary to establish the number of necessary means of transport, as well as organize transport, respectively establish the movement schedule of the means of transport and implicitly correlate the transportation system with the dynamics of the faces at the +190m, +173.5m, +157m and +140.5m horizons.

Thus, establishing the maximum transport distance is necessary to determine the required number of dump trucks for the furthest rooms from the rock salt production unloading point (the transport route on the directional preparation workings, up to the directional limits of the mining field, for the rooms located at the eastern and western limits, to which is added the route of the dump trucks on the spiral incline). Considering the above, the design of the organization of transport will be made for the conditions in which the required production capacity of 200,000 tonnes/year (800tonnes/day) is achieved in the critical situation of the longest transport distance.

It is also necessary to determine the average transportation distance from the center of gravity of the industrial rock salt reserves, within each wing of the mining field, for each horizon, to the destination/unloading point. The average distances are necessary for calculating the specific costs of rock salt transportation, which are directly related to the production system in the face. The calculation of rock salt transportation costs does not take into account the transportation of production on the conveyor belt system, which is part of the general salt transport system on the adit.

The duration of a course of a dump truck (loading/unloading/transport) varies due to the different distances and speeds of vehicles on the transport route:

$$T_{c\,\hat{i}t} = t_m + t_{aux}\text{, min.} \tag{2}$$

$$t_{aux} = t_{ib} + t_d + t_{ma}\text{, min.} \tag{3}$$

$$t_m = t_{mp} + t_{mg} = 60 \cdot \sum \frac{l_i}{k_v \cdot v_{mp}} + 60 \cdot \sum \frac{l_i}{k_v \cdot v_{mg}}\text{, min.} \tag{4}$$

where:

t_{ib} is the time of cutting the front with the roadheader and loading the dumper (t_{ib} =10.5min.);

t_{mp} – the time of travel with the loaded dumper, min.;

t_{mg} – the time of travel without load, min.;

t_d – the time of unloading by tipping the body (on average t_d=1 min.);

t_{ma} – the time of maneuvers and waiting for a complete course (t_{ma}=5min.).

l_i are the lengths of the route on which the vehicle travels at different average speeds, km;

k_v – the coefficient of speed non-uniformity (k_v = 0.8);

v_{mp}, v_{mg} – the recommended average speed of full and empty course, km/h.

To determine the maximum and minimum transport distances at the level of each horizon, the following vehicle travel distances are taken into account, which will be cumulated differently depending on the corresponding horizon in operation, as follows:

l_1 =1.20km is the maximum transport length on the directional and transverse mining preparatory working, at the limits of the exploitation field of each horizon (approximate value which is considered to be the same at the level of all four horizons in exploitation);

l_2 =0.45km - average transportation length on the directional preparatory mining working to the center of the reserves at the level of the mining field wings (approximate value that is considered to be the same at the level of all four horizons in exploitation);

l_3=0.27 km – length of the incline connecting the horizons +173.5m and +190m;

l_4=0.54 km– length of the incline connecting the horizons +157m and +173.5m;

l_5=0.81km – length of the incline connecting the horizons +140.5m and +157m.

A) Determining the ”loading-unloading-transport” time for the maximum distance

Considering the above, the design of the organization of road transport and the establishment of the required number of dump trucks will be done for the conditions in which the speed of advancement of the mining opening and preparatory workings required by the completion deadline is achieved for the critical situation imposed by the longest transport distance (table 2):

a) from horizon +190m, the maximum transport distance is: 1.20km;
b) from horizon +173.5m, the maximum transport distance is: 1.47km;
c) from horizon +157m, the maximum transport distance is: 1.74km;
d) from horizon +140.5m, the maximum transport distance is: 2.01km.

Table 2. Calculation of the effective movement time (full+empty) in a course tm (in min./course) of dump trucks, for different mining workings - maximum and average transport distance [2]

Horizon	**Length, l_i, km**	**Movement speed x (k_v=0.8), km/h**		**Movement time, min./course**		
		full course, v_{mp}	**empty course, v_{mg}**	t_{mp}	t_{mg}	t_m
Preparatory workings horizon, max.	l_1=1.200	15x0.8=12	20x0.8=16	6.000	4.500	10.5
Preparatory workings horiz. average	l_2=0.450	15x0.8=12	20x0.8=16	2.250	1.688	3.9
Spiral incline oriz.173.5 ÷ 190	l_3=0.270	6x0.8=4.8	10x0.8=8	3.375	2.025	5.4
Spiral incline oriz.157.0 ÷ 190	l_4=0.540	6x0.8=4.8	10x0.8=8	6.750	4.050	10.8
Spiral incline oriz.140.5 ÷ 190	l_5=0.810	6x0.8=4.8	10x0.8=8	10.125	6.075	16.2

Table 3. Calculation of the "loading-unloading-transport" time T_c ît (in min/course), for the maximum transport distance for horizons exploited with the roadheader [2]

Horizon	L_{total} km	$\sum l_i$	t_{ib}, min.	t_d, min.	t_{ma}, min.	t_{aux}, min.	$t_{m\,i}$, min.		$\sum t_{m\,i}$ min.	$T_{c\,ît}$, min./ course
+190m	1.20	l_1	10.5	1	3	14.5	10.5		10.5	25.0
+173.5m	1.47	l_1+l_3	10.5	1	3	14.5	10.5	5.4	15.9	30.4
+157m	1.74	l_1+l_4	10.5	1	3	14.5	10.5	10.8	21.3	35.8
+140.5m	2.01	l_1+l_5	10.5	1	3	14.5	10.5	16.2	26.7	41.2

The motion diagram of the two dump trucks, for transporting the rock salt from the rooms at the +190m horizon, is shown in fig. 13. Also, for the +140.5m horizon, the motion diagram is presented in figure 14.

Considering the analyses carried out above, it is obvious to conclude that achieving the planned production capacity of 133.33 tonnes/hour (or 800 t/shift, in a single shift per day) – for a roadheader is possible under the conditions of performing at least 4.76 courses/hour, which can be achieved at the horizontal level +190m only by the simultaneous operation of two VOLOVO A30G dump trucks. This situation is characteristic for the maximum transport distance. However, as the transport distance is shortened, by bringing the faces closer to the discharge point, technical conditions are created to achieve the planned production capacity, using only one dump truck.

B) Determination of the ”loading-unloading-transport” time for the average distance

The calculations resulting from the design of the transport organization for digging the opening and preparatory mining workings must also take into account the average transport distance, to the center of the length of the preparatory workings on the horizons +190m, +173.5m, +157m and +140.5m, for the evaluation of the average labor and fuel consumption required in the technical and economic analyses.

The results of the transport design calculations for the average transport distance, in the case of the rooms at the level of the four horizons, are summarized in Tables 4:

a) from horizon +190.0m, the average transport distance is: 0.45km;
b) from horizon +173.5m, the average transport distance is: 0.72km;
c) from horizon +157.0m, the average transport distance is: 0.99km;
d) from horizon +140.5m, the average transport distance is: 1.26km.

Table 4. Calculation of the "loading-unloading-transport" time $T_{c\,ît}$ (in min/course) from the mining rooms – the average transport distance for the horizons mined with the roadheader [2]

Horizon	**L_{total} km**	$\sum l_i$	**$t_{îb}$, min.**	**t_d, min.**	**t_{ma}, min.**	**t_{aux}, min.**	**$t_{m\,i}$, min.**		**$\sum t_{m\,i}$ min.**	**$T_{c\,ît}$, min./ course**
+190m	0.450	l_2	10.5	1	3	14.5	3.9		3.9	18.4
+173.5m	0.720	l_2+l_3	10.5	1	3	14.5	3.9	5.4	9.3	23.8
+157m	0.990	l_2+l_4	10.5	1	3	14.5	3.9	10.8	14.7	29.2
+140.5m	1.260	l_2+l_5	10.5	1	3	14.5	3.9	16.2	20.1	34.6

For the rooms of the four horizons exploited with the roadheader, tables 5 and 6 present the main technical and economic indicators achieved during the transportation of rock salt (transport productivity and specific fuel expenses).

Table 5. Summary of the main parameters of the loading and transport system, for a single dump truck, depending on the operating horizon [2]

Horizon	***Maximum transport distance***				***Average transport distance***			
	L_{total} km	**$T_{c\,ît}$, min./ course**	**$n_{c\,ît}$, courses/ hour**	**P_h, t/hour**	**L_{total} km**	**$T_{c\,ît}$, min./ course**	**$n_{c\,ît}$, courses/ hour**	**P_h, t/hour**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
+190.0m	1.20	25.0	2.40	67.20	0.450	18.4	3.26	91.30
+173.5m	1.47	30.4	1.97	55.16	0.720	23.8	2.52	70.59
+157.0m	1.74	35.8	1.68	47.04	0.990	29.2	2.05	57.53
+140.5m	2.01	41.2	1.46	40.88	1.260	34.6	1.73	48.55

Table 6. Average diesel fuel consumption in transportation for operating horizons [2]

Horizon	**$L_{2\,x\,average}$ km**	***Diesel fuel consumption***		
		10^{-2} km/tonne	**10^{-2} liters /tonne**	**lei/tonne**
+190.0m	0.900	3.214	3.520	0.196
+173.5m	1.440	5.142	5.631	0.313
+157.0m	1.980	7.071	7.743	0.430
+140.5m	2.520	9.000	9.855	0.548
Note: *Consumption=1.095 liter/km; Diesel price = 5.56 lei/liter*				

For a required production capacity of 800 tonnes/sch. (at a 6-hour shift), the hourly production capacity required by loading with the Sandvik MT520 roadheader and transporting with a VOLVO A30G dump truck is at least 133.33t/hour. Which, for the simultaneous use of two dump trucks is 66.66t/hour, for 3 dump trucks is 44.44t/hour, and for 4 dump trucks used simultaneously is 33.33t/hour. Comparing the transport productivity calculated in Table 5, column (5) with those determined above, it can be concluded that, in order for the planned productivity to be covered, the minimum number of dump trucks (with a capacity of 28 tonnes) required, adopted at each horizon is the following: 2 dump trucks for horizon + 190m (with a transport capacity reserve of 0.8%); 3 dump trucks at horizontal +173.5m and 157m (with a capacity reserve of 24.12% and 5.85%, respectively); 4 dump trucks at horizontal +140.5m (with a transport capacity reserve of 22.65%). We note that the capacity reserves are necessary to cover some blockages of dump trucks on the route or due to overlaps occurring at loading or unloading points during the production shift.

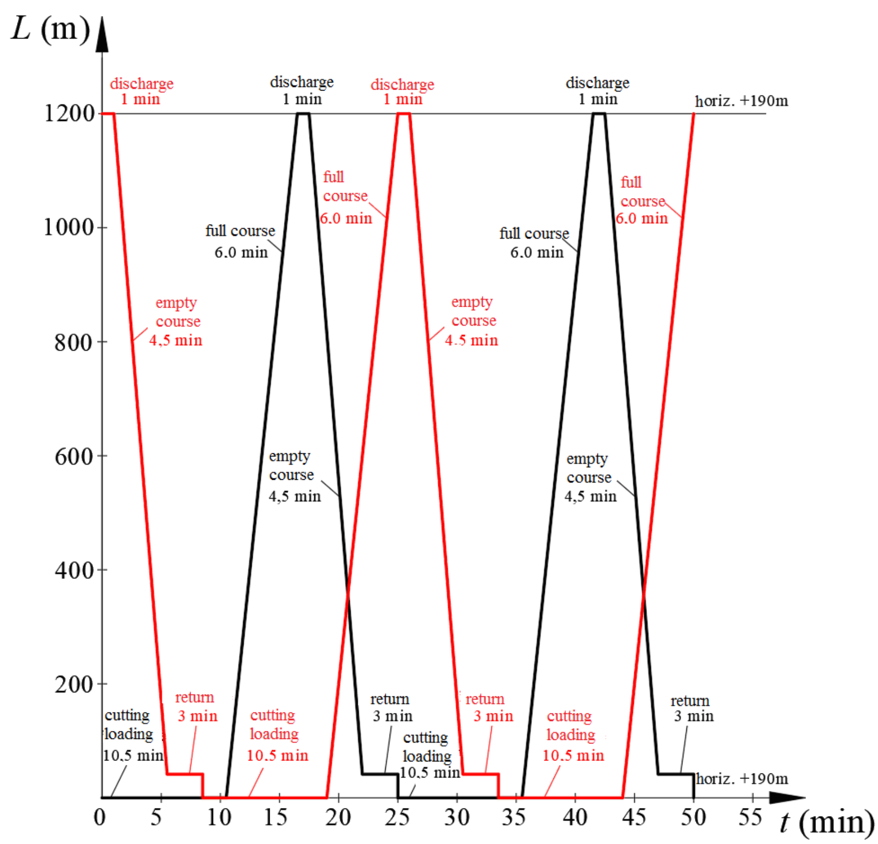

Figure 13. The motion graph of two dump trucks, for a roadheader, when exploiting the horizon +190m, at a production capacity of 800 tonnes/sch, for a maximum transport distance L = 1,200m [2]

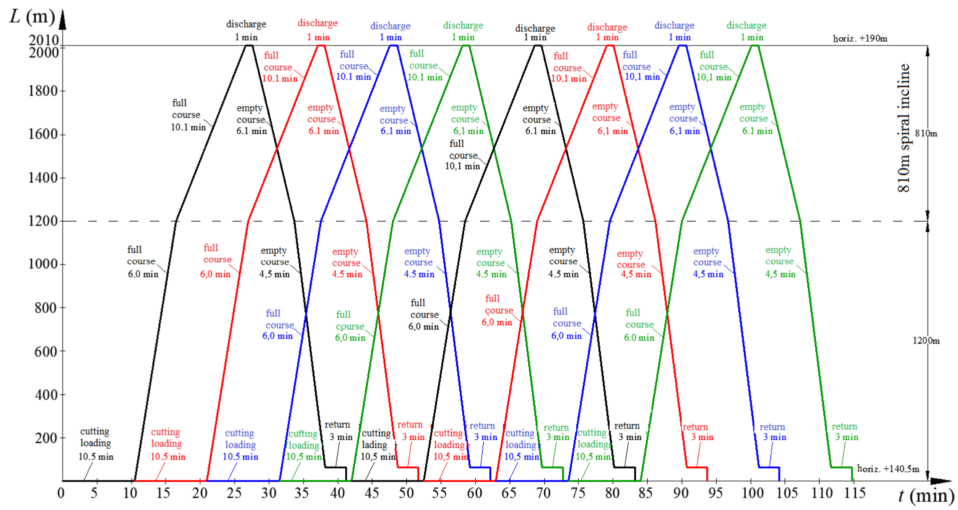

Figure 14. The motion graph of four dump trucks, for a roadheader, when exploiting the horizon +140.5m, at a production capacity of 800 tonnes/sch, for a maximum transport distance *L* = 2,010m [2]

5. CONCLUSIONS

The mechanized exploitation with the roadheader Sandvik MT520 of the rock salt deposit at the Ocnele Mari Salt Mine, respectively at the level of the horizons +190m, +173.5m, +157m and +140.5m, is planned to be carried out at a production capacity of 200,000 tonnes/year.

Mining method applied below the elevation of +210m, at Ocnele Mari is with small rooms and square pillars. The chambers have dimensions of 8m x l_c m (l_c=15m, 14m, 14m and 13m) and correspondingly, the pillars have dimensions of 15 x 15m, 16x16m, 16x16m and 17x17m.

The following machines and equipment are used in the mechanized excavation technology using the roadheader Sandvik MT520: Sandvik MT 520 roadheder; DVS 21 dry dust removal system; equipment related to the roadheader; VOLOVO A30G dump truck; JLG aerial auto-platform.

Roadheader Sandvik MT520 equipped with the Ocnele Mari Mine is the leading equipment in the production process in the face. The main technical and economic characteristic of the roadheader is the cutting capacity which, from the experience at the level of +190m horizon, is approx.160 tonnes/hour. Regarding the specific consumption of picks, the manufacturer recommends an effective minimum of 0.005 picks/m^3.

From the technical characteristics of the Sandvik MT520 roadheader, it results that the maximum sizes of the transverse profile of the rooms that can be extracted with the roadheader, located in a single position, are: maximum height of 6.3 m and maximum width of 8.17 m (covering the technological conditions at the Ocnele Mari Salt Mine).

The mining technology with the roadheader is adapted to the exploitation of the two successive slices of 6m and 2m, in 4 stages for the first slice and 3 technological stages in the second slice.

Respecting the mining method and technology with the roadheader Sandvik MT520, at the Ocnele Mari Salt Mine, at the 4 horizons, the specific costs per expense item and the total cost are between 30.6 lei/tonne (at horizon +190m) and 35.8 lei/tonne (at horizon +140.5m).

The rock salt transportation system from the face to the processing/grinding plant at +190m is carried out using VOLOVO A30G dump trucks, from where the processed salt is transported to the surface with belt conveyors, on the adit.

For a required production capacity of 800 tonnes/shift. (at a 6 hour shift), the hourly production capacity required by loading with the Sandvik MT520 combine and transporting with a VOLVO A30G dump truck is at least 133.33tonnes/hour. Which, for the simultaneous use of two dump trucks is 66.66tonnes/hour, for 3 dump trucks is 44.44tonnes/hour, and for 4 dump trucks used simultaneously is 33.33tonnes/hour. In order for the production capacity to be covered by the transport system, the minimum number of dump trucks (with a capacity of 28 tonnes) required is: 2 dump trucks for horizon + 190m; 3 dump trucks for horizon + 173.5m and +157 dump trucks for horizon + 140.5m.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

POST-MINING ECONOMIC DEVELOPMENT SCENARIOS OF THE JIUL VALLEY: ANALYSIS AND SUSTAINABLE PERSPECTIVES

Sorin Radu ILOIU [1], Mirela ILOIU[2]

Abstract: *The Jiu Valley is one of the most representative post-mining regions in Romania, having experienced profound economic and demographic decline following the gradual closure of coal mining activities. This paper examines the recent transformation of the region in the context of post-mining restructuring and European Just Transition policies. The analysis is based on official statistical data, European research project reports, and national and regional strategic documents. Four development scenarios are explored, focusing on energy transition, green reindustrialization, tourism and cultural valorization, and education- and innovation-driven development. The study highlights the structural constraints affecting the region and argues that no single pathway can ensure a sustainable transition. Instead, it emphasizes the need for an integrated approach combining economic diversification, human capital development, and institutional capacity building, offering relevant insights for regional development policy and academic research.*

Key words: *post-mining regions; just transition; regional restructuring; energy transition; sustainable regional development; Jiu Valley*

1. INTRODUCTION

The transition of mining regions in Central and Eastern Europe has become, in the last two decades, a strategic process essential for aligning Member States with the objectives of the European Green Deal and long-term decarbonisation mechanisms. Among these regions, the Jiu Valley occupies a distinct place due to its almost total historical dependence on the coal mining industry and the complexity of the socio-economic processes triggered by the decline of mining after 1990.

According to official data published in the TRACER D3.1 report, the region has experienced a significant population decline, from 167,456 inhabitants in 1990 to 120,734 inhabitants in 2018 (Figure 1). Consolidated data available until the 2021 Population and Housing Census confirm the continuation of this trend, with the total population falling below the threshold of 100,000 inhabitants, and estimates for 2024 indicated a continued downward demographic trend. [13], [8], [9]

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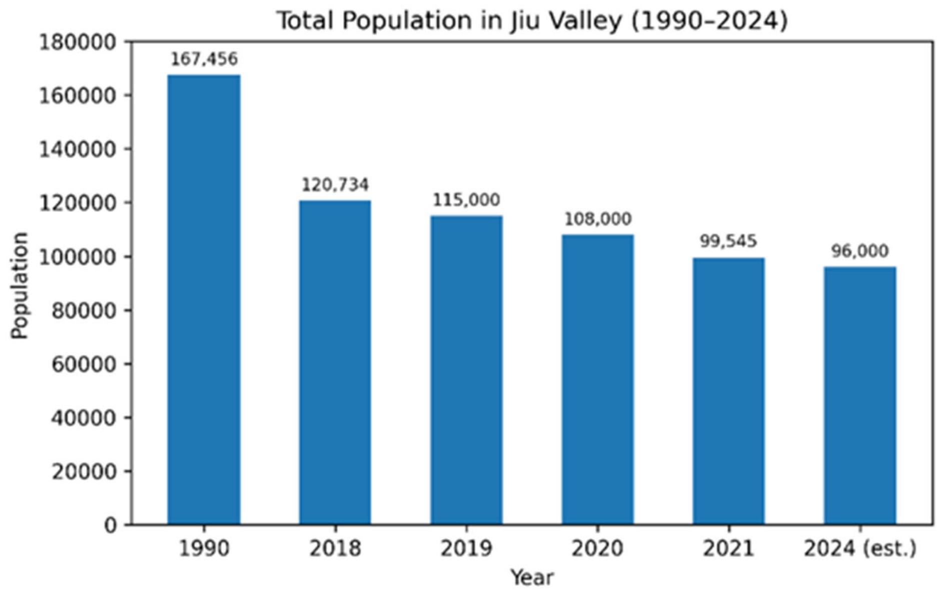

Figure 1. Population in Jiu Valley localities, 1990 vs. 2024

Demographic decline represents one of the most important structural constraints of the post-mining transition process in the Jiu Valley. As illustrated in Figure 2 , all six localities of the Jiu Valley have recorded a continuous population decline since 1990, with particularly pronounced losses in urban centers with a mono-industrial profile, such as Petroșani, Lupeni and Petrila. The data highlight not only the magnitude of the depopulation phenomenon, but also its uneven territorial distribution, reflecting differences in local economic structure, accessibility and capacity to adapt to economic changes. This demographic evolution has direct implications for the availability of labor, the functioning of social infrastructure and the feasibility of long-term development strategies in the post-mining context. [4], [8], [13]

The socio-economic impact accumulated in the region is visible at the level of the entire micro-region, through the increase in economic vulnerability, the degradation of infrastructure, the reduction of the financial contribution of the mining sector to local budgets (from 76% in 1990 to only 1.71% in 2018), but also through the change in the structure of the labor market, affected by the lack of viable employment alternatives. The restructuring processes have also determined the emergence of social phenomena specific to mono-industrial areas in transition, such as the accelerated migration of the young population and demographic aging. These developments are presented in recent academic literature, including in studies published in *Matec Web of Conferences* and in the ENTRANCES Case Study – Jiu Valley report . [4], [12], [13]

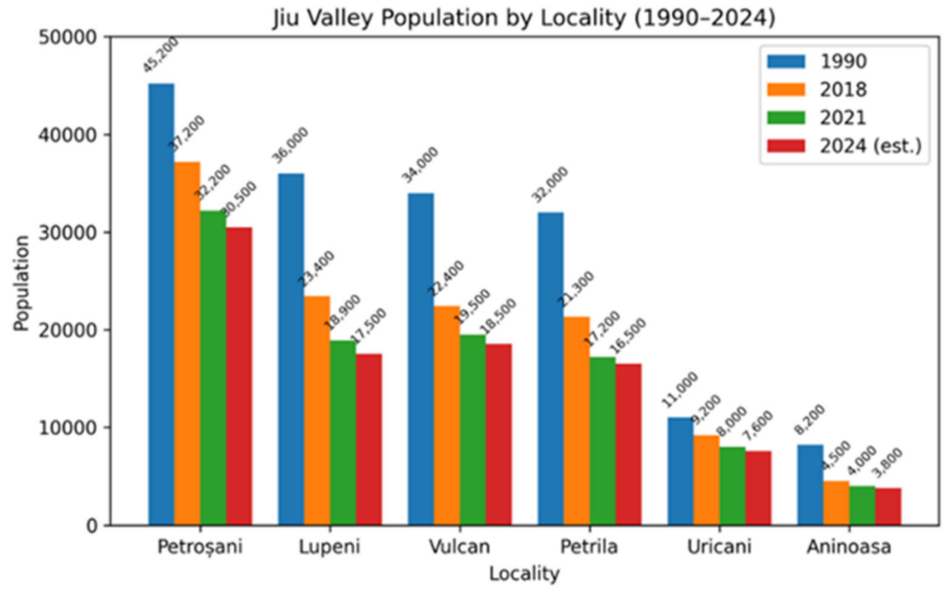

Figure 2. Resident population of Jiu Valley localities (1990–2024)

In this context, identifying realistic and sustainable scenarios for the post-mining economic development of the Jiu Valley requires a structured analytical approach, based on official data and rigorous evaluation methods. The European Union and the Government of Romania promote, through the Jiu Valley Economic, Social and Environmental Development Strategy 2021–2030, major directions such as energy transition, development of green industries, diversification of the local economy, valorization of industrial heritage, investments in education and innovation, and ecological regeneration of degraded mining lands.

This paper aims to comparatively address four possible strategic scenarios for the Jiu Valley:

(1) development of an energy pole based on renewable sources;
(2) strengthening a modern green industrial sector;
(3) tourist and cultural exploitation of mining heritage;
(4) creating a regional educational and innovative ecosystem.

2. DEVELOPMENT OF TRANSITION SCENARIOS FOR THE JIUL VALLEY IN THE POST-MINING CONTEXT

The transformations that the Jiu Valley has undergone in recent years are the result of a complex process of industrial restructuring, demographic decline and strategic reorientation determined by European policies on decarbonization and just transition. The region falls into the category of "coal and carbon intensive regions" defined at the European Union level and is explicitly mentioned in documents such as TRACER - Report on the current role of coal mining (2019), the Jiu Valley Economic, Social and

Environmental Development Strategy 2022–2030 and in the ENTRANCES project reports dedicated to the social effects of the energy transition.

According to the TRACER D3.1 report, between 1990 and 2018, the Jiu Valley recorded one of the most pronounced declines in the industrial workforce in Central Europe, with the number of mining employees decreasing from 55,000 to 4,797 people, while the region's population reached 120,734 inhabitants, corresponding to a decrease of approximately 28% compared to 1990. The consolidated official data available until the 2021 Population and Housing Census confirm the continuation of this trend, with the total population of the six localities falling below the threshold of 100,000 inhabitants. The reduction in extractive activities was also reflected in the decrease in the number of active mining perimeters (from 17 to 4) and in the annual production of coal (from 10.5 million tons to 0.8 million tons), to a very low level of activity, specific to the closure and conservation phase of mining operations after 2018. [8], [9], [13]

In the period 2022–2024, the restructuring process entered an advanced phase, characterized by the phased closure of mining operations and the reduction of extraction activities to a residual level. According to the planning and implementation documents published by the Ministry of Energy and the European Commission, mining activities in the Jiu Valley involved, at this stage, a significantly reduced workforce, estimated at a level below the threshold of 2,000 employees. In order to outline the framework for the analysis of the development scenarios, the following table (table 1) summarizes the main indicators of the structural transition. [8], [9], [13], [14]

Table 1. Evolution of relevant socio-economic indicators for the Jiu Valley (1990–2024)

Indicator	1990	2018	2021	2024 (estimate)
Total population (6 localities)	167,456	120,734	99,545	~96,000
Mining employees	55,000	4,797	~2,800	<2,000
Mining perimeters in operation	17	4	2	1
Coal production (million tons/year)	10.5	0.8	~0.3	~0.1
Mining's contribution to local budgets	~76%	~2%	<1%	<1%
Number of active enterprises (total)	–	–	2,541	3,000

TRACER D6.3 data shows that, at the beginning of 2021, 2,541 enterprises were operating in the Jiu Valley, of which 99.9% were microenterprises and SMEs, with only two large companies, confirming the transition from a mono-industrial model dominated by a single enterprise to a fragmented model of the local economy. In parallel, the European Commission's " **JTP Groundwork - Jiu Conurbation** " report mentions that the Jiu Conurbation (which includes the Jiu Valley) was included in the eligibility area of an allocation of approximately **EUR 1.2 billion** from the Just Transition Fund, an amount intended for economic diversification, professional reconversion and urban regeneration projects in Hunedoara County. [14], [3]

Against this background, the paper proposes four strategic development scenarios for the post-mining period, formulated as **directions that can be integrated** into the logic of just transition:

A. **Energy scenario** – conversion of mining infrastructure into a platform for renewable energy;

B. **The industrial-green scenario** – sustainable reindustrialization based on a green economy;
C. **The tourist-cultural scenario** – capitalizing on industrial heritage and natural resources;
D. **The educational-innovative scenario** – strengthening human capital and the innovation ecosystem.

Next, each scenario is analyzed in terms of **factual premises**, **strategic measures** and **risks/limits**, with explicit reference to data and public policy documents.

A. Energy scenario: harnessing the potential for renewable energy

In the international literature on the transition of coal regions, the conversion of mining infrastructure to renewable energy production is considered one of the most effective solutions for creating a new economic base, compatible with the objectives of the European Green Deal and the Paris Agreement. The model is applied in numerous regions in Germany, Poland or Spain, where former mining areas are reused as sites for photovoltaic, wind farms or energy storage units. [2], [6], [12]

In the case of the Jiu Valley, TRACER – Blueprint on energy transition in Jiu Valley / West Region (RO42) presents scenarios for the evolution of the local energy mix until 2050, highlighting the potential for the gradual installation of renewable capacities (photovoltaic, microhydro, biomass) on the lands released by extractive activities. The total area of the micro-region is approximately 1,033 km², and a significant part of the degraded industrial lands is already identified as available for energy projects and greening. [13], [11]

Although detailed data on projects are scattered between funding guides, county plans and submitted applications, documents from the ADR Vest and the Ministry of Investments and European Projects show that, in the context of the Just Transition Fund, renewable energy is one of the priority investment axes for the ITI (Integrated Territorial Investment) Jiu Valley , including photovoltaic systems on public buildings, medium-scale PV parks and energy efficiency measures. Organizations such as Greenpeace and Bankwatch estimate that the transition to a green energy mix in the Jiu Valley could generate **approximately 3,000 jobs** in optimistic scenarios, cumulated across the entire chain (construction, maintenance, related services), provided that the projects are accompanied by vocational training and support programs for local entrepreneurship. [3], [11], [1], [7]

Based on these sources, the energy scenario for the Jiu Valley can be structured into three **strategic axes** :

1. **Conversion of mining lands into energy platforms** – identification and legal clarification of available areas (dumps, industrial platforms, closed perimeters), correlated with the network plans of the transmission and distribution operator. The Jiu Valley coal transition strategy insists on the need to map these lands and integrate them into regeneration projects.
2. **Developing a diversified portfolio of renewable projects** – large-scale photovoltaic parks, PV systems on residential and public buildings, pilot storage projects (batteries, possibly pumped hydro in advanced scenarios). National reports on the increase in renewable capacity show that Romania aims to reach

8,000 MW of installed renewable capacity in 2026 and 10,400 MW in 2031, which creates a window of opportunity for projects in the Jiu Valley as well. [2], [11]

3. **Social integration of the energy transition** – projects must be correlated with training and professional retraining programs for former miners and young graduates, so that the economic benefits are not limited to capital rent, but are translated into jobs and local income.

This scenario has **structural advantages** (access to JTF financing, existing electrical infrastructure, compatibility with EU objectives), but also **limitations** : the number of permanent jobs created in the operating phase is relatively low, and the complexity of regulations and authorization processes may delay the actual materialization of projects. In the logic of the paper, the energy scenario is considered **the investment engine** of the transition, but it cannot function in isolation, but must be articulated with the industrial-green and educational-innovative scenarios to have a significant socio-economic impact.

B. The green industrial scenario: sustainable reindustrialization of mining platforms

The industrial-green scenario starts from the observation that the Jiu Valley has a considerable industrial infrastructure – halls, industrial railways, workshops, technical and municipal networks – which, although partially degraded, can be reused for productive activities with low carbon emissions. TRACER D6.3 shows that at the beginning of 2021, 2,541 enterprises were operating in the Jiu Valley, 99.92% of which were microenterprises and SMEs, with only two large companies (ApaServ and CEH). [14]

This fragmented structure indicates an **incipient diversification** of the local economy, but also a **vulnerability**: small firms predominate, with limited resources for investments in technology and innovation. The document “Support to the preparation of Territorial Just Transition Plans in Romania – Challenges, needs and actions” explicitly highlights the fact that the Hunedoara–Jiu Valley area is faced with a lack of well-consolidated “business support structures”, with unrealized tourism development and insufficient infrastructure for professional education, but has opportunities associated with the opening of the educational environment towards retraining and the potential for the reuse of degraded lands. [14], [3], [6]

In this context, the industrial-green scenario proposes a **sustainable reindustrialization**, structured along the following lines:

1. **Green industrial parks on mining sites:** The Strategy for the Transition from Coal and the Jiu Valley Strategy 2022–2030 explicitly emphasize the need to reconfigure industrial platforms and dumps into areas for new economic activities, including through industrial parks oriented towards industries with a low carbon footprint (production of components for renewable energy, recycling, logistics, light processing).
2. **Circular economy and recycling of industrial waste:** An example is the project concept “Petrila Planet – steps towards reactive art”, which uses the conversion of the Petrila Mine to demonstrate the potential for reusing industrial

spaces and materials in a creative and circular logic. Other TRACER projects mention innovative solutions for using ash and slag as secondary raw materials for chemical products or construction materials, revealing the possibility of new industrial niches, based on “inherited” resources of the mining sector.

3. **Support for SMEs and green start-ups:** The implementation of the Just Transition Program (PTJ) at the level of Hunedoara County includes calls dedicated to productive investments for SMEs in the ITI Valea Jiului, aiming at the modernization of production capacities, energy efficiency, digitalization and innovative activities. These instruments represent an essential financial infrastructure for transforming the industrial-green scenario from a public policy idea into a concrete portfolio of projects.
4. **Retraining the workforce for modern industries:** TRACER D6.3 identifies the need to retrain a significant number of workers, especially men in the 25–54 age group, directly affected by the decline of mining. The proposed retraining areas include technical fields (electromechanics, maintenance, automation), but also digital skills and industrial process management. Without this component, attracting industrial investment risks being hampered by a lack of adequate workforce.

To summarize the positioning of the industrial-green scenario, a qualitative analysis table can be used (expert evaluation, scale 1–5, Table no. 2):

Table 2. Qualitative assessment of the industrial-green scenario in the Jiu Valley

Criterion	Level (1–5)	Synthetic commentary
Economic potential	4	Possibility of job creation and added value in green industries
Compatibility with local resources	4	Existing infrastructure, technical tradition, available land
Institutional maturity	3	Training support structures, dependence on JTF projects
Social impact (employment)	4	Can integrate former miners and young technicians
Risks (investment, market, regulations)	3	It depends on investor interest and policy stability.

This scenario is therefore **central** to a transition model that seeks to preserve a productive component in the economy, but requires close coordination with the educational-innovative scenario and with SME support policies.

C. The tourist-cultural scenario: capitalizing on the mining and natural heritage

Industrial and cultural tourism has become, in recent decades, one of the recurring strategies for revitalizing mining regions in Europe, especially in areas such as the Ruhrgebiet (Germany), Upper Silesia (Poland) or Ostrava (Czech Republic), where old mining sites have been transformed into museums, theme parks, cultural centers or spaces for artistic and educational events. These examples are frequently cited in the literature and in reports on just transition, including the case study of the Jiu Valley in the ENTRANCES project. [4], [6], [12] The Jiu Valley has a comparable potential, both through its material heritage – mining administrative buildings, shafts, extraction and preparation facilities, industrial railway networks – and through its natural heritage, being the "gateway" to the Retezat National Park and the Parâng and Vâlcan massifs. Initiatives such as the "Petrila Planet" project, documented within TRACER as a good practice for the cultural conversion of a closed mine, demonstrate that industrial heritage can be transformed into a pole of artistic and tourist activity, with a strong symbolic impact on the community.

However, the tourism-cultural scenario is facing structural constraints. INS and TRACER data show a constant decrease in population and a low share of HoReCa companies in the total number of local enterprises, while the hotel and leisure infrastructure remains undersized. The Jiu Valley Strategy 2022–2030 recognizes these limitations and includes tourism as a development axis, but not as the main driver, emphasizing the need for correlation with investments in infrastructure, public spaces and integrated promotion. From a strategic point of view, the tourist-cultural scenario can be structured along three lines:

- **Conservation and selective reconversion of mining heritage** into cultural and tourist attractions (museums, interpretation centers, thematic routes).
- **Integrating industrial tourism with mountain and ecological tourism** , through packages that combine visits to industrial sites with outdoor activities.
- **Supporting local entrepreneurship in services** , through dedicated HoReCa schemes, guidance, cultural events and local products.

The direct economic impact of this scenario will most likely be **gradual and limited**, but its importance for the region's image, for social cohesion and for the valorization of mining identity is significant.

D. The educational-innovative scenario: human capital as a critical resource for just transition

The educational-innovative scenario represents **the soft infrastructure** without which the other scenarios cannot function in the long term. The ENTRANCES report on the Jiu Valley highlights that one of the main vulnerabilities of the region is the "brain drain" – the emigration of young people with higher education – in parallel with the persistence of an adult population with skills predominantly oriented towards the mining industry and sectors with low added value. In this context, the **Jiu Valley Coal Transition Strategy** and **the Economic, Social and Environmental Development Strategy 2022–2030** give a central role to education and vocational training, proposing measures such as: developing reconversion programs in partnership with the University of Petroșani and the economic environment, modernizing school and university infrastructure, creating competence centers and applied laboratories in areas such as renewable energy, environment, digitalization, circular economy.

The workforce data clearly shows the pressure on the education system: in less than three decades, the number of employees in mining has fallen from 55,000 to under 2,000, and the remaining jobs created or maintained in the region have been redistributed to trade, construction and basic services. Without a repositioning of the training system, there is a risk that a significant part of the active population will remain stuck in precarious occupations or migrate permanently. [13], [14], [4]

The innovative educational scenario essentially pursues three **strategic objectives** :

1. **Diversification and modernization of the educational offer** at university and postgraduate level – through study programs in fields compatible with the new scenarios (green energy, transition management, IT, data analysis, smart cities, public policies of just transition). The University of Petroșani can become a regional center of expertise for mining regions in transition, connected to European research networks (Horizon, Erasmus+, TRACER partnerships, etc.).
2. **Retraining and continuous professional training** – for former miners and workers in traditional sectors. TRACER D6.3 already proposes course profiles and pilot programs, and the Just Transition Plan documents explicitly mention the use of funds for training in "green jobs" and digital skills.
3. **Creating an ecosystem of applied innovation** – through innovation hubs, laboratories and demonstration projects in areas such as ecological rehabilitation of landfills, pollution monitoring, digital solutions for small cities, new business models in the circular economy. Recent reports on financing just transitions mention the Jiu Valley as a potential location for pilot projects in green hydrogen and green innovation solutions.

In the long term, the educational-innovative scenario is also a **demographic strategy**: by offering young people the opportunity to study and innovate in the region, it increases the likelihood of retaining human capital and attracting new residents (researchers, experts, entrepreneurs).

The analysis of the four scenarios shows that the Jiu Valley cannot rely on a single development direction, but needs a **combined transition model**, in which renewable energies, green reindustrialization, cultural tourism and education-innovation function as pieces of the same strategic architecture. At the factual level, the TRACER, ENTRANCES and Jiu Valley Strategy data outline a clear diagnosis: population decreasing below 100,000 inhabitants, mining workforce reduced to below 2,000 employees, over 2,500 active enterprises (predominantly micro-enterprises), vast industrial heritage and a window of financial opportunity opened by the allocation of approximately 1.2 billion euros from the Just Transition Fund.

In this context, the role of each scenario can be summarized as follows:

- **Energy scenario** – investment driver and main vector of alignment with European decarbonization policies;
- **The industrial-green scenario** – core of reindustrialization and job creation in productive activities compatible with the green economy;
- **The tourist-cultural scenario -** a tool for economic diversification, identity revaluation and reduction of territorial stigmatization;
- **The educational-innovative scenario** – the social and intellectual infrastructure that allows the other scenarios to function and ensures long-term resilience.

Table 3. The strategic role of transition scenarios in the Jiu Valley

Scenario	Main role	Impact horizon	Key conditions for success
Power	Investments, infrastructure	Short–medium	Stable regulatory framework, network access, public-private partnerships
Industrial green	Employment, added value	environment	Industrial parks, green SMEs, technical training
Tourist-cultural	Diversification, image	Medium–long	Heritage conservation, infrastructure, regional marketing
Educational –innovative	Human capital, adaptability	Long	Strong university, competence centers, R&D funding

3. CONCLUSIONS

The analysis carried out indicates that the Jiu Valley is in an advanced stage of post-mining transition, determined by the decline of the extractive industry, the sharp decrease in the population and the profound restructuring of the local economy. Statistical data and strategic documents confirm the loss of the central role of mining and the need to redefine the development model in the context of European policies on decarbonization and just transition. The four scenarios analyzed – energy, industrial-green, tourist-cultural and educational-innovative – show that no single direction can ensure the recovery of the region. While the energy scenario provides the investment framework for the transition, the industrial-green one supports sustainable reindustrialization and employment, the tourist-cultural scenario contributes to the diversification and revaluation of the regional identity, and the educational-innovative scenario represents the transversal infrastructure necessary for the functioning of the other directions.

In conclusion, the post-mining transition of the Jiu Valley requires an integrated and phased approach, which correlates economic investments with education, vocational training and social inclusion policies. The use of the Just Transition Fund and related European programs can support the transformation of the region into a diversified and resilient territory, aligned with the sustainable development objectives of the European Union.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

POST-MINING DECLINE AND QUALITY OF LIFE: DEMOGRAPHIC AND SPATIAL CHALLENGES IN THE JIU VALLEY, ROMANIA

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Abstract: *Former mono-industrial regions such as the Jiu Valley face demographic decline and residential degradation after the collapse of the mining industry. Visual and statistical analysis shows the link between depopulation and housing abandonment. Revitalization requires economic diversification, urban regeneration, strengthened social infrastructure, and coordinated local governance for regional resilience.*

Key words: *post-mining regions; demographic decline; housing degradation; quality of life*

1. INTRODUCTION

Across Europe, former mono-industrial mining regions are undergoing profound structural transformations driven by the energy transition, economic restructuring and long-term demographic change. The decline of coal mining, once a central pillar of regional economies, has triggered cascading social, spatial and economic effects that continue to shape local development trajectories decades after mine closures. These regions often face population loss, aging communities, housing abandonment and deteriorating living conditions, all of which directly influence quality of life and territorial resilience.

The Jiu Valley in Romania represents a particularly illustrative case of post-mining transition in Eastern Europe. Historically dependent on underground coal extraction, the region experienced rapid industrial contraction after 1990, accompanied by large-scale layoffs and outward migration. Young and economically active residents were among the first to leave, seeking employment opportunities elsewhere, while remaining communities gradually aged. This demographic imbalance has resulted in declining birth rates, reduced demand for housing and services, and the progressive degradation of the built environment.

Quality of life in post-mining regions is closely linked to both social dynamics and spatial conditions. Residential decay, abandoned housing stock and underused infrastructure are not only physical symptoms of decline but also contribute to social fragmentation, reduced safety and a diminished sense of place. In the Jiu Valley, visible signs of abandonment in rural and peri-urban settlements such as Uricani, Câmpu lui Neag and Jieț reflect deeper demographic and economic processes. These landscapes

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reveal a retreat of human presence and weakening residential stability, while simultaneously pointing to latent potential for regeneration.

While extensive literature addresses economic diversification and labor market transitions in former mining areas, fewer studies explicitly examine the interdependence between demographic decline, housing degradation and quality of life using integrated visual and statistical approaches. Visual field observation, when combined with demographic analysis, offers a valuable lens for understanding how long-term structural decline materializes in everyday living environments. Such an approach allows the identification of patterns that are often underrepresented in purely quantitative analyses.

This paper aims to analyze how demographic decline and residential degradation interact and reinforce each other in the Jiu Valley, shaping current quality-of-life conditions and influencing future development prospects. By combining photographic documentation with demographic interpretation and comparative regional insights, the study highlights both the challenges and opportunities faced by post-mining territories. The findings are relevant not only for the Jiu Valley but also for other European regions undergoing similar transitions, offering insights into the importance of coordinated urban regeneration, social infrastructure strengthening and place-based governance in building more resilient post-industrial communities.

2. METHODOLOGY

The research adopts a qualitative and exploratory methodological framework, combining visual field observation with demographic interpretation and comparative regional analysis. The primary data source consists of photographic documentation collected in rural and peri-urban areas of the Jiu Valley that exhibit visible signs of residential abandonment and structural decay. These photographs capture abandoned dwellings, collapsing buildings, unmanaged vegetation and deteriorated infrastructure, serving as visual indicators of depopulation and declining residential stability.

Visual analysis is used as a complementary method to conventional statistical approaches. Photographs function as empirical evidence of spatial processes that reflect underlying socio-economic trends. In regions affected by long-term population loss, the built environment often changes more slowly than demographic indicators, making visual observation particularly useful for identifying cumulative effects of decline. The selected locations, including Uricani, Câmpu lui Neag and Jieț, represent settlements where demographic contraction and housing degradation are especially pronounced.

To contextualize visual findings, the study draws on secondary demographic data from national statistics and regional studies, focusing on population trends over the past two and a half decades. These data confirm a substantial population decline, particularly among young adults, reinforcing the link between migration, aging and housing abandonment. Although the study does not include primary sociological surveys, the triangulation of visual and statistical data strengthens the interpretative framework.

A comparative dimension is introduced by referencing post-mining regions such as Upper Silesia in Poland and the Ruhrgebiet in Germany. These cases provide useful benchmarks for understanding how similar structural challenges have been addressed through coordinated regeneration strategies, institutional capacity and long-term investment. The comparison is not intended as a direct policy transfer but as an analytical tool to highlight contextual differences and potential pathways.

The methodological limitations include the exploratory nature of the analysis and the absence of household-level survey data. However, the approach is suitable for identifying spatial patterns, raising research questions and informing future, more detailed investigations.

Figure 1. Abandoned rural dwelling illustrating advanced structural decay.

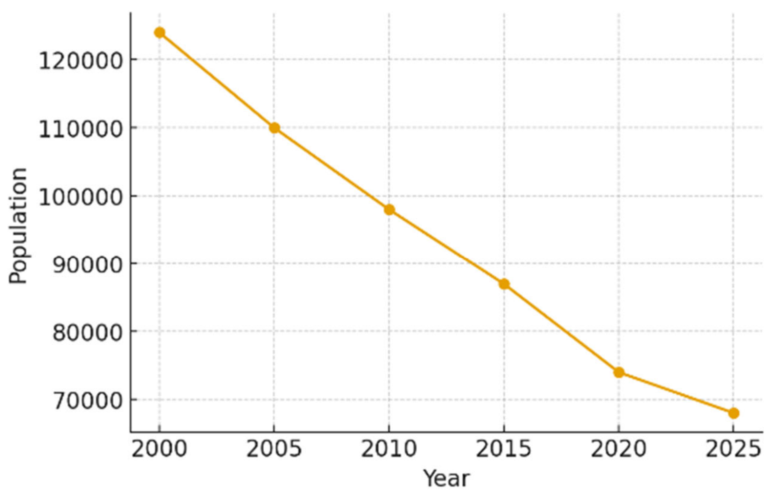

Figure 2. Estimated population decline in Valea Jiului (2000–2025).

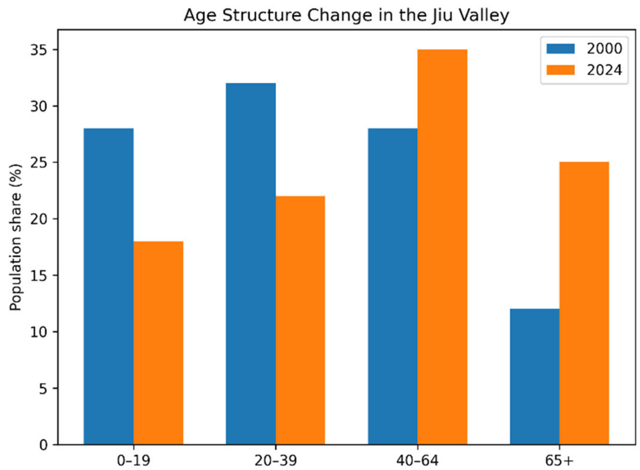

Figure 3. Age Structure Change in the Jiu Valley

The figure illustrates a significant shift in the age structure of the Jiu Valley population between 2000 and 2024, marked by a clear decline in younger age groups and a pronounced increase in the elderly population. The share of residents aged 20–39 has decreased substantially, reflecting sustained outmigration of the working-age population. At the same time, the growing proportion of people aged 65 and over highlights accelerated population ageing, with direct implications for housing demand and local service provision.

The findings reveal a strong interdependence between demographic decline and residential degradation in the Jiu Valley. Population loss reduces demand for housing and local services, leading to abandonment and underinvestment in the built environment. In turn, deteriorating living conditions further discourage settlement retention and return migration, reinforcing a self-perpetuating cycle of decline.

The visual evidence highlights how housing abandonment is unevenly distributed, with rural and peripheral settlements being particularly affected. These areas often lack sufficient public investment and face limited economic alternatives, accelerating physical decay. Similar patterns have been observed in other European post-mining regions, where residential degradation initially followed industrial decline but later became a barrier to regeneration

Comparative analysis shows that regions such as the Ruhrgebiet managed to partially reverse these trends through integrated urban regeneration, cultural reuse of industrial heritage and strong institutional coordination. In contrast, the Jiu Valley faces constraints related to limited administrative capacity, fragmented governance and delayed investment. Nonetheless, the region retains significant assets, including natural landscapes, cultural heritage and a strong local identity rooted in mining history.

The discussion underscores that improving quality of life in post-mining regions requires more than economic diversification alone. Housing rehabilitation, public space improvement and access to community services are equally critical. Addressing residential degradation can generate positive spillovers by enhancing safety, social cohesion and local attractiveness..

3. CONCLUSIONS

This study demonstrates that demographic decline and residential degradation in the Jiu Valley are deeply interconnected processes that jointly shape quality-of-life outcomes in post-mining regions. The long-term effects of industrial restructuring, outward migration and population aging have materialized not only in statistical indicators but also in the physical fabric of settlements, where abandoned and deteriorating housing has become a visible marker of decline.

The analysis highlights that residential degradation is both a consequence and a driver of demographic contraction. As housing conditions worsen and local services diminish, the attractiveness of remaining settlements declines further, reinforcing population loss and limiting recovery potential. However, the presence of extensive natural landscapes and industrial heritage suggests that decline is not irreversible.

Improving quality of life in the Jiu Valley requires coordinated, place-based interventions that address both social and spatial dimensions of transition. Urban regeneration, housing rehabilitation and the strengthening of community infrastructure should be integrated with economic diversification strategies. Experiences from other European post-mining regions demonstrate that long-term commitment, institutional capacity and local engagement are essential for successful transformation.

Future research should build on this exploratory approach by incorporating sociological surveys, GIS-based spatial analysis and policy evaluation to better capture residents' perspectives and measure intervention impacts. By linking demographic trends, residential conditions and quality of life, this paper contributes to a broader understanding of post-industrial regional resilience and offers relevant insights for policymakers and researchers working on just transition and sustainable territorial development.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

NON-GOVERNMENTAL ORGANIZATIONS AS DRIVERS OF SOCIO-ECONOMIC RECOVERY IN POST-MINING REGIONS EVIDENCE FROM ROMANIA

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Abstract: *The structural decline of mining activities has generated persistent socio-economic challenges in former mono-industrial regions across Europe, including unemployment, population outmigration, demographic ageing and social vulnerability. In this context, non-governmental organizations (NGOs) have emerged as key actors complementing public policies in supporting local recovery processes. This paper examines the role of NGOs in the socio-economic recovery of post-mining regions in Romania, with a particular focus on community-based interventions, labour market reintegration and social inclusion. Using a qualitative and descriptive-analytical approach, the study analyses policy documents, statistical data and selected case evidence from Romanian post-mining areas. The findings indicate that NGOs contribute significantly to mitigating the social impact of mine closures by providing social services, promoting educational and vocational programmes, supporting vulnerable groups and facilitating access to alternative employment opportunities. Moreover, NGOs act as intermediaries between local communities, public authorities and funding mechanisms, particularly within the framework of the Just Transition agenda. Despite their positive impact, the effectiveness of NGOs is constrained by limited financial sustainability and institutional capacity. The paper concludes that strengthening partnerships between NGOs and public institutions is essential for enhancing the long-term socio-economic resilience of post-mining regions.*

Key words: *non-governmental organizations; post-mining regions; socio-economic recovery; regional development; labour market restructuring; social inclusion; just transition*

1. INTRODUCTION

The decline of mining activities represents one of the most significant structural transformations of European economies in recent decades, with profound effects on regions historically dependent on the extractive industry. Mine closures have led to massive job losses, demographic imbalances, outward migration of the active population and increased social vulnerability, directly affecting community cohesion and territorial resilience. These challenges are particularly evident in post-mining regions of Central and Eastern Europe, where economic transition has often been rapid and insufficiently supported by effective reconversion policies.

In Romania, post-mining regions such as the Jiu Valley, Gorj and Maramureș continue to experience the cumulative effects of industrial restructuring, manifested through structural unemployment, population ageing and a high level of dependence on

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social transfers. Although public policies have aimed to reduce these disparities, limited institutional capacity and budgetary constraints have diminished the effectiveness of governmental interventions, leaving significant space for action by non-state actors.

In this context, non-governmental organizations (NGOs) have assumed an increasingly important role in supporting the socio-economic recovery of post-mining regions. By providing social services, implementing educational and vocational training programmes, promoting social inclusion and facilitating access to funding, NGOs help mitigate the social impact of industrial decline and stimulate local development. At the same time, they act as intermediaries between local communities, public authorities and national and European funding mechanisms, particularly within initiatives related to the Just Transition framework.

Against this background, the present study aims to analyse the role of NGOs in the socio-economic recovery of post-mining regions in Romania. The paper adopts a qualitative and descriptive-analytical approach, based on the analysis of public policy documents, relevant statistical data and selected examples of good practice. The main objective is to highlight the contribution of NGOs to social inclusion, labour market reintegration and the strengthening of community resilience, while also identifying the limitations and challenges associated with their interventions.

2. LITERATURE REVIEW

2.1. Post-mining regions and structural socio-economic decline

The closure of mining activities has been widely recognised in the academic literature as a major source of long-term socio-economic decline in mono-industrial regions. Unlike short-term economic shocks, mine closures generate structural disruptions that affect employment, demographic dynamics and regional development trajectories over extended periods (Stoica & Bleahu, 2014). Empirical evidence from Europe shows that former mining regions often experience persistent unemployment, population loss and deteriorating living conditions, particularly where economic diversification is limited.

Research on industrial transition highlights that post-mining regions are especially vulnerable due to their historical dependence on a single sector and the specificity of mining-related skills (OECD, 2020). Studies analysing regions such as the Ruhrgebiet in Germany, Upper Silesia in Poland and former mining areas in Romania demonstrate that the social consequences of mine closures often outlast economic recovery efforts (Hudson, 2015). These regions frequently face difficulties in attracting new investments, leading to prolonged stagnation and spatial inequalities.

In Central and Eastern Europe, the effects of mining decline have been compounded by the rapid pace of economic transition after 1990. Rodríguez-Pose (2018) argues that many post-industrial regions have become “places that do not matter” in national development strategies, experiencing declining public investment and weakened institutional capacity. This context has intensified socio-economic disparities between former mining regions and more dynamic urban centres.

2.2. Labour market restructuring and social vulnerability in post-mining regions

Labour market restructuring is a central dimension of post-mining transition. The literature consistently shows that former miners and industrial workers face significant barriers to labour market reintegration due to skills mismatch, age structure and limited access to retraining opportunities (Faggian, McCann & Sheppard, 2017). Mining jobs are characterised by highly specialised skills that are not easily transferable to emerging sectors, increasing the risk of long-term unemployment.

Several studies highlight that labour market exclusion in post-mining regions is closely linked to social vulnerability. Long-term unemployment contributes to poverty, social exclusion and reduced access to education and health services, particularly in regions with weak local economies (European Commission, 2021). These dynamics often lead to outward migration of younger and more educated individuals, further shrinking the local labour force and accelerating population ageing.

The OECD (2020) emphasises that public labour market policies alone are often insufficient to address the complex social consequences of industrial decline. Active labour market policies need to be complemented by local-level interventions that account for community-specific needs. This gap in policy implementation has increased the relevance of non-state actors, including non-governmental organizations, in supporting labour market adjustment and social inclusion.

2.3. Non-governmental organizations and regional development

The role of non-governmental organizations (NGOs) in regional development has been extensively discussed in the literature on civil society and the social economy. Salamon and Anheier (1998) underline that NGOs are particularly effective in addressing social needs in contexts where state capacity is limited or uneven. Their proximity to local communities and flexible organisational structures allow them to respond more rapidly to emerging social challenges.

In disadvantaged and post-industrial regions, NGOs often complement public authorities by delivering social services, supporting vulnerable groups and fostering community participation (Evers & Laville, 2004). Research on regional development indicates that NGOs contribute to rebuilding social capital, which is essential for restoring trust and cooperation in communities affected by industrial decline (Putnam, 2000).

Moreover, NGOs are increasingly involved in development initiatives related to education, social inclusion and local governance. Defourny and Nyssens (2010) argue that NGOs and social enterprises play a crucial role in promoting inclusive growth, particularly in regions facing structural economic challenges. Their activities help mitigate the social costs of economic restructuring and support more balanced territorial development.

2.4. NGOs and labour market reintegration

The contribution of NGOs to labour market reintegration has been analysed within the broader framework of active inclusion and social innovation. NGOs frequently implement programmes targeting long-term unemployed individuals, young people not in employment, education or training (NEETs), and other vulnerable groups, providing personalised support that public employment services may not adequately deliver (OECD, 2019).

In post-mining regions, NGO-led initiatives often focus on vocational training, skills development and support for social entrepreneurship. Empirical evidence suggests that such initiatives can improve employability and enhance social integration, even in contexts where job creation is limited (Borzaga et al., 2017). By combining training with social support, NGOs help reduce barriers to labour market participation.

However, the literature also highlights important limitations. NGO interventions are frequently constrained by project-based funding, limited institutional capacity and difficulties in scaling successful programmes (Salamon, 2014). As a result, their long-term impact on employment outcomes depends heavily on stable partnerships with public institutions and supportive policy frameworks.

2.5. NGOs within the Just Transition framework

The concept of Just Transition has gained increasing attention in relation to coal and mining regions undergoing energy transition. Heffron and McCauley (2018) define Just Transition as an approach that seeks to balance environmental objectives with social justice, ensuring that affected workers and communities are not left behind.

Within this framework, NGOs are recognised as key stakeholders in representing community interests, monitoring social impacts and facilitating inclusive decision-making processes (European Commission, 2022). In post-mining regions, NGOs often act as intermediaries between local communities and national or European institutions, particularly in the context of funding mechanisms such as the Just Transition Fund.

Studies focusing on Central and Eastern Europe highlight that NGO involvement is especially important in regions with low levels of public trust and limited administrative capacity (OECD, 2023). By enhancing participation and transparency, NGOs contribute to the legitimacy and effectiveness of transition policies.

3. RESTRUCTURING OF MONO-INDUSTRIAL REGION OF JIU VALLEY

The restructuring of the Jiu Valley represents a profound and prolonged structural transformation, marked by the collapse of mining employment, significant demographic decline and the reconfiguration of local socio-economic systems in the absence of a dominant industrial base.

Figure 1 highlights the sharp and long-term decline of mining employment in the Jiu Valley, from approximately **60,000 employees in 1989** to around **2,100 in 2024.** The most pronounced contraction occurred during the late 1990s, following large-scale mine restructuring and workforce reductions.

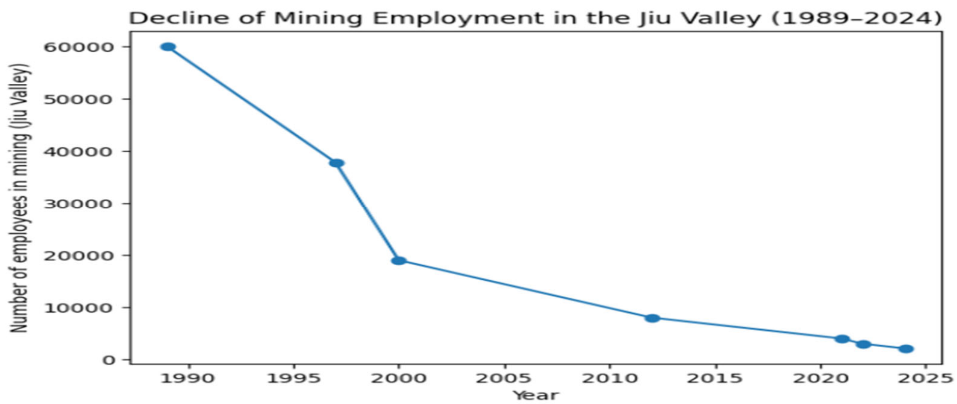

Figure 1. Decline of mining employment in Jiu Valey1989-2024

After 2000, employment continued to decrease steadily, indicating the persistent structural nature of industrial decline. This trajectory underscores the profound socio-economic impact of mine closures and the need for alternative development mechanisms, including social and community-based interventions.

The establishment of non-governmental organizations in post-industrial regions is essential for mitigating the social and economic impacts of industrial decline, particularly in contexts marked by unemployment, social exclusion and institutional fragility. By providing social services, supporting labour market adaptation and fostering community engagement, NGOs contribute to strengthening local resilience and facilitating long-term socio-economic recovery.

Figure 2 presents the cumulative evolution of non-governmental organizations (NGOs) in Romania, Hunedoara County and the Jiu Valley between 2006 and 2025. At the national level, the number of newly established NGOs increased cumulatively from **4,647 organizations in 2006 to 90,052 organizations by 2025**, indicating a substantial expansion of the non-profit sector over the last two decades.

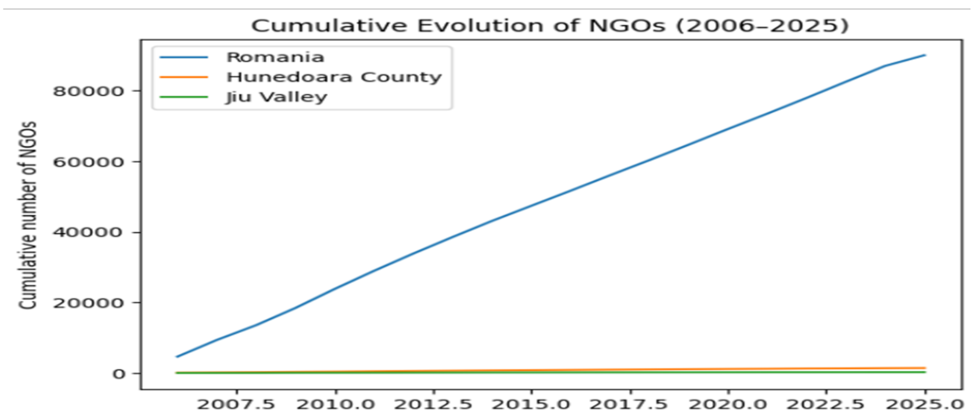

Figure 2. Cumulative Evolution of NGOs (2006–2025)

This steady growth reflects the progressive institutionalisation of civil society in Romania, despite periodic fluctuations in annual NGO registrations.

In Hunedoara County, the cumulative number of NGOs rose from **67 organizations in 2006** to **1,410 organizations in 2025.** Although the absolute scale is considerably smaller than at the national level, the relative increase is significant, highlighting the capacity of a structurally disadvantaged, post-industrial county to sustain civil society development over time.

The Jiu Valley exhibits a more modest but consistent growth pattern. The cumulative number of NGOs increased from only **4 organizations in 2006** to **220 organizations in 2025.** This evolution reflects the specific socio-economic constraints of the region, including population decline, labour market contraction and prolonged effects of mining restructuring. Nevertheless, the continuous increase in the number of NGOs suggests an adaptive response of local communities to long-term socio-economic challenges, with civil society actors gradually filling gaps left by industrial decline and limited public intervention.

Overall, the cumulative trends indicate that while the numerical growth of NGOs in post-mining regions remains limited in absolute terms, their expansion is steady and persistent. This supports the argument that NGOs have become an increasingly embedded component of the socio-economic fabric of post-mining territories, contributing to social support, community resilience and local development, rather than large-scale employment generation.

4. THE SOCIAL AND ECONOMIC ROLE OF NGOS IN POST-MINING REGIONS

Following the closure of mining activities, post-mining communities are exposed to a range of structural social challenges, including long-term unemployment, persistent poverty, outward migration and the erosion of social cohesion. In this context, non-governmental organizations (NGOs) emerge as key actors in mitigating social vulnerability and supporting community stability.

NGO interventions primarily focus on the provision of social services and targeted support for vulnerable groups. These include the operation of community-based services such as day-care centres, assistance for children and elderly persons, and support for individuals lacking stable income sources. Additionally, NGOs play a crucial role in preventing social exclusion and early school leaving by implementing educational support programmes and community outreach initiatives.

Another important dimension of NGO activity relates to the provision of social and psychological counselling for former miners and their families, addressing the long-term effects of job loss, identity disruption and social marginalisation. Through these interventions, NGOs contribute to the preservation of community cohesion and the strengthening of social capital in a context marked by economic decline and demographic contraction. Furthermore, by promoting volunteering and civic participation, NGOs foster social engagement and reinforce local networks of solidarity.

Overall, NGOs contribute to stabilising post-mining communities by reducing immediate social risks and by creating the conditions necessary for long-term social recovery and resilience.

Although NGOs cannot substitute the economic functions of the mining industry, the literature and empirical evidence indicate that they play a complementary role in local economic recovery processes. Their economic contribution is primarily indirect, focusing on labour market adaptation and economic diversification rather than large-scale job creation.

NGOs support professional reconversion and skills development by implementing training programmes tailored to the needs of long-term unemployed individuals and former industrial workers. These initiatives enhance employability and facilitate labour market reintegration in emerging sectors. In parallel, NGOs contribute to the development of the social economy by supporting social enterprises, cooperatives and other community-based economic initiatives.

A further economic function of NGOs lies in their capacity to attract and manage European and public funding in territories characterised by limited private investment. Through project-based activities, NGOs generate indirect employment opportunities, including positions within the non-profit sector and jobs associated with community services. Moreover, NGOs support local initiatives in areas such as alternative tourism, culture and education, thereby contributing to the diversification of local economic structures.

While operating at a relatively small scale, NGO activities contribute to the diversification of local economies and support the adaptation of the workforce to new socio-economic conditions in post-mining regions.

In the context of the energy transition and the decarbonisation of economies dependent on extractive industries, non-governmental organizations (NGOs) acquire a strategic role in ensuring the social dimension of transformation processes. In regions affected by mine closures, NGOs act as intermediaries between local communities, public authorities and funding mechanisms, contributing to the reduction of social imbalances generated by economic restructuring.

NGOs represent the interests of communities impacted by job losses and economic decline, ensuring that local needs are better reflected in decision-making processes. At the same time, they support the implementation of the social component of the transition by providing social services, training programmes and inclusion measures for vulnerable groups. An important function is the facilitation of access to dedicated financial instruments, such as the **Just Transition Mechanism**, through NGOs' capacity to initiate, manage and implement projects adapted to local contexts.

In addition, NGOs contribute to monitoring the social impact of public policies associated with the energy transition, thereby enhancing transparency and institutional accountability. Through these functions, non-governmental organizations help transform a potentially disruptive economic transition into a more equitable, inclusive and community-oriented process.

Figure illustrates the catalytic role of non-governmental organizations in post-mining regions. Following mine closures and associated socio-economic shocks, NGOs intervene through social services, training, advocacy and community-based projects.

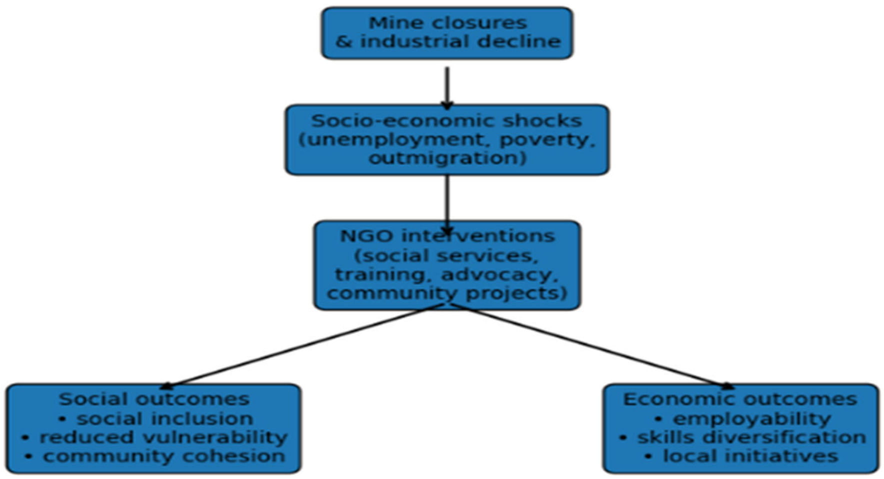

Figure 3.

These interventions generate both social outcomes (social inclusion, reduced vulnerability, community cohesion) and economic outcomes (enhanced employability, skills diversification and local initiatives), contributing to territorial resilience.

5. CONCLUSIONS

Despite the growing body of literature on post-mining regions and NGO involvement, several gaps remain. Empirical evidence from Romania remains relatively scarce compared to Western European post-mining regions. This study contributes to the existing literature by providing a focused analysis of the role of NGOs in the socio-economic recovery of Romanian post-mining regions, linking social inclusion, labour market reintegration and community resilience. By situating NGO interventions within the broader context of post-mining transition and regional development, the paper addresses an underexplored area and offers insights relevant for both academic research and policy design. The socio-economic restructuring of post-mining regions represents a complex and long-term process, shaped by the collapse of mono-industrial economic structures, persistent labour market imbalances and profound demographic changes. The case of Romanian post-mining territories, particularly the Jiu Valley, illustrates the depth and persistence of these challenges, as evidenced by the dramatic decline in mining employment and the limited capacity of traditional economic sectors to absorb displaced workers.

The findings of this study highlight the increasingly important role played by non-governmental organizations in supporting socio-economic recovery in post-mining regions. While NGOs cannot replace the economic functions of the mining industry, they contribute significantly to mitigating social vulnerability, strengthening social cohesion and supporting labour market adaptation. Through the provision of social services, vocational training, community development initiatives and social economy projects, NGOs help stabilise communities affected by industrial decline.

Moreover, NGOs act as key intermediaries between local communities, public authorities and funding mechanisms, particularly within the framework of Just Transition policies. Their ability to mobilise resources, address local needs and foster civic participation enhances territorial resilience and improves the inclusiveness of transition processes. However, the effectiveness of NGO interventions remains constrained by limited financial sustainability and their dependence on project-based funding.

The socio-economic recovery of post-mining regions requires an integrated approach in which NGOs function as complementary actors alongside public policies and private investment. Strengthening institutional partnerships and ensuring long-term support for civil society initiatives are essential for achieving sustainable and socially balanced development in post-industrial territories.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

PREVENTING BLACKOUTS AND ENSURING GRID STABILITY DURING THE ENERGY CRISIS: CASE STUDY – PAROȘENI COAL THERMAL POWER PLANT

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Abstract: *The current energy crisis requires strict measures to prevent blackouts and maintain the stability of the electrical grid. The Paroșeni Thermal Power Plant, part of the Valea Jiului Energy Complex and fueled by coal, plays a strategic role in national energy security by providing continuous electricity and contributing to grid balancing during peak demand periods. This paper analyzes methods for preventing power outages, operational strategies, and their impact on the stability of the energy system.*

Key words: *Paroșeni Thermal Power Plant, coal, energy crisis, efficiency, environmental protection*

1. INTRODUCTION

In 2025, Romania went through a tense period for the energy system due to:
- high energy demand in the cold season;
- some production units temporarily out of service (including hydro and gas-fired);
- delays in constructing new gas-fired power plants intended to replace coal units.

Under these pressures, authorities resorted to emergency solutions to ensure sufficient electricity, including restarting or keeping coal plants operational. The Paroșeni Thermal Power Plant was reactivated to support the energy system.

Recently (November 2025), the Paroșeni plant (TA4 unit, ~150 MW) was restarted after four months of technical works.

This restart is part of measures to ensure winter energy security amid rising demand.

Role of Paroșeni in the crisis:
- it is part of the Valea Jiului Energy Complex and produces electricity based on coal from local deposits.
- it is one of the oldest plants in Romania, modernized, with relatively modest production (~150 MW).
- in December 2025, it was started to cover the production gap left by other non-operational units (e.g., Brazi).

Problems and challenges:
- the plant was shut down in July 2025 due to a technical incident (damaged transformer), straining the energy grid.

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- the complex director warned about the risk of blackouts if gas units are not built on time.

Future of the power plant:

- Strategic projects include converting Paroșeni to biofuel, complementing it with a gas unit, and investing in renewables in the Valea Jiului area.

Relevance of Paroșeni in the Crisis Context:

- coal-fired plants like Paroșeni serve as a "safety net."
- they help maintain grid stability and prevent power outages.
- the coal model is considered incorrectly as obsolete in the long term, due to environmental and high-cost reasons.

Effects of the Energy Crisis on Prices and the Economy

Electricity and Gas Prices:

- Significant increases in 2024–2025 due to:
    - higher demand in the cold season;
    - reduced hydro and gas production;
    - more expensive EU imports.
- Consequence:
    - higher household and business bills, affecting budgets and production costs.

Impact on the Economy:

- Heavy industry and the energy sector face major pressures;
- Higher subsidies for the population and urgent investments in old units (e.g., Paroșeni) to avoid blackouts.

Risks

- Rising inflation;
- Dependence on traditional fuels maintains vulnerability to external shocks.

2. ROMANIA'S ENERGY TRANSITION PLANS

- Gradual closure of coal-fired power plants (Valea Jiului Complex by 2030).
- Investments in renewables: solar, wind, hydro.
- Increasing the efficiency of gas-fired plants, operating complementarily with renewables.
- Digitization of the grid and implementation of smart grid systems.

2035 Objectives:

- Reducing CO_2 emissions by 40–45% compared to 1990 levels;
- Share of renewables in the energy mix >35–40%;
- Gradual and unjustified elimination of coal from primary production. [10, 11, 12, 13]

3. TEMPORARY ROLE OF PAROȘENI THERMAL POWER PLANT

- Serves as a safety net during the energy transition.
- Contributes to price stabilization and prevents blackouts.

Table 1. Factors Influencing Energy Prices

Factor	Expected Impact
Transition from coal to renewables and gas	Higher short-term costs, medium-term reduction
International gas and oil prices	High volatility, rapid impact on prices
Energy demand	Moderate increase, stable household consumption
EU imports	Cheaper energy during peak periods, dependence on EU prices
State subsidies	Consumer protection, budget pressure

4. TEMPORARY ROLE OF PAROȘENI THERMAL POWER PLANT

Electricity (lei/kWh):
- 2026: ~1.8–2.0
- 2027–2028: 1.7–1.9
- 2029–2030: 1.5–1.7

Natural Gas (lei/m³):
- 2026: ~7–8
- 2027–2028: 6–7
- 2029–2030: 5.5–6.5

Alternative scenarios:
1. Optimistic: rapid renewable investments, faster price decrease
2. Pessimistic: delays, high import dependence, high prices
3. Realistic: mix between optimistic and pessimistic, seasonal fluctuations, gradual stabilization

Implications for economy and consumers:
- households: higher bills 2025–2026, stabilization by 2028, slight reduction towards 2030;
- industry: short-term cost pressure, medium-term reduction via efficiency;
- state: continued subsidies and acceleration of energy transition. [3, 9]

5. ADVANTAGES OF COAL-BASED ENERGY

- High domestic availability – coal is abundantly available in Romania, reducing dependency on energy imports.
- Contribution to grid stability – coal plants can provide continuous electricity and respond to peak demand to prevent blackouts.
- Predictable costs – locally mined coal prices are more stable than imported fossil fuels, enabling safer production planning.
- Operational flexibility – coal plants can serve as baseload or support intermittent renewables (solar, wind).
- Utilization of domestic resources – coal exploitation stimulates the local economy and creates jobs in extraction and energy sectors.

6. CARBON FOOTPRINT OF PAROȘENI THERMAL POWER PLANT

The Paroșeni Thermal Power Plant, fueled by coal, significantly contributes to greenhouse gas emissions, particularly carbon dioxide (CO_2). The carbon footprint analysis evaluates both direct emissions from fuel combustion and indirect emissions from coal extraction and transport activities.

Key aspects:

1. Direct CO_2 emissions – Coal combustion generates large amounts of CO_2, a major contributor to climate change.
2. NO_x and SO_2 emissions – Besides CO_2, combustion produces nitrogen oxides and sulfur dioxide, contributing to air pollution and acid rain.
3. Specific emission factor – Depending on coal quality and plant efficiency, estimated CO_2 emissions are 0.9–1.1 kg CO_2/kWh.
4. Reduction measures – Technologies such as particle filters, desulfurization systems, and optimized combustion can increase efficiency and reduce emissions.
5. Impact on sustainability – While coal ensures energy security, the high carbon footprint requires a gradual transition to lower-emission sources or carbon capture technologies. [6, 7]

Table 2. Example of CO_2 emissions calculation

Parameter	Value
Installed capacity	200 MW
Thermal efficiency	38%
Annual coal consumption	1,000,000 t
Specific CO_2 emissions	0.94 t CO_2/MWh

Annual electricity production:

$$E_{annual} = 200\ \text{MW} \times 7{,}000\ \text{h} = 1{,}400{,}000\ \text{MWh}$$

Annual CO_2 emissions:

$$CO_2 = 1{,}400{,}000\ \text{MWh} \times 0.94\ \text{t}\ CO_2/\text{MWh} = 1{,}316{,}000\ \text{t}\ CO_2/\text{year}$$

Comments:

- increasing efficiency to 42% reduces emissions;
- co-firing 10% biomass → 5–10% reduction;
- offsetting with local forests reduces net footprint.

Carbon capture and storage (CCS) recommendations:

Carbon capture and storage (CCS) is essential to reduce the carbon footprint of coal plants while maintaining energy security.

Main recommendations:

- Implement CCS technologies in existing plants:
  - priority for large plants like Paroșeni with high emissions potential.
  - evaluate technical and economic feasibility of chemical, physical, or biological CO_2 capture systems.
- Develop CO_2 transport and storage infrastructure:

- dedicated networks for transporting captured CO_2 to secure geological sites (e.g., deep saline formations or depleted hydrocarbon reservoirs).
- continuous monitoring to prevent leaks.

o Government support and financing:
- fiscal incentives and subsidies for carbon capture investments.
- public-private partnerships to accelerate CCS deployment.

o Local research and development:
- pilot projects to adapt CCS technologies to Romanian conditions.
- collaboration with research institutes and universities to optimize costs and efficiency.

o Integrate CCS in the national energy strategy:
- CCS as a complementary element in the transition to renewables.
- medium- and long-term plans to gradually reduce coal dependency while maintaining grid stability.

o Education and awareness:
- information campaigns to increase social acceptance of carbon capture and storage technologies. [1, 2, 4, 5]

7. ENVIRONMENTAL BENEFITS AND DESULFURIZATION

Flue gas desulfurization is essential in coal plants like Paroșeni to reduce air pollution and environmental damage [8].

Main benefits:

- Reduction of sulfur dioxide (SO_2) emissions
  - desulfurization systems can remove up to 90–95% of SO_2, reducing acid rain formation.
- Ecosystem protection
  - reduces soil and water acidity, protecting local flora and fauna.
  - prevents forest and crop degradation around the plant.
- Air quality improvement
  - reduces pollutants affecting public health (respiratory, cardiovascular diseases).
- Compliance with EU standards
  - ensures conformity with European industrial emissions and environmental protection regulations.
- Compatibility with other emission reduction technologies
  - can integrate with CO_2 capture and particle filters for minimal global environmental impact.

Efficiency depends on coal quality and regular maintenance, which further reduces environmental impact and ensures compliance with EU standards and national energy transition objectives.

8. CONCLUSIONS

- Strategic role of Paroşeni Thermal Power Plant:

- essential component of the Romanian energy system, acting as a safety net during energy crises.
- restarting and maintaining plant units prevents blackouts and stabilizes the grid.

- Contribution to Energy Security

- using local coal ensures continuous electricity production, reduces import dependence, and supports the national energy system during peak demand.

- Environmental Challenges

- coal combustion generates significant CO_2, NO_x, and SO_2 emissions, requiring mitigation technologies such as desulfurization and CCS.

- Technologies and Mitigation Measures

- filters, optimized combustion, co-firing with biomass, and desulfurization reduce emissions while maintaining efficiency.

- Role in Energy Transition

- medium-term coal plants, including Paroşeni, act as energy security sources, complementing the energy mix until renewable and gas capacities are fully developed.

- Importance of Integrated Measures

- keeping coal plants operational, implementing emission reduction technologies, and developing CO_2 capture infrastructure ensures energy continuity, environmental protection, and compliance with national and EU objectives.

General conclusion:

Although based on traditional coal technology, Paroşeni remains indispensable for grid stability and blackout prevention, provided modern environmental mitigation measures are applied and integrated into a coherent national energy transition strategy.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

UTILIZATION OF UNDERGROUND MINING SPACES IN ENERGY AND URBAN INFRASTRUCTURE: CASE STUDY OF THE LIVEZENI–BUMBEȘTI HYDROELECTRIC FACILITY AND NATURAL STABILITY MODELS

Daniela Ionela CIOLEA[1]

Abstract: *Underground spaces represent a strategic resource for mining, urban infrastructure, and energy development, providing mechanical stability, natural protection, and a stable microclimate. This paper presents an analysis of technical, geological, geomechanical, hydrogeological, and safety criteria required for the efficient selection and utilization of subterranean spaces. The case study of the Livezeni–Bumbești hydroelectric facility demonstrates how mining engineering principles can be applied to underground energy infrastructure, through the construction of large adduction galleries and a central cavern, minimizing environmental impact and protecting equipment. The example of Sura Mare Cave illustrates the natural stability of unsupported underground voids, offering a model for the design and monitoring of mining or industrial excavations. The results highlight the advantages of using underground spaces over surface solutions, including durability, safety, technical efficiency, and landscape integration, showing that subterranean spaces can be successfully repurposed for energy, urban, and industrial applications with significant techno-economic and environmental benefits.*

Key words: *underground spaces, mining engineering, geomechanical stability, hydroelectric facilities, subsurface reuse, environmental protection*

1. INTRODUCTION

The underground environment represents a valuable resource for mining, transport, storage, civil protection, and urban infrastructure. Accelerated urbanization and environmental constraints increase interest in the rational exploitation of subterranean spaces. Excavations generate modifications of natural stresses in the rock mass, and their stability is crucial for operational safety and sustainable reuse. [1, 2]

2. TECHNICAL JUSTIFICATION FOR UTILIZING UNDERGROUND SPACE

Selection criteria for underground mining spaces [3, 7, 8]:

The selection of an underground mining space for different uses must be based on a set of technical, geological, geomechanical, hydrogeological, technological, and safety criteria, ensuring exploitation in safe, efficient, and durable conditions.

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a. Geological criteria

The geological formation in which the underground space is located must present high stability and homogeneity. Main factors analyzed:

- type of rock (salt, limestone, granite, clay, etc.);
- degree of fracturing and stratification;
- presence of faults and tectonic dislocations;
- thickness and continuity of the geological layer.

Importance: compact and homogeneous rocks provide increased safety and impermeability; tectonized formations are avoided, especially for permanent storage.

Example: salt formations are preferred for hazardous waste and hydrocarbons storage due to their natural impermeability.

b. Geomechanical criteria

Mechanical stability of the rock mass is essential for the long-term safety of the underground space. Evaluated parameters:

- compressive and shear strength;
- elastic, plastic, or viscoplastic behavior of the rock;
- natural stresses in the rock mass;
- time-dependent behavior (creep, convergence).

Importance:

- prevents collapses and excessive deformations;
- allows correct sizing of tunnels and chambers.

Example: in salt mines, creep must be considered, imposing limitations on volume and duration of use.

c. Hydrogeological criteria

The relationship between the underground space and groundwater must be rigorously analyzed. Factors analyzed:

- groundwater table level;
- permeability and porosity of rocks;
- hydrostatic pressure;
- risk of infiltration or flooding.

Importance:

- prevents groundwater contamination;
- protects structures and equipment;
- maintains sealing of storage.

Example: Hazardous waste storage is excluded in areas with active aquifers.

d. Sealing criteria

Natural and artificial sealing of the underground space is crucial for certain uses. Evaluated parameters:

- rock capacity to limit migration of fluids and gases;
- possibility of artificial sealing (dams, plugs);
- long-term stability of seals.

Importance: prevents leakage of hazardous substances; maintains controlled internal pressures.
Example: salt caverns are ideal for gas storage under pressure due to intrinsic sealing properties.

e. Subsurface climate criteria

The underground microclimate directly influences functionality and durability. Parameters analyzed:

- average temperature and its variations;
- relative humidity;
- natural air circulation;
- air quality (gases, aerosols).

Importance:

- preservation of stored products;
- human comfort for tourism or healthcare uses;
- reduced energy consumption.

f. Safety and protection criteria

Safety of people and the environment is a fundamental criterion. Analyzed factors:

- risk of explosions, fires, and gas accumulation;
- possibility of creating evacuation routes;
- access for emergency interventions;
- protection against radiation and contamination.

Importance: Compliance with civil protection and occupational safety standards;

- reduction of major risks.

g. Technological and construction criteria

Possibility of adapting the underground space to technological requirements is essential. Factors analyzed:

- geometry of tunnels and chambers;
- accessibility and existing infrastructure;
- possibility of reinforcement and redevelopment;
- compatibility with technological equipment.

h. Economic criteria

Selection must be justified economically. Evaluated factors:

- costs of development and maintenance;
- estimated service life;
- cost–benefit ratio;
- utilization of existing mining infrastructure.

i. Environmental criteria

Impact on the environment must be minimized. Analyzed factors:

- risk of soil and water pollution;
- modification of hydrogeological regime;
- compliance with environmental legislation;
- possibility of site restoration.

j. Legislative and administrative criteria

The underground space must comply with existing legal frameworks. Checked factors:

- legal status of the mine;
- regulations regarding underground use;
- required permits;
- zoning restrictions.

3. ADVANTAGES OF USING UNDERGROUND SPACE COMPARED TO SURFACE SOLUTIONS

Compared to a surface power plant, underground use offers:
- reduced visual and landscape impact;
- protection of installations against extreme weather;
- harmonious integration into environmentally sensitive areas;
- increased safety and operational lifespan.

These advantages align with reasons why abandoned mining spaces are recommended for reuse. [4]

4. CORRELATION WITH REUSE OF UNDERGROUND MINING SPACES

Although the Livezeni–Bumbești facility does not directly use abandoned mines, it demonstrates:
- the potential of underground space as energy infrastructure;
- applicability of mining technologies in non-mining domains;
- modern direction for underground reuse after mining activities cease.

Thus, the facility can be considered a technical model for:
- conversion of abandoned mines into underground power plants;
- using existing galleries for energy infrastructure;
- integrating energy production into subterranean space. [5]

5. CORRELATION WITH MINING SPACE SELECTION CRITERIA

The Livezeni–Bumbești facility fully complies with technical selection criteria:

Table 1. Technical selection criteria

Criterion	**Application in Facility**
Geological	Stable rock mass
Geomechanical	Appropriately sized tunnels and caverns
Hydrogeological	Infiltration control
Technological	Underground access and infrastructure
Economic	Reduced operational costs
Environmental	Low impact on protected area

The Livezeni–Bumbești hydroelectric facility represents a complex application of underground mining space principles, demonstrating that the underground can be efficiently used not only for resource exploitation but also for energy production, with minimal environmental impact and significant techno-economic benefits.

6. STABILITY ANALYSIS AND SUPPORT METHODS

6.1. Zones of influence around underground excavations

Excavation creates distinct zones characterized by deformation:
- collapse zone: rocks immediately surrounding the void that may fail.
- fracture zone: rocks with cracks and micro-failures.
- elastic zone: rocks deform elastically under induced stresses.

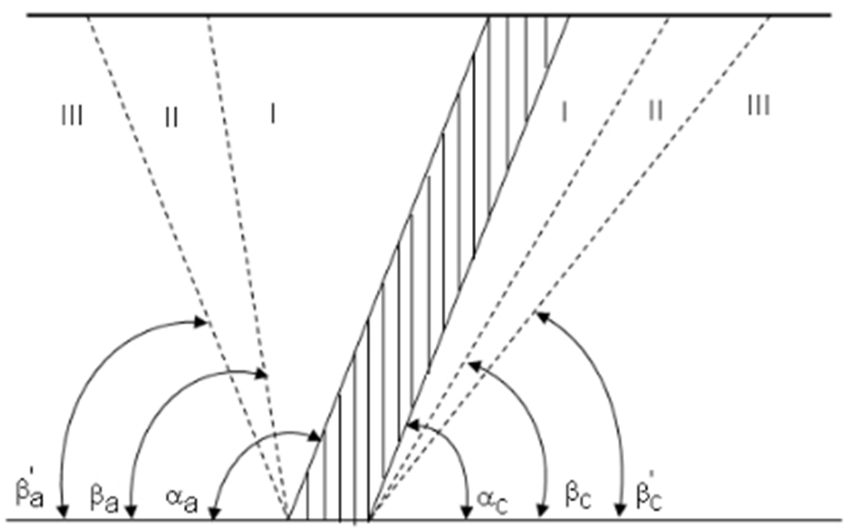


Figure 1. Zones of influence around an underground excavation

Understanding these zones allows engineers to design effective support systems and determine the size of safety pillars. [8]

6.2. Natural vs. imposed stability

Natural stability: occurs when rock mass properties are sufficient to maintain the void without additional support.

Imposed stability: requires support systems such as metal frames, anchors, shotcrete, or combinations.

Table 2. Support systems used in underground mining

Type of support	Application
Metal support	Weak rock masses
Anchors	Moderate conditions
Shotcrete	Surface reinforcement
Combined systems	High-stress environments

6.3. Modern techniques for stability evaluation

Numerical modeling: Finite Element Method (FEM), Discrete Element Method (DEM), Boundary Element Method (BEM) simulate stress redistribution and failure mechanisms.

Monitoring systems: extensometers, convergence measurements, seismic monitoring for detecting deformations and anticipating instabilities.

Risk-based approaches: integrate probability of failure with operational and environmental risks for decision-making.

6.3. Underground mining space development – technical explanations and examples

Underground mining space development is an efficient technical solution for utilizing mine voids due to geomechanical stability, natural protection from rock mass, and constant thermal conditions. Recommended uses:

A. Single-use storage – materials requiring permanent isolation.

a) Nuclear waste: underground mining spaces, especially in stable formations (salt, compact clay, granite), provide high sealing, long-term stability, and natural radiation protection.

b) Hazardous waste: chemicals, industrial residues, or contaminated materials – eliminates contact with the biosphere and reduces leakage risk.

B. Hydrocarbon storage – strategic and safe storage of petroleum, natural gas, LPG.

a) Salt caverns – natural sealing, high pressure resistance, large storage volume.

b) Artificial voids in hard rocks (limestone, granite).

c) Aquifers – hydrocarbons injected into permeable layers.

d) Abandoned mines – reusable after checking stability and sealing.

C. Long-term storage – leverages stable microclimate.

a) Compressed air storage (CAES)

b) Drinking water storage

c) Molasses storage

d) Alcoholic beverages (wine, beer, liqueur)

e) Natural refrigerators and freezers

f) Archive storage
D. Civil protection shelters and special objectives
a) Civil protection shelters
b) Sports activities (running, cycling, climbing)
c) Tourism, museum, and recreational activities
d) Balneotherapy and sanatoriums
E. Production and infrastructure zones
a) Underground hydroelectric power plants – reduced landscape impact, equipment protection

7. CASE STUDY: LIVEZENI–BUMBEȘTI HYDROELECTRIC FACILITY

The Livezeni–Bumbești hydroelectric facility represents a relevant example of utilizing underground space, applying principles similar to those used in underground mining operations. Although the main purpose of the facility is electricity generation, the adopted construction solutions are specific to mining developments, demonstrating the versatility and efficiency of underground use.

7.1. Types of underground spaces used

The facility includes several types of underground spaces similar to mining:
- large adduction tunnels – ensure water transport with minimal flow losses.
- underground caverns for hydroelectric plants – large technological spaces, similar to mining exploitation chambers.
- access, ventilation, and evacuation galleries – equivalent to shafts and auxiliary galleries in mining.
- escape tunnels – allow water return to the natural riverbed, similar to mine drainage tunnels.

7.2. Technical structure of the facility

Intake structure:
- located on the Jiu River, with a low dam.
- raises water level and directs flow to the adduction tunnel.
- equipped with protective grates, shut-off valve, and sediment evacuation system.

Adduction tunnel
- excavated underground in the rock mass.
- large cross-section, concrete-lined, several kilometers long.
- transports diverted flow to the underground plant with minimal hydraulic losses.

Surge chamber and penstock
- surge chamber absorbs overpressure and protects pipelines.
- penstock, made of steel or prestressed concrete, connects adduction tunnel to turbines.

Underground hydroelectric plant
- located in a cavern excavated in the rock mass.

- components: Francis turbine, synchronous generators, auxiliary installations (cooling, lubrication, control).
- access, ventilation, and drainage galleries.
- geotechnical reinforcements: bolts, anchors, shotcrete.

Tailrace tunnel: returns water to the Jiu River underground without affecting natural flow.

7.3. Correlation with mining underground spaces

The Livezeni–Bumbești facility respects principles of underground mining space utilization:

1. Geological and geomechanical:

- stable rock mass, resistant to large excavations.
- tunnel and cavern dimensions designed for existing stresses.

2. Hydrogeological:

- controlled collection and drainage of infiltrations.
- managed hydrostatic pressures without affecting major aquifers.

3. Advantages over surface solutions:

-reduced visual and landscape impact.
- protection of installations from extreme weather.
- increased operational safety and lifespan.

4. Reuse and technical applicability:

- model for converting abandoned mines into underground power plants.
-integration of energy production in underground space with economic and environmental benefits.

7.4. Operation of the facility

Operation of the facility:
- partial diversion regime, maintaining Jiu River ecological flow.
- diverted water passes through tunnels, central caverns, and penstocks, returning to the riverbed without major disruption.
- benefits: high energy efficiency, environmental and equipment protection.

Table 2. Types of underground spaces

Type of underground space	Function in the facility	Mining equivalent
Adduction tunnel	Transport water to hydroelectric plant	Mining transport tunnel
Central cavern	Placement of hydroelectric plants/equipment	Mining exploitation chamber
Access and ventilation gallery	Personnel, equipment, and air circulation	Shafts and auxiliary galleries
Escape tunnel	Water evacuation to natural riverbed	Mine drainage tunnel

This underground organization allows optimal utilization of the rock mass, providing natural protection and mechanical stability similar to mining requirements.
Advantages of using underground space

1. Stability and safety:

- rock mass provides a safe environment, reducing collapse and deformation risks.
- dimensions of central cavern and tunnels are sized based on geomechanical criteria.

2. Environmental protection and landscape integration:

- reduced visual and acoustic impact compared to surface plants.
- maintains natural river flow and protects local ecosystems.

3. Technical efficiency and durability:

- stable underground climate, unaffected by weather.
- equipment protection against extreme events.
- potential for reusing mining spaces or creating extensions for energy infrastructure.

Correlation with mining engineering principles:

Use of underground space in Livezeni–Bumbești reflects mining principles:
Space selection: stable, homogeneous rock mass with favorable geomechanical characteristics.
Sizing and reinforcement: caverns and tunnels designed for stress redistribution induced by excavation.
Water management: infiltration and hydrostatic pressures controlled, analogous to underground hydrocarbon or waste storage.
Access and monitoring systems: access and ventilation galleries, continuous structural monitoring.

This approach shows that underground space is used not only as transit or storage but as an active environment for complex technological infrastructure, applying rock mass stability and management principles from mining engineering.
Visual synthesis of underground space utilization, the table 3 and the figure 2:

Table 3. Types of underground spaces and their functions

Underground space type	**Function in facility**	**Mining equivalent**	**Benefits**
Adduction tunnel	Water transport to underground plant	Mining transport tunnel	Minimal hydraulic losses, rock mass protection
Central cavern	Placement of hydroelectric plants/equipment	Mining exploitation chamber	Structural stability, equipment protection, long lifespan
Access and ventilation	Personnel circulation, air circulation	Shafts and auxiliary galleries	Operational safety, controlled ventilation
Escape tunnel	Water evacuation to riverbed	Mine drainage tunnel	Maintains natural river regime, environmental protection

```
+-----------------------------+
| Stable rock mass            |
+-----------------------------+
          |
+-----------------------------+
| Adduction tunnel -> Water transport-> Mining transport tunnel
+-----------------------------+
          |
+-----------------------------+
|Central cavern -> Plant placement - Mining exploitation chamber
+-----------------------------+
          |
+-----------------------------+
 Access  &  ventilation  gallery|-Access/ventilation->Shafts  and
                                 auxiliary   galleries
+-----------------------------+
          |
+-----------------------------+
| Escape tunnel | --> Water evacuation --> Mine drainage tunnel
```

Figure 2. Underground functions and mining engineering correlation

The Livezeni–Bumbești facility uses underground space strategically and multidisciplinary:
- rock mass ensures stability and protection.
- galleries and caverns allow efficient technological operation.
- underground microclimate reduces losses and increases durability.
- environmental integrity and visual impact are minimized.
- mining solutions are successfully applied in an energy context, demonstrating reuse and valorization of underground spaces.

This synthesis can be used as a table and diagram in the paper to illustrate the connection between mining engineering and underground energy infrastructure.

8. RELEVANT NATURAL EXAMPLE OF UNSUPPORTED VOID STABILITY – SURA MARE CAVE

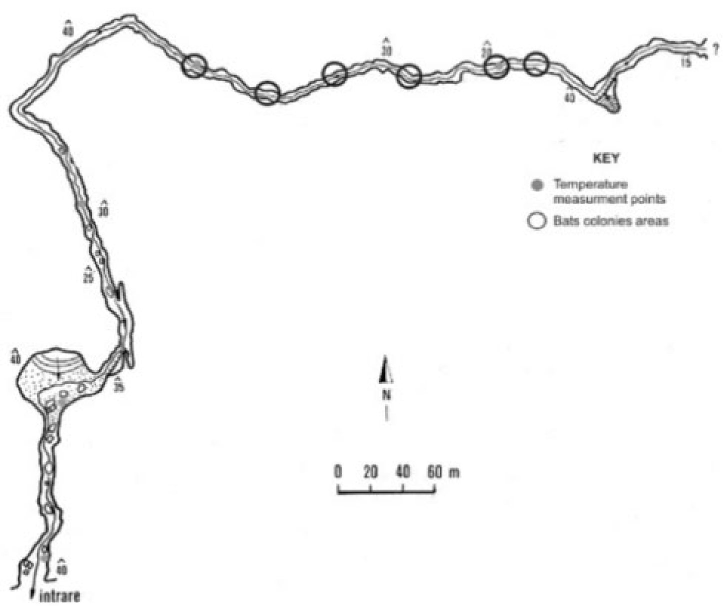
Sura Mare Cave is located in the Apuseni Mountains (Pui, Hunedoara County).

Relevant characteristics for natural stability:

1. Shape and dimensions:
- the cave has halls and galleries with variable sizes, naturally vaulted ceilings, reducing tensile stresses and favoring natural equilibrium of limestone mass.
- some galleries have curvilinear or slightly elliptical shapes, recommended in mining for tensile stress reduction.

2. Rock mass:
- relatively hard limestone with high compressive strength, allowing natural stability without artificial support.
- rock structure disperses vertical and horizontal excavation-induced stresses, preventing collapse or excessive convergence.

Figure 3.



The sector with bat colonies situated along the first 850 m from the entrance in Şura Mare cave.

Figure 4.

3. Examples of natural balancing:
- natural vaulting/arching of ceilings – chambers and corridors retain shape due to rock converting vertical load to lateral compression.
- formation of natural columns or limestone pillars contributes to long-term stability of larger halls.

4. Importance for mining study:
- clear example of natural stability, equivalent to an unsupported mining tunnel.
- studying such caves allows engineers to observe how void size and shape, rock strength, and internal structures contribute to rock mass equilibrium.

Scientific interest of Sura Mare Cave:

Sura Mare Cave has significant scientific interest due to geological, geomechanical, and biological characteristics, and as an example for studying natural stability of underground voids.

1. Geology and morphology:
- cave develops in limestone, with complex structures of galleries, halls, and naturally vaulted ceilings.
- curvilinear shapes and elliptical gallery profiles allow natural stress distribution, ideal for structural equilibrium study.
- internal sediments and speleothems provide information on mineralization and deposition processes.

2. Geomechanics and natural stability:
- real example of unsupported void stability, useful for mining and civil engineering.
- observation of natural vaults, columns, and limestone pillars allows study of rock mechanics and void geometry influence on mass behavior.
- enables testing hypotheses about stress distribution, collapse, and deformation without artificial support.

3. Hydrology and underground climate:
- stable microclimate with constant temperature and humidity, natural laboratory for microclimate studies.
-groundwater flow and lakes allow analysis of erosion and deposition processes.

4. Biodiversity and ecology:
- cave hosts troglobiont-adapted fauna (bats, invertebrates).
- biological studies contribute to understanding ecological adaptations and conservation role of caves.

5. Importance for research and engineering:
- natural model for design and evaluation of mining or tunnel stability.
- observing rock geometry and structure effects on stability without costly artificial experiments.
- provides data for long-term monitoring of deformations and geomechanical processes.

Sura Mare Cave represents a multidisciplinary natural laboratory:
- for geology and geomorphology – insights on limestone formation and underground morphology.
- for geomechanics and mining engineering – example of natural unsupported void stability.
- for biology and ecology – underground biodiversity and microclimatic conditions.

9. CONCLUSIONS

1. Underground spaces are a strategic resource for mining, urban, and energy infrastructure, providing mechanical stability, natural protection, and constant climate for long-term operation.

2. Application of mining engineering principles enables correct sizing and reinforcement of tunnels and caverns, as well as efficient water and infiltration management, ensuring operational safety.

3. Advantages over surface solutions include reduced visual and acoustic impact, equipment protection from weather, and increased operational durability and safety.

4. Reuse of underground spaces is feasible for power plants, storage, data centers, or urban infrastructure, with Livezeni–Bumbești demonstrating applicability of mining technologies in non-mining domains.

5. The Livezeni–Bumbești hydroelectric facility highlights the efficiency of underground utilization for energy infrastructure:

- adduction tunnels and central caverns sized according to geomechanical criteria, providing stability and equipment protection.
- infiltration control and hydrostatic pressure management minimize environmental and aquifer impact.
- underground placement reduces visual, acoustic, and landscape impact, ensuring durable operation and high energy efficiency.

6. Natural models, such as Sura Mare Cave, provide a natural laboratory for studying unsupported void stability and rock mass behavior evaluation.

7. Integration of sustainability and environmental protection is ensured through continuous monitoring, infiltration management, and post-excavation planning, allowing safe, efficient, and durable underground utilization with long-term economic and environmental benefits.

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GROUND-PENETRATING RADAR DIAGNOSIS OF STRUCTURAL DEGRADATION IN THE TROTUȘ SALT MINE (TÂRGU OCNA, ROMANIA): MULTI-LEVEL CORRELATION OF FRACTURING, FLOOR HEAVE, AND WATER INGRESS

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Abstract: *Long-term stability in operating salt mines is commonly controlled by the interplay between tectonic stress, salt creep, and water ingress along discontinuities. This study presents an integrated structural diagnosis of selected sectors in the Trotuș Salt Mine (Târgu Ocna, Romania), focusing on levels VII–IX, where historical instability indicators and active deterioration have been reported. High-frequency Ground-Penetrating Radar (GPR) profiling (500 MHz shielded antenna) was applied along accessible galleries and, where possible, across roof/ceiling surfaces. The radargrams reveal recurrent signatures of: (i) roof-thickness variability and local thinning, (ii) near-vertical attenuation corridors consistent with preferential water pathways, (iii) laterally continuous reflectors disrupted by fracturing or shearing, and (iv) deformation features associated with floor heave. By correlating these geophysical observations with mine development information, visible damage mapping, and historical instability records, we outline a practical workflow for delineating risk-prone zones and prioritizing monitoring and reinforcement. The results support GPR as a reliable non-destructive tool for early warning and for optimizing safety decisions in room-and-pillar salt mine environments.*

Key words: *Ground-penetrating radar; salt mine stability; room-and-pillar; water intrusion; fractures; floor heave; risk zoning; Romania*

1. INTRODUCTION

Salt mines developed in tectonically influenced evaporite settings require continuous stability surveillance because progressive damage can evolve from subtle cracking to major roof falls or surface subsidence. In Romania, old and active salt workings are particularly sensitive to water intrusion, which accelerates dissolution, weakens discontinuity surfaces, and can trigger cascading instability across stacked mine levels [9,14,15].

The Târgu Ocna mining area hosts the Trotuș Mine, a major operational salt mine with extensive underground networks created by successive exploitation stages and

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mining methods. Modern use also includes tourism development at specific mine levels—factors that increase the value of reliable risk evaluation and monitoring [20-22].

This paper aims to:

- identify GPR-based indicators of roof/pillar deterioration and water ingress across levels VII–IX;
- correlate anomalies vertically (between levels) and laterally (along galleries) to infer propagation patterns;
- provide a practical basis for risk zoning and targeted mitigation in active salt mine conditions.

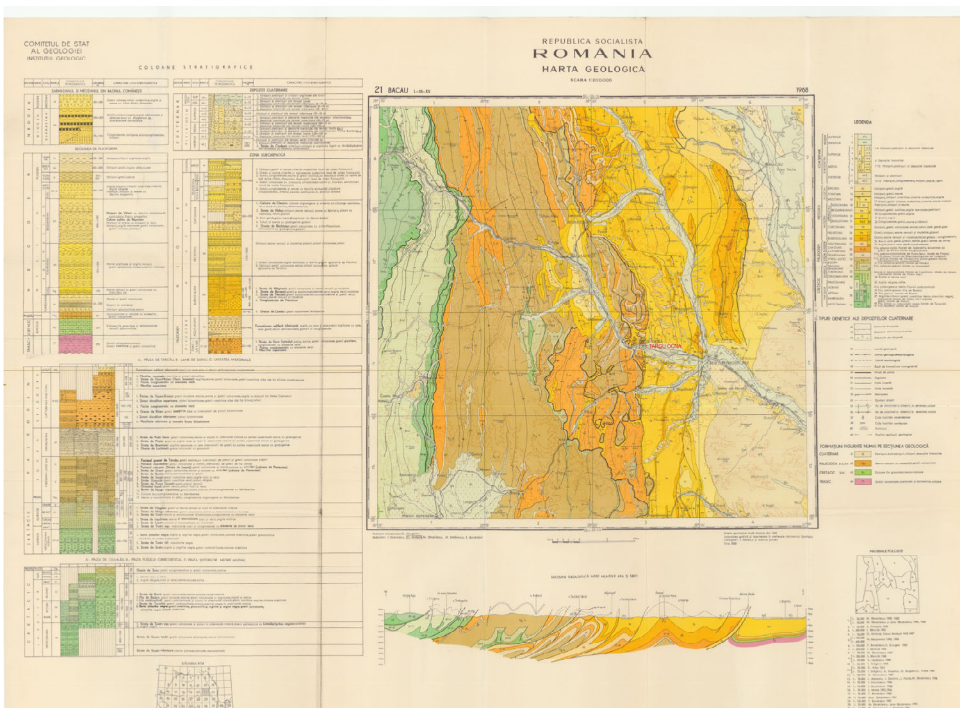

Figure 1. Geological map, Bacău sheet, scale 1:200000, Geological Institute, 1968

2. SITE CONTEXT AND INVESTIGATION TARGETS

The investigated sectors belong to a room-and-pillar mining layout, where roof competence and pillar integrity are key controls on long-term stability. Water infiltration evidence (e.g., damp zones, drip points, stalactitic precipitates) and cracking/floor heave observations were used as field constraints during interpretation [16,18,19,23].

The survey targeted galleries and accessible surfaces on levels VII, VIII, and IX. In practice, coverage is constrained by operational safety and access corridors; therefore, GPR lines were acquired where the cart (or ceiling access equipment) could be safely deployed [23].

3. MATERIALS AND METHODS

3.1. GPR equipment and acquisition design

Data were collected with a Zond-12e GPR Advanced system and a 500 MHz shielded antenna, selected as a balance between resolution and penetration in salt rock. Profiles were acquired in continuous mode along accessible galleries on levels VII–IX, with additional ceiling/roof profiling where feasible [1-3, 23].

Representative acquisition parameters included a dry-salt medium setting ($\varepsilon_r = 6$), 1024 samples, continuous sounding mode (Channel 1), software stacking = 1, and a customized 148 ns time window. Detailed acquisition settings are summarized in Table 1.

Table 1. GPR acquisition settings used in the survey

Parameter	**Value**
Medium / velocity model	Dry salt (εr = 6)
Antenna	500 MHz shielded
Sounding mode	Continuous
Channels mode	Channel 1
Samples	1024
Software stacking	1
Time range	Customized 148 ns
Range per sample	145 ps
High-pass filter	Super Strong
Pulse delay	307 (of 1024)
Gain	2 points: 12 dB/sample at sample 0; 48 dB/sample at sample 1023

3.2. Processing workflow

Processing followed standard underground GPR practice: time-zero correction, background removal, gain compensation, band-pass filtering, and migration to improve geometric positioning of reflectors and discontinuities. Interpretation focused on characteristic signatures of roof thickness variability, sub-vertical attenuation corridors (possible water paths), discontinuity planes, void-like responses, and disturbed reflectivity associated with weakened zones [1-4].

3.3. Interpretation logic and correlation

Anomalies were interpreted using a multi-source approach:

- Geophysical evidence: radar facies changes, reflector truncations, diffraction patterns (fig. 3), and attenuation corridors (fig. 2).
- Direct observations: visible fractures, moisture points, and floor uplift zones.
- Contextual constraints: mine layout, pillar positions, and known/historic instability areas where available.

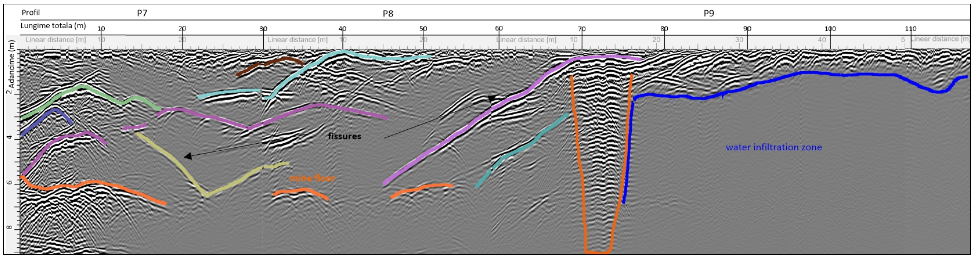

Figure 2. Attenuation corridor interpreted as water pathway

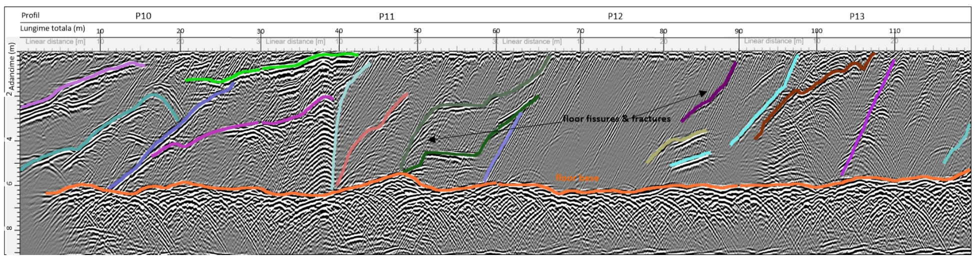

Figure 3. Reflector truncation interpreted as fracturing

4. RESULTS

4.1. Level VII: cracking, localized ingress, and floor deformation

On level VII, radargrams frequently show discontinuous roof reflectors and localized high-attenuation features aligned with mapped cracks and damp zones. Several sectors exhibit responses consistent with fractured or disturbed salt near the roof and with deformation features that match field observations of floor heave and associated cracking [6-8, 23].

4.2. Level VIII: disturbed reflectivity and chamber-margin effects

Level VIII presents a heterogeneous pattern, with localized disturbed reflective horizons suggestive of weakened salt volumes or incipient voiding. Changes in apparent floor/roof response are more evident near chamber margins, consistent with stress redistribution effects in room-and-pillar systems [16,18,19, 23].

4.3. Level IX: recurrent vertical corridors and thinning indicators

Level IX shows systematic occurrence of sub-vertical attenuation corridors, interpreted as preferential moisture pathways (or water-affected zones) crossing the radar section. In multiple locations, these features coincide with roof-thinning indicators and with sectors historically reported as instability-prone [6, 9, 23].

4.4. Cross-level correlation and risk zoning

When interpreted features are correlated vertically and laterally, repeated patterns emerge: pillars and sectors affected on one level tend to align with affected sectors on adjacent levels, indicating propagation or shared structural controls (tectonic discontinuities, stress concentration corridors, or persistent infiltration pathways). This supports defining risk zones based on the spatial convergence of fractures, floor heave, and infiltration indicators across levels [16, 18, 19, 23].

5. DISCUSSION

GPR is effective in resistive media such as salt for imaging fractures and discontinuities and has a documented role in underground mine roof hazard investigations. In the present case, practical value comes from combining GPR anomaly mapping with mine development context and direct observations, enabling prioritization of zones for reinforcement and monitoring [1-3, 6-8].

Water intrusion remains a dominant destabilizing factor in Romanian salt mine settings; therefore, the repeated appearance of vertical attenuation corridors across multiple levels should be treated as a first-order risk signal, especially where these corridors intersect structurally controlled discontinuity zones [9].

Limitations should be acknowledged: locally increased moisture and any clay-rich inclusions can reduce radar penetration and complicate amplitude-based interpretations. For operational decision-making, repeated surveys (time-lapse), integrated geological mapping, and local monitoring sensors (e.g., extensometers, humidity/flow sensing, microseismic) are recommended in high-risk corridors [1-4, 12].

6. CONCLUSIONS

1. High-frequency GPR (500 MHz) provided diagnostic indicators of structural degradation in the Trotuș Mine across levels VII–IX, including reflector disruption, thinning signatures, and attenuation corridors consistent with water paths [6-8, 23].
2. Cross-level correlation suggests that damage and ingress pathways can propagate or remain structurally linked between stacked mine levels, supporting multi-level risk zoning rather than isolated single-level assessments [16, 18, 19, 23].
3. The integrated workflow (GPR + mapping + historical/development context) offers a practical basis for prioritizing reinforcement and implementing continuous monitoring in active salt mine environments [4, 12, 23].

Table 2. Summary of characteristic GPR signatures and interpretation criteria used for risk zoning

GPR signature (appearance)	**Likely interpretation**	**Field / contextual cross-check**	**Practical risk implication**
Sub-vertical attenuation corridor; loss of reflections and reduced amplitudes	Preferential moisture pathway / water-affected salt; locally increased conductivity	Drip points, damp walls/roof, salt dissolution traces, proximity to known water sources	Prioritize monitoring; consider access restrictions if persistent and wide

Reflector truncation or offset; sharp break in continuity	Fracture/fault zone; shear plane intersecting roof or wall	Visible cracking, joint sets, alignment with mapped discontinuities/pillar boundaries	Potential detachment surfaces; evaluate support/mitigation
Clusters of diffractions (hyperbola-like events) near roof	Open cracks/void-like discontinuities; small cavities or fractured blocks	Local spalling, debris, acoustic anomalies; repeated features across adjacent lines	Localized roof-fall hazard; inspect and reinforce if needed
Chaotic/low-coherence zone over short interval	Disturbed salt fabric; crushed zone or strongly fractured volume	Deformation signs, uneven surfaces, historical instability records	Medium-to-high risk corridor; consider detailed follow-up
Progressive roof-thickness reduction (shallower roof reflector; reduced two-way time)	Roof thinning (dissolution or mechanical loss) / reduced competent thickness	Roof geometry checks, convergence measurements, historical maintenance logs	Increase support and surveillance; avoid heavy loads below
Floor-related reflector warping; upward bending and irregular shallow reflections	Floor heave / creep-related deformation; stress redistribution near chamber margins	Measured floor uplift, rail/roadway deformation, operational observations	Operational constraint; plan leveling/rehabilitation and monitor evolution

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

VALORIZATION OF METALLURGICAL SLAGS IN THE CONTEXT OF THE CIRCULAR ECONOMY

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Abstract: *The paper discusses the issue of industrial slag, which is a byproduct of various industrial processes. This slag contains significant amounts of metals that can be harmful to the environment if not properly managed. Therefore, recovering these metals is essential to prevent environmental contamination. Metallurgical slag processing employs various methods to recover valuable metals, which are essential for resource conservation and environmental sustainability. The primary techniques include mineral processing methods such as crushing, grinding, magnetic separation, and hydrometallurgical processes. Each method has its unique advantages and applications, contributing to the efficient recovery of metals from slag. This paper presents pyrometallurgical and hydrometallurgical methods for extracting metals from metallurgical slags.*

Key words: *metalurgical slags, piromettalurgical valorization, hydromettalurgical valorization*

1. INTRODUCTION

The development of the metallurgical industry depends on addressing key issues related to the relationship between industry and the environment, with a particular focus on pollution control and the conservation of natural and energy resources. In this context, the steel industry must move away from the concept of "waste" and adopt an approach that recognizes metallurgical slags as valuable by-products that can be reused and reintegrated into various industrial processes. [1], [3]

The concerns pursued in the development strategies of steel plants around the world fall into two directions:

- the development of high-performance technologies in which emissions are substantially reduced;
- increasing the yields of recovery and recycling of by-products up to values close to 100%.

The essential changes in this millennium must be related to the development of metallurgical technologies according to the requirements of industrial ecology.[2]

The concern for complying with legislative requirements regarding environmental protection and the need to harmonize economic progress with the rational management of material and energy resources must lead to the valorization of waste through technologies that provide the optimal solution from both economic and ecological perspectives. It is essential to promote technologies that ensure:

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- Rigorous waste management;
- Controlled disposal of all waste categories;
- Reduction at source of the quantity and harmfulness of generated waste;
- Advanced recycling of resulting waste by reintroducing it at various stages of the technological flow, thereby ensuring the conservation of natural raw material resources;
- Increased utilization of waste by transforming it into raw materials for other industries.

In order to be able to establish the possibilities of valorization of the presented material or energy resources, the analysis of the contents of useful elements, of the mineralogical and granulometric composition, is made, based on representative samples, appropriately taken and brought to the required quantities for the tests.

Compared to the practice and trends shown worldwide, the Romanian steel industry lags behind, both in the areas of collection, transport and storage of all categories of waste, as well as in terms of solutions for valorization through recycling and/or their use.[24]

2. PYROMETTALURGICAL VALORIZATION OF METALURGICAL SLAG

The Wäelz process is the most used process for the recovery of pulverulent waste in rotary kilns (fig. 1).[4],[25]. It applies to dusts generated during steelmaking that have a high content of zinc and lead (~20%), for which recycling in various flow stages technology in the steel sector is difficult to achieve.

The process is based on the direct reduction of the elements, followed by the volatilization of zinc, lead and cadmium and the reoxidation of these elements that will be collected in the bag filter. A powder enriched in zinc is obtained whose concentration varies from 56% to 74%. Since the process can be hampered by the presence of chlorine (from the refractory materials), slag from the waste and fluorine (from the fluorine used in steelmaking), these elements must be removed before the waste is recovered. Together with the dust from the electric furnace, the wastes that can be recovered through this process are the dusts and sludges from agglomeration, furnace, converter, which were previously enriched in zinc and lead. Dusts and slurries are pelletized with an addition of 25% fine coke and 15% sand.

The obtained pellets are placed in a rotating tubular furnace where they are maintained for 4 hours at a temperature of 1000-1250^0 C. The process results in Wäelz oxide, a product with a high content of ZnO and PbO (ZnO+PbO>70%), directed to non-ferrous metallurgy and Wäelz slag that can be used in road construction. Waste recovery facilities using the Wäelz process are complex and expensive; they become economically efficient only when processing dusts and slurries with a Zn+Pb>20% content.

Currently, several Wäelz plants are in operation worldwide. In Austria, at Voest Alpine Linz, such a facility processes ~50,000-55,000t/year of powdery waste. Iron recovery from waste in Wäelz processing is low and is only justified if the plant is modified to incorporate a direct iron reduction furnace.

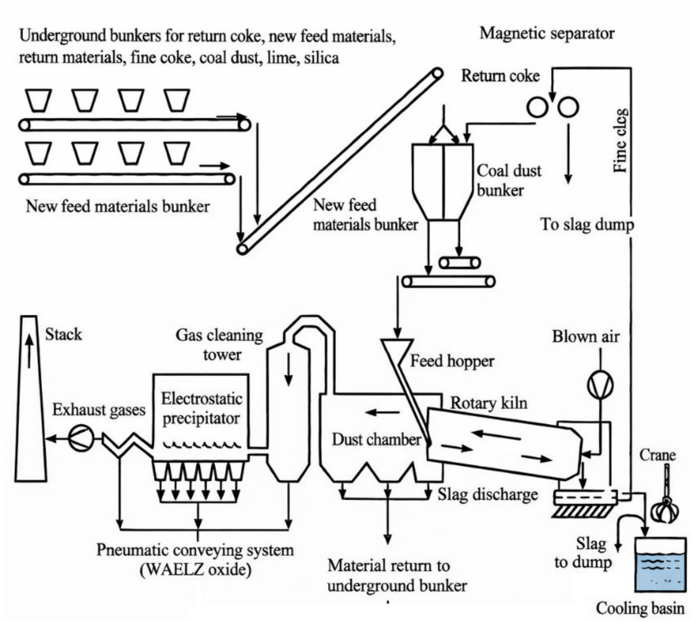

Figure 1. Scheme of the Wäelz process

The INMETCO process allows the recovery of pulverulent waste which, due to the high content of zinc and lead, the physical characteristics as well as the small quantities collected, cannot be directly used in the production processes of cast iron or steel (fig.2). [5], [6], [7]. Since 1978, the International Materials Recycling Society, INMETCO of Ellwood City, USA. put into operation a facility for recycling dust and other types of waste from American and Canadian industry. The installation was designed for a processing capacity of 50,000t/year. Nickel, chromium and iron recovered from waste are reintroduced into the stainless steel manufacturing process, and zinc, cadmium, lead are separated from the gas treatment plants and directed for recovery in the non-ferrous metal industry.

The waste that can be recycled through this process are:

- coal dust and coke dust;
- dust and sludge from agglomeration;
- furnace dust and sludge;
- dust and sludge from the converter, electric arc furnace;
- steel swarf and rolling mill sludge containing oil.

In addition to this waste, this facility can also process used Ni-Cd batteries, used water containing chromium or from electrolytic coatings, materials recovered from casting pots. The INMETCO process has two stages: production and reduction of raw pellets.

The production of raw pellets is made from a mixture of fine-grained waste and reducing agents. If necessary, binders are added, their quantity being determined by ensuring the resistance of the raw pellets when heated in the rotary hearth oven. The carbon content of the raw pellets is conditioned by the further processing of the product resulting from the reduction process, an iron sponge. Coal, coke and other waste containing carbon can be used as reducing agents.

Reduction of raw pellets. The raw pellets, introduced as a thin layer in the rotary hearth furnace, are transported through different temperature zones as a static bed. This avoids the mechanical generation of dust that could later be entrained in the exhaust gas.

The product obtained by this process is an iron sponge with a high iron content. At the same time, a secondary dust and a slag is obtained. Dust rich in ZnO and PbO (~50...60%ZnO, ~10...15%PbO) can be used in non-ferrous metallurgy and the gas containing N2~64%, O2~2%, CO2~15%, H2O~19% can be used to obtain steam.

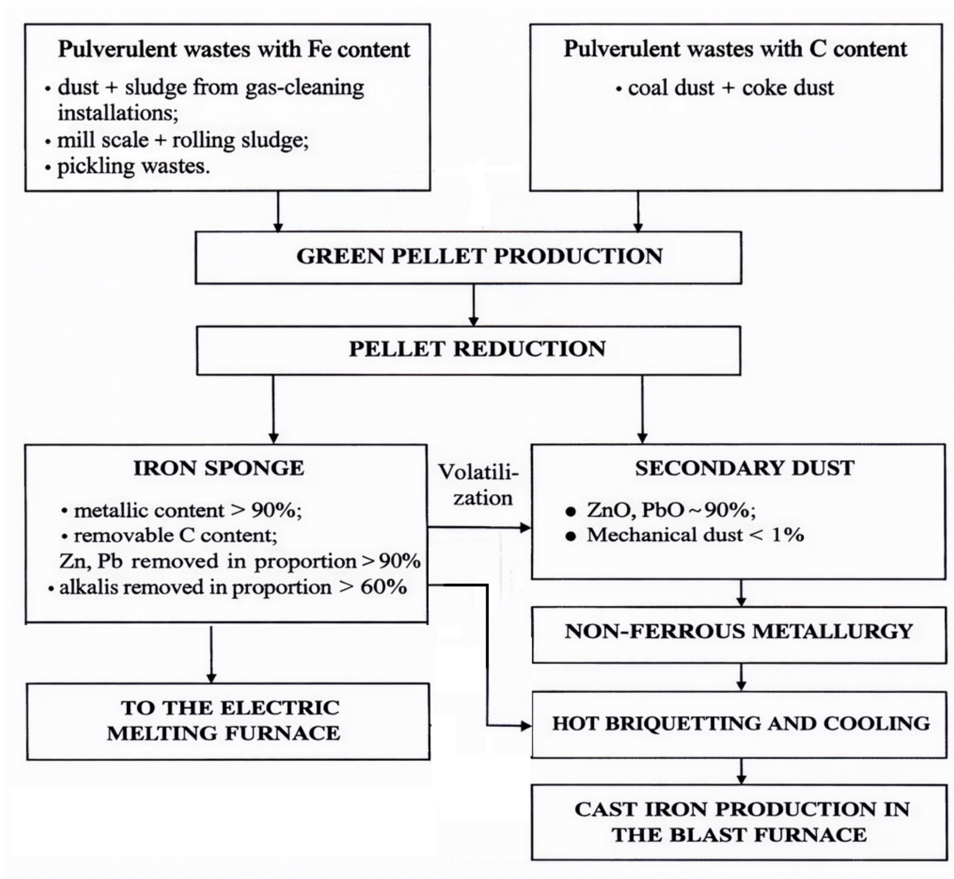

Figure 2. Waste recovery through the INMETCO process

The ZWS Lurgi process (Zierkulierende Wirbelschicht) applied in Germany realizes the processing of fine and coarse fractions, pre-dried, separated from agglomeration dust and sludge, furnace dust and sludge, fine dust and converter sludge, electric furnace dust with a content of Zn=0.5%.

The process takes place in a controlled reducing atmosphere, with the aim of separating zinc without reducing the iron from its oxides. The schematic diagram of a ZWS Lurgi installation is shown in Figure 3.[8], [9], [10].

The operating principle of such an installation consists in the fluidization of fine dust particles in a reactor that uses coke gas heated to a temperature of ~750^0 C as a carrier gas. The rate of coke gas introduction into the reactor is higher than normal fluidization speed, to determine the faster evacuation of fine solid particles on the upper part of the reactor, making it possible to pass them through two cyclones, one for return and the other for separation.

The high temperature in the separation cyclone causes the volatilization of zinc and lead. These elements are subsequently condensed and recovered in the form of a dust rich in zinc and lead (Zn = 25.7%, Pb = 7.8%, K_2O = 6.9%), which can be further processed in non-ferrous metallurgy.

Coarse dust particles, with high iron content and low concentrations of undesirable elements (Zn = 0.3%, Pb = 0.002%, K_2O = 0.2%), which could not be sufficiently entrained to exit through the upper section, are discharged through the bottom part of the reactor. This coarse dust will be used as input material in the sintering feed.

The advantages of this procedure are:

- the diversity of pulverulent waste that can be processed;
- the simultaneous processing capacity of both fine and coarse fractions, there being no condition imposed regarding the granulometric composition;
- the possibility of the advanced valorization of the obtained products, the recycling of a part in agglomeration and the valorization of another in non-ferrous metallurgy.

This process was applied for the first time on an industrial scale at Thyssen Stahl AG Germany, being later adopted at other metallurgical plants in England, Belgium, USA, France.

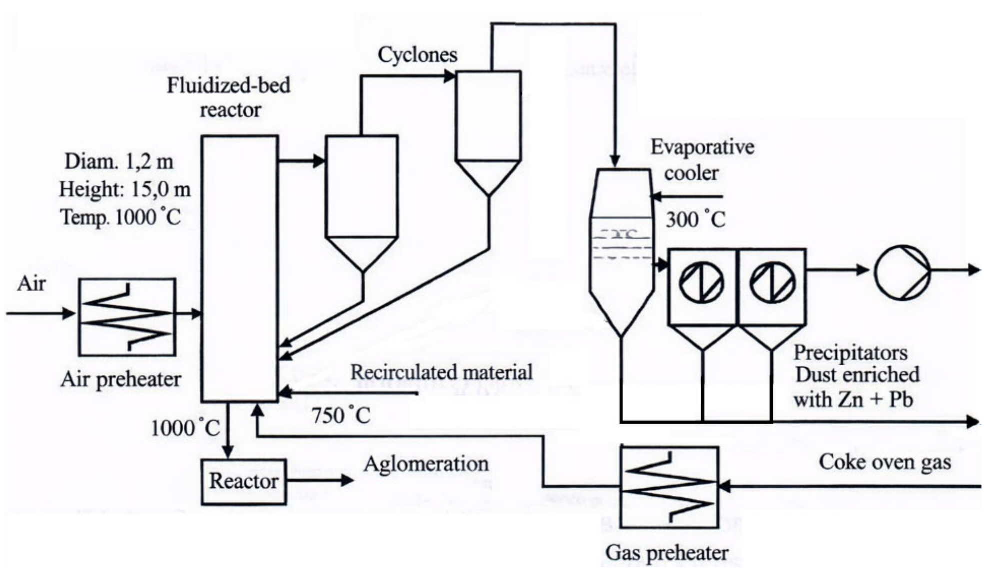

Figure 3. Basic diagram of the installation

The Contop process is a pyrometallurgical process based on the principle of selective reduction at temperatures higher than 1000^0 C. It was developed by KHD Humbold, WEDAG AG Köln at the end of 1988.

The process, initially used for melting copper concentrates, was later adapted to the processing of powdery waste generated in steelmaking, such as furnace dust and sludge, converter dust and sludge, electric furnace dust, dust generated from secondary metallurgy processes, slag and sludge from rolling. The technological flow diagram of the process is presented in fig. 4.[11],[12].

Before processing, the waste must be dry and have a uniform granulation (96% of the particles must be smaller than 1 mm in size. Through this process, the dusty mixtures are melted in an oxygen atmosphere, with the further processing of the slag melt rich in iron and the recovery of zinc and lead.

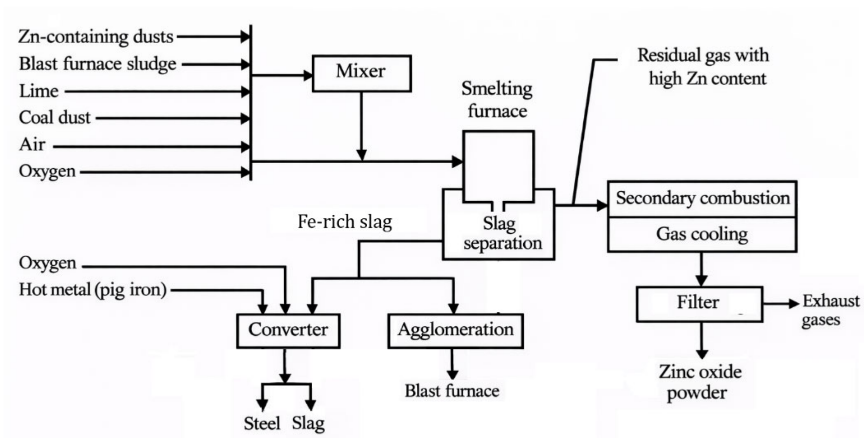

Figure 4. Valorization of pulverulent waste through the Contop process

The obtained products are the following: - zinc and lead concentrate with PbO+ZnO=50-60% which will be directed to non-ferrous metallurgy; - slag with an iron content between 40-60% that can be used by recycling in agglomeration, in the load of the converter charge or in road constructions. Contop plants operate in Chuquicamta-Chile, Palabora-South Africa and in Bolivia.

VAI Linz Austria applied the CONTOP technology for the recovery of zinc from metallurgical by-products. The main installation in CONTOP is a vertical cyclone for melting and cooling of tubular construction. Powdery materials, blown through a pneumatic system, are injected tangentially into the cyclone where the fuel is also introduced together with the oxygen required for combustion.

The thermal process takes place in the upper part of the installation, where temperatures of ~1800^0 C are reached. The vaporization of zinc and lead (possibly copper if it is present in the powdered material) takes place. After passing through the cyclone, the vapors condense and are recovered in a filter. The other solid materials with a high iron content, resulting in the form of droplets, are directed to be recovered in other processes (eg agglomeration).

3. HYDROMETTALURGICAL VALORIZATION OF METALURGICAL SLAG

Eliminates the disadvantage of processing waste at high temperature regimes. Whatever the schemes applied in the hydrometallurgical processes, the degree of purity of the obtained products is high, unlike those obtained by pyrometallurgical processes, where additional refining operations are necessary.[22], [23].

The stages of the hydrometallurgical processing processes in order to recover and capitalize on useful elements such as iron, zinc, lead, cadmium, etc. from the dust captured in the technological flows of the steel plants are:

- leaching of zinc, lead and other elements at temperatures close to ambient;
- recycling of solid residue enriched in iron in steel industry or other industrial branches;
- purification of solutions, for example by cementation, in order to separate lead, cadmium, etc.;
- recovery of zinc in the form of ZnO or ZnS by precipitation or metallic zinc by electrolysis.

Numerous variants of hydrometallurgical processes have been studied and tested. Some have been implemented at an industrial scale, either integrated into the production flows of steel plants or as part of independent technological lines.

Others have been developed only at laboratory scale or within pilot installations, with the prospect of being applied under favorable conditions.

3.1. Processes based on the use of sulfuric acid

The first zinc recovery processes from steel mill dust were based on the use of sulfuric acid in the leaching stage. They did not give satisfactory results due to the high Fe/Zn ratio in the dust captured in electric arc furnaces. Since ZnO is easily soluble in weakly acidic solutions and zinc in the form of $ZnOFe_2O_3$ ferrites is not soluble in them, a large part of zinc remains in the residue along with iron. The process becomes advantageous only if it is preceded by a step of reducing the zinc in the ferrites which leads to the minimization of the zinc precipitation. At the same time, the high content of halogens in the treated dusts means that the process cannot be well controlled in the electrolysis stage of solutions rich in zinc.

The H-MAR process is a variant of the MAR process - "Metals and Acids Recovery" which is intended for the separation of zinc and copper. The technological flow of the H-MAR process was initially tested for the direct leaching of steel mill dust to obtain metallic zinc by electrolysis. The pilot plants were used to extract the elements from the dusts rich in copper or zinc, recovered during the rolling of brasses.

The technological flow of the process can be separated into two sequences, the copper recovery circuit and the zinc recovery circuit, fig.5.[13], [14], [15].The copper circuit. The copper-rich material is solubilized at 60^0 C in a pH-controlled lye, which has a final pH=2-2.5. When the charged material also contains metallic zinc (brass or cast iron), the dissolution of copper, thus preventing cementation of metallic copper, is favored by maintaining oxidizing conditions by adding MnO_2. The copper-rich leach solution is filtered and directed to the solvent extraction circuit. Copper is extracted in four steps with kerosene solution containing LIX84 and separated in three steps with sulfuric acid as electrolyte. Metallic copper is recovered from the electrolyte by electrolysis.

The zinc circuit includes controlled solubilization at 60^0 C under oxidizing conditions. Zinc dust with low copper content is leached together with the residue from copper refining and some of the refined zinc. The leaching solution is maintained at a pH of ~2 for most of the leaching time and then slowly increases towards the end to 4.5. The aim is thus to decrease the iron content below 10ppm. The leach solution is filtered and purified to remove metallic impurities such as copper, nickel and cadmium through a cementation operation, filtered again and finally loaded into the solvent extraction circuit. Zinc is extracted in three stages with kerosene solution containing DEPHA. The amount of zinc transported in the leaching stage is greater than 20-25g/l, the remaining zinc in the raffinate being recycled during leaching. Zn separation is efficient, metallic zinc being recovered by electrolysis of the solution.

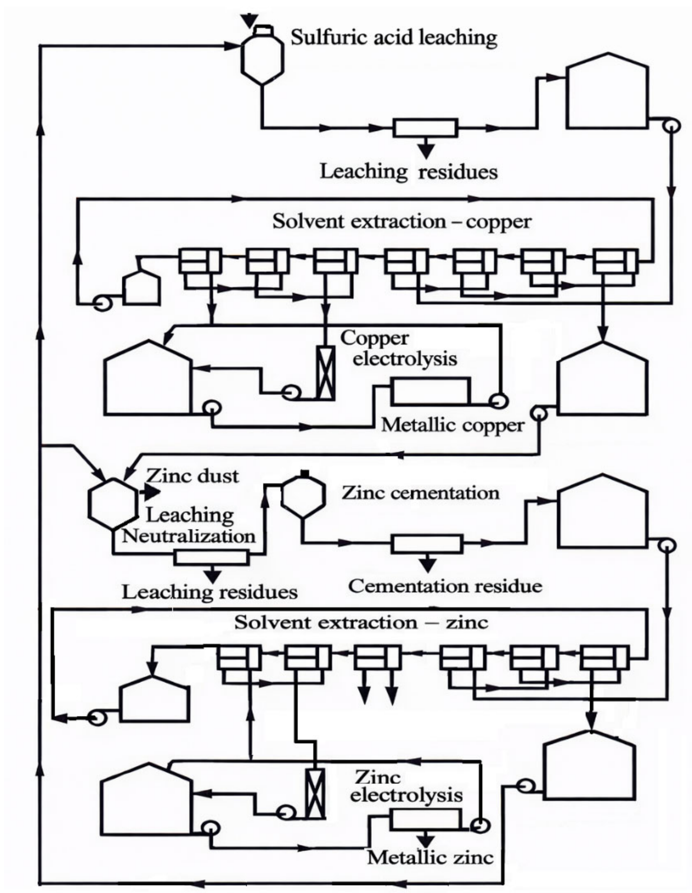

Figure 5. H-MAR process flow for zinc and copper recovery

3.2. Processes based on alkaline leaching

Alkaline leaching in NaOH or KOH solutions offers a series of advantages since the iron, almost entirely insoluble, remains as a residue. Like the 99 processes based on acid leaching, they are also limited by the impossibility of recovering zinc in the form of ferrites, as previous reduction operations are required

The Cebedeau process was developed by the University of Liege-Belgium in cooperation with the firms Cebedeau Liege and SERH from Saint Florentin-France. This procedure applies especially to the dust collected at the electric furnace; the technological flow diagram being given in fig.6.[16], [17],[18].

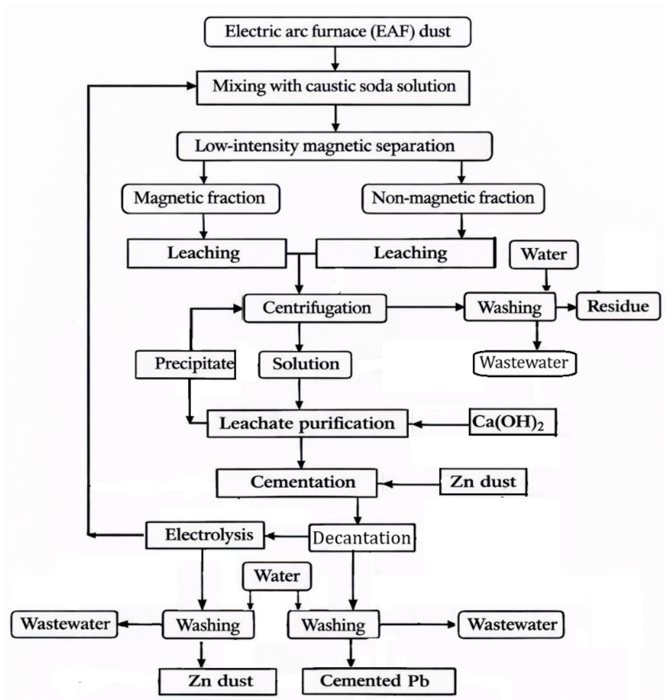

Figure 6. The flow of pulverulent waste recovery through the Cebedeau process

3.2. Processes based on leaching in solutions of ammonia chlorides or alkaline chlorides

The AmMAR procedure. The AmMAR concept of the MAR process – "Metals and Acids Recovery" can be applied for the processing of a wide variety of recyclable materials, fig. 7. [19], [20], [21]. Depending on the nature of the load and the elements that want to be recovered, specific technological flows are established, from the sequence of known chemical operations based on solubilization in ammonia, ammonium chloride or carbonates. The procedure is intended for the treatment of materials containing two or more elements such as iron, chromium, copper, nickel, zinc.

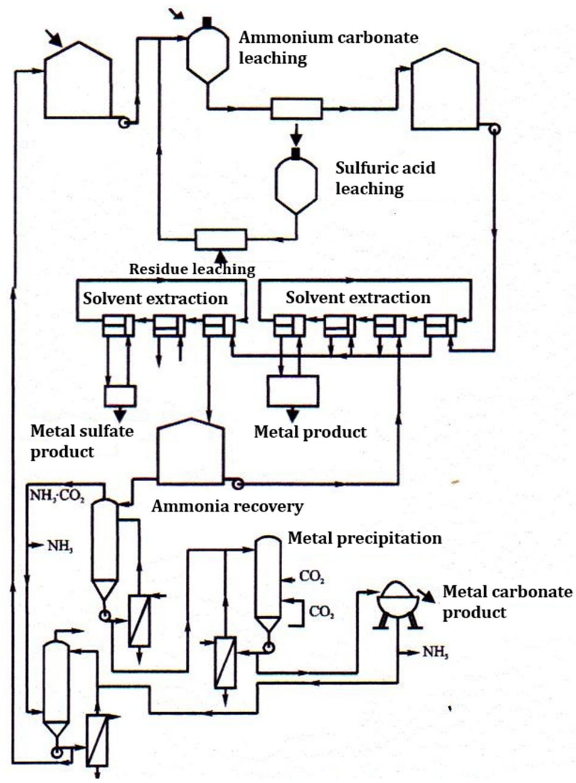

Figure 7. AmMAR ammonia process flow

It includes several stages, the main ones being leaching and solvent extraction when copper and nickel are separated: - primary separation by leaching when metals such as zinc, copper and nickel are dissolved as ammonia complexes of these metals, chlorides or other complexes with chlorine , and iron and chromium remain in the solid residue as hydroxides; - copper and nickel are recovered separately from the leaching solution by solvent extraction; after selective separation, nickel sulfate results from crystallization and metallic copper from electrolysis; - excess ammonia is evaporated from the resulting extraction raffinate and absorbed in the leaching filtrate; - the remaining zinc in the extraction raffinate is precipitated in the form of carbonate, associated with the already existing ammonium carbonate or by the addition of CO_2, the resulting filtrate is recycled in the leaching stage; - treating the water with lime, if it contains sludge and if necessary proceed to the evaporation of ammonia.

4. CONCLUSIONS

The valorization of this waste aims to achieve the following:

- Recovery of useful elements contained within the waste;
- Recovery of combustible mass for the production of eco-friendly fuels;

- Controlled disposal of all waste categories;
- Reduction at source of the quantity and harmfulness of generated waste;
- Increased utilization of waste by transforming it into raw materials for other industries or into finished products;
- Advanced recycling of resulting waste by reintegrating it into various stages of the technological process, thereby conserving natural raw material resources;
- Soil improvement for agricultural purposes;
- Reclaiming land occupied by tailings ponds for agricultural or forestry use.

Pyrometallurgical processes are suitable for high-value metal recovery but are energy-intensive.**Hydrometallurgical approaches** offer high selectivity but raise environmental concerns related to effluent treatment.

While these methods are effective, challenges such as low metal concentrations and complex slag compositions can hinder recovery efficiency. Alternative approaches, including innovative combinations of techniques, may offer solutions to these limitations.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

BRUCITE UTILIZATION IN INDUSTRIAL APPLICATIONS

Camelia BĂDULESCU[1]

Abstract: *Brucite [$Mg(OH)_2$] is an important natural source of magnesium, usable in multiple industrial applications due to its thermal stability, controllable chemical reactivity and neutralization properties. In technological processes, brucite can be utilized to obtain high-purity magnesium oxide (MgO), through controlled calcination, subsequently used in the manufacture of refractory materials, fireproof composites and technical ceramic products. Also, due to its metal ion fixation capacity and alkaline behavior, brucite has applicability in industrial wastewater treatment and gas desulfurization processes. In the current context of sustainable development, brucite utilization also offers an ecological solution for CO_2 capture, through direct carbonation reactions, generating useful products such as magnesium carbonate. The paper analyzes the methods of processing, purification and activation of brucites, the optimal technological parameters for conversion to MgO and the potential for integrating these processes into low-carbon industrial chains.*

Key words: *brucite, $Mg(OH)_2$, MgO, calcination, carbonation, refractory materials*

1. PHYSICO-CHEMICAL AND TECHNOLOGICAL PROPERTIES OF BRUCITE

Brucite has the ideal chemical formula $Mg(OH)_2$ and crystallizes in the trigonal system, with a structure similar to that of goethite and portlandite [14]. The crystal lattice is made up of layers of Mg^{2+} ions octahedrally coordinated by OH^- ions, which gives the mineral a lamellar structure and a theoretical density of approximately 2.39 g/cm^3. In nature, brucite can be associated with minerals such as serpentine, dolomite, calcite or talc, forming magnesium-rich rocks such as magnesite and dolostone. Common impurities in brucite include Fe^{2+}, Al^{3+}, Mn^{2+} and Ca^{2+}, which can significantly influence the physicochemical properties and calcination behavior. The purity of the raw material is a critical parameter for industrial applications, especially in the production of high-performance. In the presence of CO_2, brucite reacts to form magnesium carbonate, a process exploited in modern carbon capture and storage (CCS) technologies:[10]

$$MgO\cdot Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$$

From a technological point of view, brucite has a high machinability. It can be ground, granulated or calcined depending on the industrial destination. The essential parameters for the technological processes are:

- particle size (which influences the reactivity and specific surface area),

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- calcination temperature,
- heating and cooling rate,
- reaction pressure (in carbonation or sintering processes)

In industrial applications, natural brucite is often subjected to purification, granulometric classification and mechanical activation steps, in order to improve homogeneity and reactivity. These processes allow the material to be adapted to specific requirements in the field of refractories, composite materials, construction or environmental protection.[1], [5]

Figure 1. Brucite

The solubility of the compunds from the brucitic ore is very little. The solubility of $CaCO_3$ decreases with the temperature increasing, while the solubility of $Ca(HCO_3)_2$ increases with the temperature increasing.[4]

2. INDUSTRIAL APPLICATIONS AND DEVELOPMENT PROSPECTS

Brucite and its derivatives (especially magnesium oxide – MgO) have been used over time in a wide range of industries due to their versatile physicochemical properties:

Refractory industry: MgO obtained by calcining brucite is used in the manufacture of refractory bricks, plates and concretes resistant to high temperatures (up to 2000°C). These materials are indispensable in metallurgical furnaces, steel foundries, cement kilns and in the glass industry.

Chemical industry: $Mg(OH)_2$ is used as a weak base in chemical synthesis, in the production of magnesium salts (sulfate, chloride, acetate), but also as a neutralizing agent in various technological processes.

Pharmaceutical and food industry: due to its high purity and non-toxic nature, $Mg(OH)_2$ is used in pharmaceutical products (antacids, laxatives) and as a food additive (E528).[3]

Plastics and rubber: Brucite serves as an environmentally friendly flame retardant additive, reducing the flammability of thermoplastic materials and replacing traditional halogenated compounds, considered pollutants.

Recent advances in advanced materials and green technologies have significantly expanded the potential for brucite:

- **Carbon capture and storage (CCS):** The carbonation reaction of brucite is being studied as a method for permanent CO_2 sequestration. $Mg(OH)_2$ can fix CO_2 in the form of stable $MgCO_3$, contributing to the reduction of industrial emissions.
- **Functional nanomaterials and composites:** $Mg(OH)_2$ and MgO can be obtained in the form of nanoparticles, used in catalysis, dielectric materials, anti-corrosive coatings and materials with antibacterial properties.
- **Decontamination and water treatment:** due to its absorption and neutralization capacity, $Mg(OH)_2$ is used to remove heavy metals, phosphates and acidic compounds from industrial and municipal waters.[2],[9],[11],[12].
- **Batteries and energy storage:** MgO is being investigated as a dielectric material and as a component in magnesium batteries, offering a safer and cheaper alternative to lithium-based systems.
- **Sustainable composite materials: $Mg(OH)_2$ is integrated into biodegradable polymers (PLA, PHA) to increase** thermal stability and reduce fire risk, without compromising mechanical properties.

Current trends indicate a clear orientation towards the complete and ecological valorization of brucite. Advances in the field of calcination processes with reduced energy consumption, as well as the implementation of fluidized bed and flash calcination plants, allow for increased yield and reduced production costs. At the same time, the integration of mineral carbonation and waste heat recovery processes into brucite processing flows opens up the possibility of developing zero-emission technologies.[8]

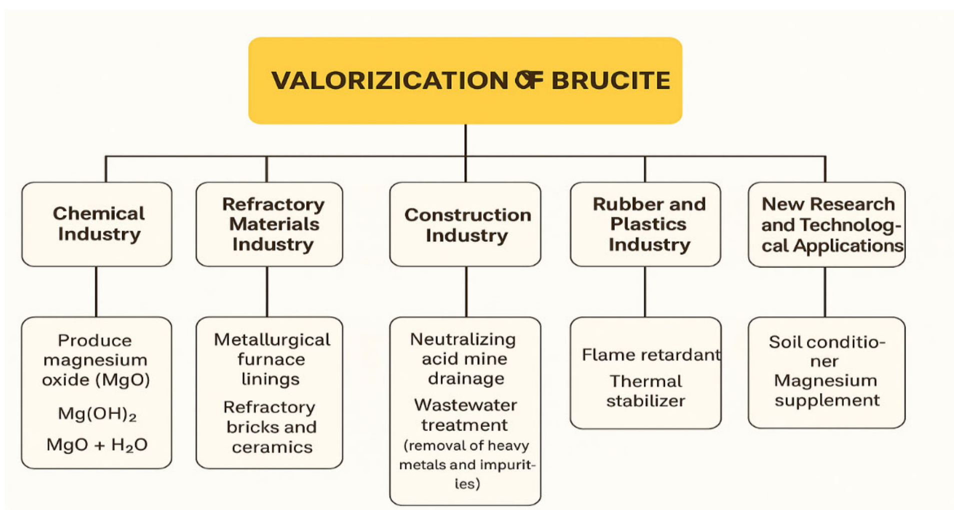

Figure 2. Directions for brucite utilization

In this context, this paper aims to analyze the main directions of industrial exploitation of brucites, emphasizing the technological aspects related to extraction, purification, calcination and chemical transformation. It also evaluates the opportunities for integrating these processes into sustainable, low-carbon industrial systems, in line with the principles of circular economy and energy efficiency.

3. PROCESSING TECHNOLOGY OF THE BRUCITIC LIMESTONE
Case study - The deposit from Budureasa, Romania

The Budureasa deposit is recognized as one of the main occurrences of brucite ($Mg(OH)_2$) associated with dolomites in the Apuseni Mountains; lenticular deposits occur, sometimes with significant Mg content (areas with important brucite). [6],[7]

Preliminary analyses show a typical mixed composition (calcite, dolomite, brucite) and an average MgO content in studied samples of ~22–23% (signaling potential for processing).

In figure 3 are rendered also the main products and their features.

The best results for coarse or grinded material were obtained with Mozley concentrator. The concentrate has 37-39% MgO and the weight recoveries were 12-15%. In figure 2 is presented the technological flow sheet for brucitic limestone processing, in order to obtain magnesia with purity around 98% and two secondary products rich in calcium carbonate as final products too.

The proposed technology assures a total capitalization of the rough material, without tailings and without negative effects on environment. The physical and thermo-chemical operations assure a global efficiency of 85% and a low energetically consumption due to an efficient calcinations and solubilization circuit. .

The technical solution is available for the processing of a brucitic limestone with 22-25% MgO. The first part of the technology allows to get a concentrate with 35-40% MgO after two grinding stage and a pneumatic concentration. The concentrate is calcinated at 500-600 ^{o}C, when the brucite are decomposed to magnesia, very reactive in regard with the carbon dioxide.

The brucitic concentrate calcined, so called “activated concentrate” is solubilized with carbon dioxide at 2-5 atm pressure. The solubilisation result is the magnesium bicarbonate. After a filtration, results a rich solution in magnesium bicarbonate and a secondary product rich in limestone.

The solution of magnesium bicarbonate is boiled 20-30 minutes for the precipitation of magnezite. The suspension is filtered at 80^{o}C, resulting a magnesium concentrate with a purity of 98%.

The main advantages of this technology are:

- an energy consumption reducing;
- a high efficiency of the magnesia recovery;
- a decreasing of ratio solubility by addition the magnesium ions in excess through the time of reaction reducing.

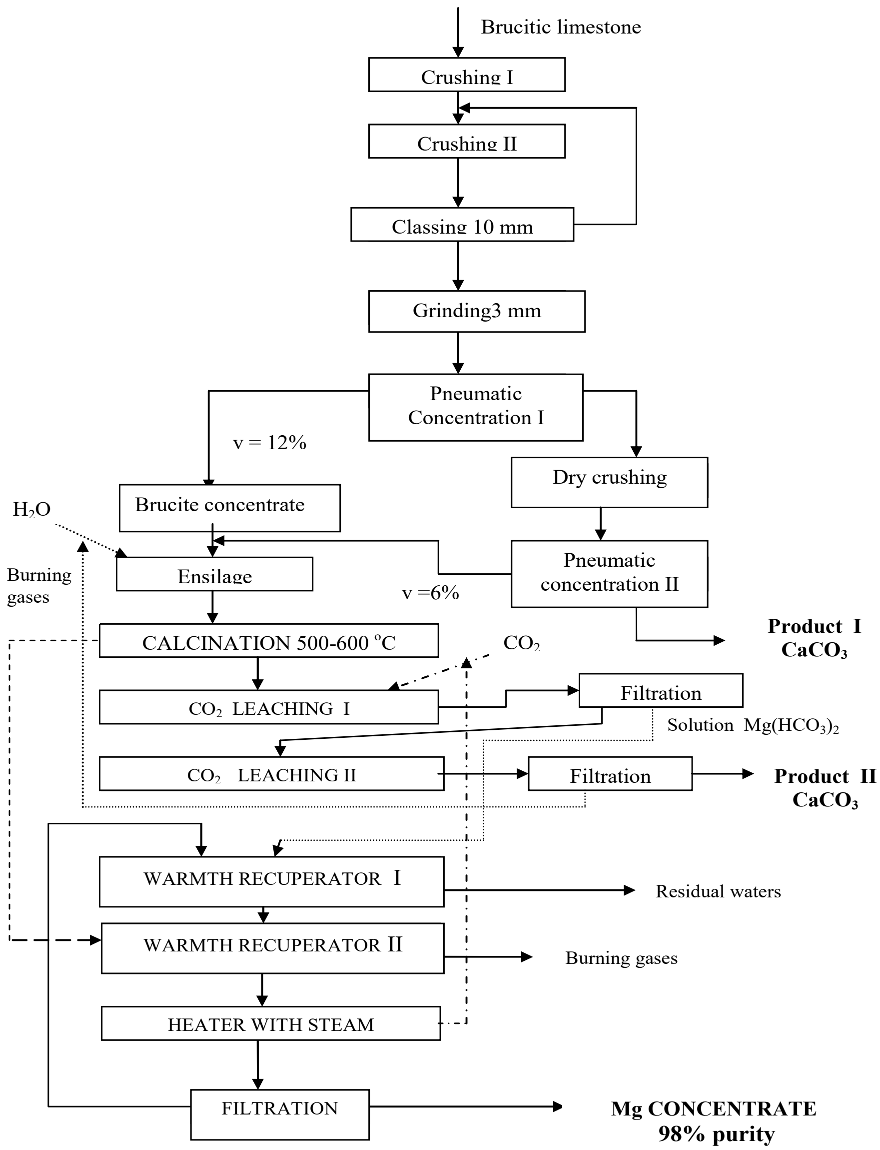

Figure 3. Technology for magnesia getting

4. CONCLUSIONS

The recovery of brucites depends on the cost-benefit ratio of the process, the quality of the raw material and the proximity to the markets. The implementation of modern calcination technologies with energy recovery and the use of renewable sources (biogas, hydrogen) can significantly reduce the carbon footprint of the process.

The integration of the extraction, calcination and carbonation processes into a circular system allows for a complete technological chain, in which waste and emissions are reintroduced into the production circuit, contributing to the objectives of industrial sustainability.

Advantages of brucite valorization

- Reduction of industrial waste
- Conservation of natural magnesium resources
- Environmentally friendly and non-toxic material
- Contribution to sustainable and circular economy practices

Economically, the global demand for high-purity MgO and environmentally friendly fire retardant additives is growing, driven by strict fire safety regulations and the transition to clean materials. Thus, the valorization of brucites can represent a strategic resource for emerging industries based on sustainability and innovation.

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OCCUPATIONAL RISKS IDENTIFICATION AND ASSESSMENT IN PETROLEUM PRODUCTS ANALYSIS LABORATORY WITHIN AN OIL AND GAS COMPANY

Roland Iosif MORARU [1]

Abstract: *Work accidents in the world generate damages that significantly affect national economies (losses having the order of billions of Euros worldwide, annually), but primarily affect human destinies. The assessment of risks associated with economic activities, be they production, transport, services, HORECA or tourism, etc. constitutes the basic and - at the same time - of utmost importance - stage in the substantiation of pragmatic, realistic and feasible measures to control the hazards inherent in any occupational field. This article presents to those interested a relevant synthesis of a research carried out in order to highlight and quantify the hazards - and implicitly the associated risks - generated by the specific characteristics of the environment and work equipment used in a quantitative and qualitative analysis laboratory in a relevant Oil and Gas company operating nationally.*

Key words: *accident at work, hazard identification, risk evaluation and assessment, oil and gas, petroleum analysis, laboratory*

1. INTRODUCTION

This work summarizes the analysis/assessment of occupational accident and illness risks for middle management workers of a nationally representative company operating in the "Oil and Gas" field. Within the unit, a rigorous analysis of the system for identifying, assessing and evaluating hazards and subsequently risks in the field of occupational health and safety of equipment, personnel and the entire work and management process is required, taking into account the hazards and all specific activities undertaken at the company level. [1].

Occupational risk assessment involves identifying - as far as possible **- all** hazards within the system under analysis and quantifying their magnitude, based on the combination of the two relevant parameters: the severity and frequency of the maximum possible consequences for the human operator's body [2]. In this manner, partial risk levels are established for each identified risk factor, as well as global risk levels for the entire functional unit being assessed [3].

The legislation establishes risk assessment as the primary responsibility of the employer and the staff of the OSH departments, to assess the risks of accidents and illnesses at the workplace and to propose adequate protection measures, which will constitute the annual prevention and protection program, with assistance from specialized institutions. [4]; "risk assessment involves identifying all risk factors that

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may lead to accidents or occupational diseases and determining the level of risk, based on the combination of severity and probability of the maximum foreseeable consequence" [5], [6].

In order to facilitate compliance with the obligations provided by law and the provisions of the ISO 45001 standard, the company's management assessed the risks at the workplace, using the INCDPM method in this paper and the SUVA method through an application available at the company level [7]. The INCDPM method was approved in 1993 by the Ministry of Labor and Social Protection and has been tested to date in most industrial fields [8].

2. MATERIAL AND METHOD

2.1. General presentation of the company under investigation

RQC Company, whose main activity is the performance of technical testing and analysis (CAEN code 7120), is the laboratory company established in 2004 within the Petromidia refinery, which quickly became a benchmark on the Romanian market for petroleum product and environmental factor analysis. Through its laboratories, accredited by RENAR in accordance with SR EN ISO/ IEC 17025:2018, RQC offers the full range of analysis services for petroleum products (solid, liquid, gaseous), for environmental factors (water, air, soil, waste), workplace noxious assessment, petrochemical product analysis, as well as biofuel analysis (biodiesel and bioethanol).

The company's mission is to provide customers with services at a high level of quality and accuracy, within the requested deadline, in compliance with the norms for the prevention and elimination of environmental pollution, as well as with the legal requirements regarding labor protection and employee health. Professional experience, high-performance technical and technological equipment and certifications from professional institutions position these laboratories as the first choice in the field of industrial analysis for the entire area of Dobrogea.

The tests conducted by RQC are recognized in over 70 countries around the world, signatories to the international recognition agreements concluded by RENAR (I.L.A.C., M.L.A., E.A.). This organizational entity was the first company in Romania to complete the implementation of a laboratory data management program (LIMS), as part of the strategy to automate and optimize laboratory processes and operations. The human resource is qualified and constantly growing. Most of the staff has over 10 years of experience in the field of activity and new staff are still being trained ("Toghether we grow" - internship programs). The total number of RQC employees, at the end of 2024, reached 208. RQC Company aims to increase the level of performance and competence of its personnel through training, using existing resources. Participation in external training courses in the technical and quality fields is carried out according to annual training plans. Maximizing opportunities for improvement within the organization can be observed through "cross training" programs between RQC laboratories (multiple skills-training employees for flexible response to changing production schedules).

Material resources (infrastructure): the condition of buildings, measuring and monitoring equipment, information systems, means of transport, communication, utility networks is periodically evaluated by QHSE managers based on the Audit/Inspection Programs, to maintain compliance and continuous improvement. The company's strategy is to constantly improve the activity, through the acquisition of new and high-performance equipment [9].

2.2. Petroleum Products Laboratory

This laboratory offers the full range of tests for product quality analysis, according to product requirements in national and international standards. The laboratory provides complete analysis services for solid, liquid and gaseous petroleum products. The Petroleum Products Laboratory is divided into specific technical units (chromatography UT, special analysis UT, manufacturing UT, analytical UT), thus covering the full range of analyses for all types of samples, such as:

a. Technical unit “manufacturing””

Performs physical tests for liquid petroleum products (density, distillation, viscosity, oxidation stability of gasolines, ignition, freezing, etc.), tests for the ignition behavior of gasolines and diesel fuels (octane number and cetane number) and other tests (figure 1).

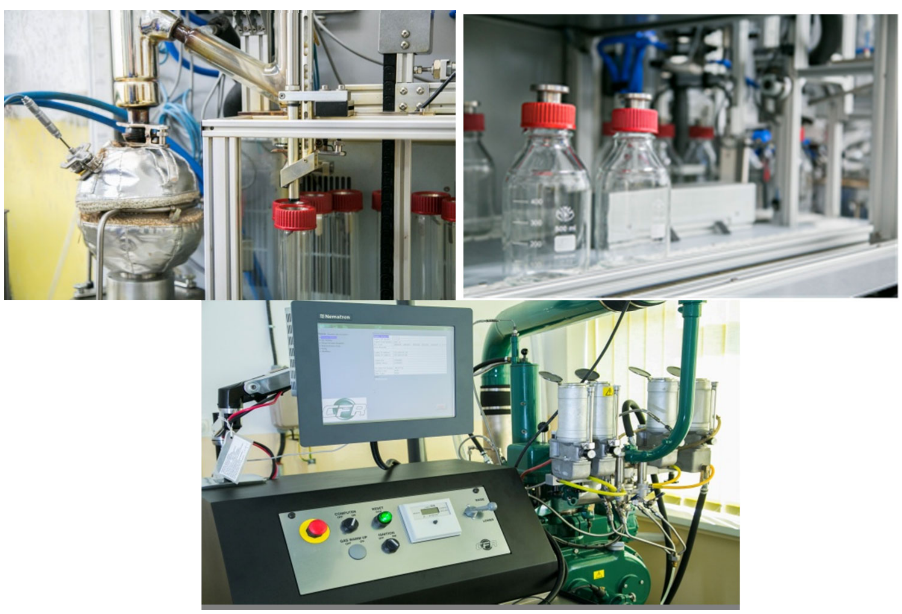

Figure 1. Experimental stands used in the technical manufacturing unit

b. Technical unit "chromatography"

Performs chromatographic analyses to determine the composition of gaseous and liquid petroleum products, determine the classes of hydrocarbons in gasoline, determine the content of benzene and oxygenated compounds in gasoline, determine polycyclic aromatic hydrocarbons, total in diesel, oil, etc. (Figure 2).

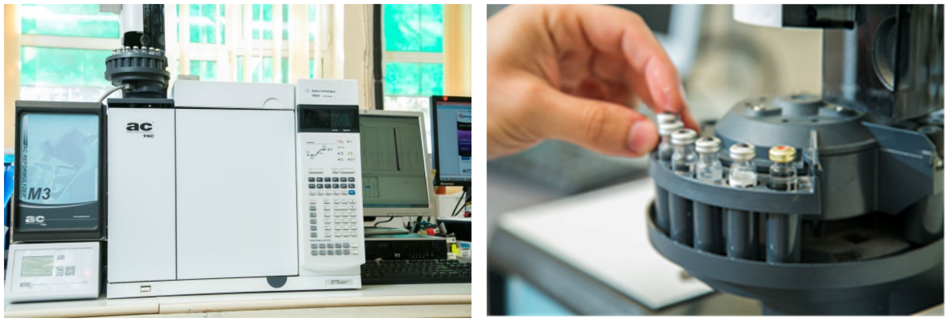

Figure 2. Instrumental techniques from the "chromatography" technical unit

c. Technical "analytical and special" unit

Performs special and spectral analyses for liquid, gaseous and solid petroleum products (determination of sulfur content, oxidation stability for diesel fuels, gum content, residual carbon, metal content, hydrocarbon groups in liquid samples, etc.), figure 3.

Figure 3. Measuring devices and systems related to the "analytical and special" technical unit

In recent years, RQC has developed the necessary skills in the market for elemental coal analysis. Coal-specific analyses (power, moisture, volatility, ash, sulfides, metals) are the main analyses used in calculating combustion power and controlling gas emissions into the atmosphere. At the same time, RQC laboratories also perform analyses for natural gas/blast furnace gases, in order to calculate the greenhouse gas emission factor (figure 4).

New trends in the market for the analysis of non-polluting products (biofuels) have led RQC to develop its analysis capabilities for biodiesel and bioethanol. The Petroleum Products Laboratory is accredited for sampling at the pump nozzles of fuel distribution stations and other commercial distribution points, according to the SR EN 14275:2013 standard.

Figure 4. Apparatus used for the analysis of natural gas/blast furnace gases, in order to calculate the greenhouse gas emission factor

The laboratories implement the integrated quality-environment-occupational safety system, in accordance with the standards ISO 9001:2015 - Quality Management System, ISO 14001:2015 - Environmental Management System and ISO 45001:2018 - Occupational Health and Safety Management System. At the same time, in order to increase the quality of the services offered, RQC laboratories have been carrying out, since the beginning of their activity, both internal quality checks and external checks, by participating in various interlaboratory tests, at national and international level. The continuous efforts made to improve quality are confirmed by the excellence certifications obtained through these participations.:

- CALITAX (Spain), South-Eastern European Interlaboratory Study "Water Analysis" (Serbia and Montenegro), LGC Standards (UK), IELAB (Spain) for water, air and soil analysis;
- InterTek Caleb Brett (Olanda), Institute for Interlaboratory Studies (Olanda) și British Petroleum Laboratories - Air BP (Great Britain) – for petroleum product analysis;
- ASTM International USA – for polymer analysis.

The distribution of workers by jobs/positions is summarized in table 1.

Table 1. List of workplaces for which occupational health and safety risk assessment was carried out

No.	Department	Workplace	No. of workers
1.	**Navodari Petroleum Products Laboratory**	Chemist II - Analytical Technical Unit	15
2.		Special analysis laboratory technician	2
3.		Manufacturing Lab Technician I	11
4.		Manufacturing Lab Technician II	11
5.		Laboratory Chemist - Octane Number Manufacturing Technical Unit	5
6.		Oil foreman	1
7.		Laboratory assistant taking samples	10
8.		Laboratory chemist - Chromatography Technique Unit	14
9.		Chemist laboratory assistant - Expedition Technical Unit (day shift)	1

No.	Department	Workplace	No. of workers
10.		Chemist laboratory assistant - Expedition Technical Unit (shift schedule)	5
11.		Manufacturing technical unit coordinator	1
12.		Coordinator of the Analytical Technical Unit	1
13.		Coordinator of the Special Analyses Technical Unit	1
14.		Technical Unit Coordinator Expedition	1
15.		Chromatography technical unit coordinator	1
16.		Metrological measurements analyst	1
17.		Test Manager	5
18.		Driver	2
19.		Petroleum Products Laboratory Manager	1
20.	**QHSE**	QHSE Supervisor	1
21.		QHSE specialist	2
22.	**Total**		**23**

2.3. The risk assessment method applied

The assessment of occupational safety and health risks is a fundamental process aimed at identifying, evaluating, and mitigating potential hazards in the workplace that could harm workers' physical or mental well-being. It forms the cornerstone of effective risk management and is crucial for ensuring compliance with regulatory standards, fostering a culture of safety, and improving organizational productivity [10]. OSH risk assessment serves multiple purposes:

- **Protecting worker health and safety** by preventing accidents, injuries, and illnesses.
- **Compliance** with legal and regulatory frameworks.
- **Reducing costs** associated with workplace incidents, including insurance premiums, legal liabilities, and lost productivity.
- **Promoting employee morale** by demonstrating a commitment to worker welfare.

The standard process typically involves four key steps [11]:

- **Hazard Identification**: Recognizing sources of potential harm, including physical, chemical, biological, ergonomic, and psychosocial hazards.
- **Risk Analysis**: Determining the likelihood and severity of harm resulting from each identified hazard.
- **Risk Evaluation**: Comparing the estimated risks against predefined criteria to prioritize actions.
- **Risk Control**: Implementing measures to eliminate or minimize risks, following the hierarchy of controls—elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE).

Risk assessments can be conducted using various qualitative and quantitative methods, such as: Checklists and observation; Job safety analysis (JSA); Failure mode and effects analysis (FMEA); Hazard and operability studies (HAZOP); Risk matrices. Common challenges include:

- Inadequate training or awareness
- Poor documentation or follow-up
- Evolving risks due to changes in technology, work practices, or workforce composition
- Underestimation of psychosocial risks, such as stress or burnout

To enhance the effectiveness of OSH risk assessments:

- Engage workers in the assessment process
- Ensure continuous monitoring and periodic review
- Integrate risk assessments into overall safety management systems
- Provide regular training and clear communication

A robust OSH risk assessment is not a one-time activity but an ongoing commitment to workplace safety and continuous improvement [12]. By systematically identifying and addressing risks, organizations can create safer, healthier, and more resilient work environments [13].

The risk assessment method developed by INCDPM Bucharest is an analytical and semi-quantitative approach, approved by the Ministry of Labor and Social Protection in 1993, aimed at quantitatively determining the level of risk for a specific job, sector, department, or enterprise. This method is based on the identification of all risk factors within the analyzed system, using pre-established checklists, and on quantifying risk by combining the severity and frequency of the most foreseeable consequence.

The application of the method results in two summary documents: the "Risk Assessment Sheet" and the "Proposed Measures Sheet," which serve as a foundation for prevention programs targeting work accidents and occupational illnesses. The method can be applied both during the design phase of workplaces and during their operational phase, involving multidisciplinary evaluation teams [14].

The safety level of a workplace is considered to be inversely proportional to the level of risk, and the assessment involves prioritizing the identified risks and determining appropriate preventive measures [15].

This analysis tool retains its validity and utility, despite its quasi-exhaustive use in occupational risk assessments in Romania and - especially - despite its euphemistically inappropriate use by a large majority of practitioners in the field, nationally.

Considering that the representatives of the Romanian Labor Inspectorate continue to favor the use of the method, as well as its evident efficiency in facilitating the hierarchy of sources of danger that generate risks in work systems encountered in work environments characteristic of the vast majority of companies, in this research we resorted to its application [16], [17].

This was done with great care, however, from the perspective of the correct application of the predefined tools, the aggregation and - especially - the interpretation of the results obtained. Increased attention was paid to the assessment team's efforts in the phase of identifying risk factors, in the quantitative estimation of the maximum foreseeable consequence and in the allocation of the likelihood classes associated/assigned to each of the individual/specific risks identified [18], [19].

3. ANALYSIS AND PRIORITIZATION OF OCCUPATIONAL RISKS. CASE STUDY: METROLOGICAL MEASUREMENT ANALYST

The Metrological Measurements Analyst within the Petroleum Products Analysis Laboratory, Metrologist Specialist I, within RQC LLC, ensures the metrological calibration activity and supervises the maintenance activity of the laboratory equipment, used to determine specific quality indicators, to ensure quality in accordance with the requirements of the applicable standard. The component elements of the evaluated work system are shown in Table 2.

Table 2. Relevant components of the analyzed work system

Means of production	Working Task	Work Environment
➢ office furniture; ➢ office equipment (computer) ➢ laboratory utensils (burettes, pipettes, laboratory glassware) ➢ personal protective equipment; ➢ Atomic absorption apparatus AAS Vario 6 ➢ Calorimeter PARR 6200 ➢ Spectrophotometer CINTRA ➢ Microwave system TOP wave ➢ Analytical balance AB 204-S ➢ KERN balance type EW 1500 2 M ➢ BINDER ED 53 oven ➢ LABLINE oven ➢ SINDIE sulfur analyzer; ➢ lubricity determination device, type HFR 2; ➢ KF 831 coulometer; ➢ FIA apparatus; ➢ apparatus for determining oxidation stability (diesel);	✓ Records data regarding the evaluation of providers of maintenance, repair, calibration, verification of measuring and testing equipment, control of measuring and testing equipment with radioactive sources (e.g. X-ray sources); ✓ Takes over the accompanying documents of the delivered materials and keeps/archives them appropriately; ✓ Participates in the reception of supplied products; ✓ Ensures metrological verification within the laboratory in order to carry out tests in accordance with the requirements of the procedure in force: - prepares calibration/ metrological verification programs; -monitors the implementation of calibration/ metrological verification programs; - makes specific records for measuring and testing equipment according to the rules in the procedures; - prepares and updates the list of measuring and testing equipment in the laboratory;	The Petroleum Products Laboratory within the RQC-LLC Company, a member of the KMGI group, is located on the Petromidia Platform and is of the "on shore" type, located in the vicinity of the crude oil and intermediate products processing facilities; The metrological analyst's activity is carried out mainly indoors (laboratory building, 90-95%); • working conditions are specific to administrative spaces and testing and trial laboratories (finished and interphase petroleum products). • natural and artificial lighting; • natural and artificial ventilation; • air currents on the work route; • polluted air from neighboring workplaces. • Reagents: Hydrochloric acid, Hydrofluoric acid, Phosphoric acid, Potassium iodide, Ascorbic acid, Potassium antimony tartrate hemihydrate, Zinc oxide, Petrol, Hydrazine sulfate, Oil, Sodium chloride, Potassium

➢ METTLER DL 25 titrator; ➢ MILLIPORE vacuum pump; ➢ ABBE refractometer; ➢ titrator "TITRANDO 808; ➢ microscope N 334 with micrometric subler; ➢ apparatus for determining coke MCRT-140; ➢ X-ray spectrometer Chlora; ➢ conductivity meter MLA 900; ➢ titration apparatus KARL FISCHER DL 38; ➢ electric furnace Carboite; ➢ spectrometer Epsilon; ➢ analyzer for determining sulfur, chlorine, nitrogen, type MULTI EA 3100; ➢ bath for determining gum content; ➢ sulfur analyzer type TS 4000; ➢ sulfur analyzer type Explorer; ➢ digital analyzer of salts in crude oil type SC 960; ➢ potentiograph METROHM; ➢ calcination furnace LABORTHERM TYPE L 9/11 /B 170; ➢ ultrathermostat U 15C;	- displays the inventory of measuring and testing equipment in the laboratory rooms; - makes the periodic verification plan for measuring and testing equipment; - monitors the implementation of repairs for measuring and testing equipment; checks and is responsible for the existence of periodic calibration/ calibration books and repair/ maintenance books Manages records regarding control activity in order to maintain the history of measuring and testing equipment in the laboratory: - maintains records regarding the control of measuring and testing equipment; - maintains records in the records of measuring and testing equipment; - maintains records necessary for software records; ✓ Collaborates with other designated employees to centralize/integrate available data at the level of technical units regarding EMI calibration/verification works. ✓ Updates documentation according to standards/reference documents (e.g. "Measurement Results Traceability Policy" RENAR) regarding traceability provided through calibration, reference materials (RMs) and certified reference materials (CRMs). ✓ Makes available the available evidence appropriate for	chloride, Boric acid, Bromophenol blue, Bromocresol green, Bromothymol blue, Methyl red, Sodium thiosulfate, Cadmium acetate, Sulfuric acid, Sodium hydroxide, Potassium hydroxide, Isopropyl alcohol, Isooctane, Acetone, Sodium biphenyl, Nitric acid, Silver nitrate, Potassium bromate-bromide, Heptane, Toluene, Hydranal coulomate, Petroleum ether, Wijs reagent, Dichloromethane, Cyclohexane, Perchloric acid, Acetic acid, Sodium acetate, Crystal violet indicator, Phenolphthalein, Methyl orange, Xylene, Methyl alcohol, Butyl alcohol, Potassium iodide, Sodium chloride, Calcium chloride, Magnesium chloride, Zirconium propoxide solution, Silica gel with humidity indicator, Ethyl alcohol, Starch, Ethanolamine, Barium hydroxide, Ammonia, Ammonium chloride, Lead acetate, Hydranal composite ethanol, acetone, n-pentane, n-heptane, 3 pentanol, nanodecanoate. • Petroleum products: gasoline, diesel, fuel oil, crude oil, oil, gas, petroleum coke, petroleum sulfur, light naphtha, biodiesel, bioethanol, MTBE, calor economic 3;

➢ particle counter AVCOUNT TYPE SA 1000-0; ➢ Gas Chromatograph ➢ Liquid Chromatograph ➢ Vapor pressure determination apparatus ➢ Corrosion apparatus ➢ Huber CC 805 Frigistat ➢ Ultrasonic bath; ➢ Heating sleeve;	metrological traceability and declared measurement uncertainty to the accreditation body that must evaluate this evidence.	• Gases: oxygen cylinders, helium, argon, nitrogen, acetylene.

The risk assessment sheet related to the analyzed job/functional unit is shown in the table 3, where the meaning of the notations is: *WSE - Work system element; IR - identified risk; RF – risk factor; MC - Maximum consequence; S - Severity; Likelihood; RL - Risk level; WE - Working equipment; OE - Occupational environment; WT - Working task; HF - Human factor; N-negligible; LTI – Lost Time Injury from 3 to 45 days; INV invalidity; D – death.*

Table 3. Job evaluation sheet: Metrological Measurements Analyst

Unit: RQC		***WORK PLACE RISK ASSESSMENT CARD***	**Number of exposed individuals: 1**			
Petroleum Products Laboratory			**Exposure length:** 8 hours/shift			
Metrological Measurements Analyst			**Assessment team:** Laboratory manager; Worker representative; QHSE officer; Occupational medicine doctor			
WSE	**IR**	**The concrete form of manifestation of risk factors (description, parameters)**	**MC**	**S**	**L**	**RL**
WE	Mech. RF	1. Means of transport in traffic while commuting to/from work (collision);	D	7	1	3
		2. Grabbing hands and clothing when working on printers, scanners, etc;	LTI 3-45	2	1	1
		3. Parts, moving objects - objects that move, tip over, drawers that open, swivel office chairs - injuries to the body;	LTI 3-45	2	1	1
		4. Failures in laboratory equipment or failure and breakage of glassware assemblies used to analyze products;	D	7	1	3
		5. Lack of water (power cut-off) in case of accidental splashes in the eyes or on the skin with petroleum products or reagents;	INV. III	4	1	2

		6. Monitor malfunctions leading to excessive emission of electromagnetic radiation;	LTI 3-45	2	2	2
		7. Malfunctions of radiation sources present in work equipment (example: X-ray tube - sulfur content determination equipment);	LTI 3-45	2	2	2
		8. Falling/overturning of the monitor, central unit, furniture items on limbs or fingers, due to their unstable positioning;	LTI 3-45	2	1	1
		9. Overturning/rolling of storage containers, parts, tools and subassemblies from storage shelves by accidental contact due to lack of fall protection;	LTI 45-180	3	2	2
		10. Overturning, falling or leaking of laboratory vessels and sample containers - splashing/scalding/irritations/dermatological allergies;	LTI 45-180	3	2	2
		11. Movements under the effect of gravity: sliding, rolling, overturning, free fall of stored materials, laboratory equipment, etc;	LTI 45-180	3	3	3
		12. Falling of objects from a height - hitting the body, hitting the head;	LTI 45-180	3	1	2
		13. Electrical cables, extension cords on access paths, with disorderly routes - danger of falling due to tripping;	LTI 45-180	3	1	2
		14. Accidental spill of petroleum products on the floor - danger of slipping;	LTI 45-180	3	2	2
		15. Accidental hand injuries caused by office accessories (cutter, hole punch, stapler, etc.);	LTI 3-45	2	1	1
		16. Pressure gauges without timely metrological verification, unsealed or not marked in red (p max, inlet-outlet, O2 = 200/10 bar, respectively C2H2 = 25/1.5 bar);	D	7	1	3
		17. Fixed connections/poor quality materials for technical gases that supply the equipment (e.g. oxygen, hydrogen, acetylene, nitrous oxide, etc.);	D	7	1	3
	Thermal RF	18. Accidental contact with very hot surfaces of equipment (t ≈ 900 °C);	LTI 3 – 45	2	5	3
	Electrical RF	19. Indirect electric shock through spillage, leakage of liquid substances into the housings of electrical appliances;	D	7	1	3
		20. Electric shock through direct contact, in case of damage to the insulation of the cables related to the equipment or due to the use of ungrounded power sources;	D	7	1	3
		21. Non-compliant, improperly installed sockets - danger of electric shock;	D	7	1	3

		22.Electrical installation in normal construction instead of explosion-proof - danger of explosion, fire;	D	7	1	3
	Chemical RF	23. Generation of static electricity in potentially explosive environments;	LTI 3 – 45	2	5	3
		24.Poisoning by accidentally touching a lethal concentration of toxic vapors in the laboratory. Oil residues accumulated in uncovered containers in work areas; direct contact – dermatitis (chemical burns);	D	7	1	3
		25. Corroded gas installations that supply gas bulbs used for heating during analyses - risk of fire, explosion.	D	7	1	3
		26. Hydrogen leaks from defective cylinders - risk of explosion.	D	7	1	3
		27. Danger of fires/explosions in the vicinity, the tank farm or installations within the oil platform, which may affect the laboratory building.	D	7	2	***4***
OE	Physical RF	28. Air temperature: high/low depending on the season for occasional field trips;	LTI 3-45	2	2	2
		29. Air currents formed by opening windows and doors for better ventilation in the laboratory or during trips outside.	LTI 3-45	2	2	2
		30.Air currents formed in rooms due to inadequate door and window seals, or ventilation;	LTI 3-45	2	2	2
		31. Inadequate temperature and humidity regulation in air conditioning systems.	LTI 45-180	3	1	2
		32. Insufficient artificial lighting in certain areas;	LTI 3-45	2	2	2
		33. Noise produced by work equipment, ventilation, etc	LTI 3-45	2	2	2
		34. Slipping on wet, icy surfaces (floors, stairs) when moving around the laboratory, on stairs or outside;	LTI 45-180	3	2	2
		35. Electromagnetic radiation generated by monitor operation.	LTI 3-45	2	3	2
		36. Formation of pneumoconiogenic dusts during cleaning at the workplace.	LTI 3-45	2	3	2
		37.Natural disasters (lightning, floods, wind, hail, landslides, rockfalls, land or tree collapses, earthquakes,etc)	D	7	1	3
		38.Slipping due to improper footwear.	INV. III	5	1	3
	Chemical RF	39.Smoke, gases, toxic, flammable vapors from neighboring workplaces.	D	7	1	3

	Biological RF	40.Microorganisms in suspension in the air from unclean air conditioner filters - allergies, respiratory problems.	LTI 3-45	2	2	2
		41.Presence of dangerous animals and insects - bites, scratches, stings (stray animals, mosquitoes, ticks), etc).	D	7	1	3
		42. Contamination with SARS Cov-2 type viruses etc. through contact with contaminated people.	D	7	1	3
WT	Inadequate WT content	43. Incorrect or outdated operations, rules, work procedures, erroneously received instructions for carrying out the activity.	D	7	1	3
		44. Failure to update job descriptions, work instructions and procedures, fire evacuation plans, etc. in relation to changes that have occurred.	D	7	1	3
		45.. Performing tasks and operations ordered by the supervisor, for which he/she does not have the appropriate preparation/qualification/training	D	7	1	3
		46. Lack/non-processing of technical data sheets for substances and reagents used in the laboratory and failure to take the security measures required by the use of toxic substances with special regulations.	D	7	1	3
		47. Failure to signal or insufficient signaling of risks in the laboratory as well as failure to display evacuation plans.	LTI 45-180	3	3	3
		48. Failure to comply with the recommendations of the occupational physician when assigning work tasks, performing work at height without a medical certificate (fitness certificate - fit to work at height));	D	7	1	3
		49. Lack of training / Inadequate training of personnel regarding work instructions, risks of occupational accidents and illnesses, occupational health and safety instructions, first aid measures, fire prevention and extinguishing rules, how to intervene in emergency situations.	D	7	1	3
		50. Ambiguities and/or conflicts regarding the work task, perceived differently and resulting in wrong actions.	LTI 45-180	3	1	2
		51. Storage of materials to be shipped or coming from the supply process on the access routes within the laboratory premises .	LTI 3-45	2	5	3
	Physical overload	52. Dynamic effort when handling large masses (packaging laboratory equipment for shipment to the supplier in the calibration process).	ITM 45 – 180	3	5	***4***

		53. Predominantly "sitting" position during prolonged work on work equipment without taking into account the recommendations of the occupational medicine doctor - orthostatic strain.	LTI 3-45 zile	2	5	3
	Psychic overload	54. Psychological stress associated with risks in laboratories: risk of explosion, fire, intoxication, etc.	LTI 3-45	2	3	2
		55. Eye fatigue due to workload that requires prolonged computer work (not alternating with another type of activity). Overstrain of attention to repetitive short-cycle movements.	LTI 45-180 zile	3	4	3
		56. Psychological stress due to predominantly intellectual activity.	LTI 3-45	2	3	3
		57. High workload and performing tasks against the clock during busy periods - fatigue to exhaustion, mental stress, involuntary mistakes.	LTI 45-180	3	1	2
HF	Wrong actions	58. Using laboratory equipment for purposes other than those for which it was designed.	LTI 45-180	3	1	2
		59. Incorrect and unergonomic position on the chair, while working in a seated position.	LTI 3-45	2	5	3
		60. Failure to observe the minimum visual distance from the computer monitor.	LTI 3-45	2	3	2
		61.Nerespectarea pauzelor de lucru la birou/calculator, ceea ce poate duce la afecţiuni dorso lombare si optice;	LTI 45-180	3	2	2
		62. Potential poisoning by eating in laboratory workrooms;	LTI 45-180	3	3	3
		63. Using laboratory glassware for drinking or eating.	DECES	7	1	3
		64. Improper handling of reagent containers and/or sample containers.	LTI 45-180	3	3	3
		65. Use of petroleum products and reagents for purposes other than testing (cleaning clothes, cleaning objects, cleaning nails, etc.)	INV. II	5	1	3
		66. Using open fire/smoking in unauthorized places.	D	7	1	3
		67. Interventions to the equipment during its operation.	D	7	1	3
		68. Carrying out unauthorized interventions on electrical installations or other works by laboratory personnel.	D	7	1	3
		69. Failure to follow hygiene rules before eating and smoking (washing/disinfecting hands).	LTI 3-45 zile	2	2	2
		70. Carrying out operations unforeseen by the job: travel/stationary in dangerous areas, prohibited, etc.	D	7	1	3

		71. Leaving the workplace unannounced. Travel with a risk of falling from a height due to imbalance, slipping (on access stairs, on platforms, etc.)	LTI 3-45	2	2	2
		72. Falling at the same level due to imbalance: slipping, tripping or falling from a low height by stepping on a step (from footrests).	LTI 45-180	3	3	3
		73. Failure to comply with traffic rules within the company (accidents caused by means of transport) during occasional trips;	D	7	1	3
		74. Lack/disconnection/removal of protective devices on work equipment;	LTI 45-180	3	3	3
		75. Actions that may affect the safety and health of oneself and other participants in the work process: blocking access or escape routes, blocking access routes to hydrants, electrical installations and escape doors with various materials, failing to keep access and escape routes clean, blocking laboratory windows with furniture, shelves, equipment or other objects.	D	7	1	3
		76. Being at work under the influence of alcohol, drugs, medications (which may affect the worker's mental capacity) or in an advanced stage of fatigue.	D	7	1	3
		77. Entering areas with a risk of explosion with a switched-on mobile phone or ignition sources.	D	7	1	3
		78. Removing substances from the laboratory and conducting unauthorized experiments.	D	7	1	3
		79. Incorrect closing or failure to close gas supply installations - fires, explosions or poisoning.	D	7	1	3
		80. Presenting at work with symptoms specific to SARS CoV-2 contamination, employees do not respect communication flows.	D	7	1	3
	Omissions	81. Omission of operations that ensure safety at work;	D	7	1	3
		82. Poor hygiene of the workplace and annexes.	LTI 3-45	2	2	2
		83. The protective equipment and means of protection provided are incomplete.	LTI 45 -180	3	3	3
		84. Failure to declare belonging to groups sensitive to specific risks (pregnant women, lactating or breastfeeding women, young people under 18 years of age) in order to be protected against dangers that specifically affect them.	D	7	1	3
		85. Delays in performing periodic medical check-ups as scheduled (there is a risk of using medically unfit personnel).	LTI 45 -180	3	3	3

The overall risk level of the workplace is:

$$Nrg = \frac{2(4x4)+50(3x3)+27(2x2)+4(1x1)}{2x4+50x3+27x2} = \frac{594}{216} = 2.65$$

Remark: 2.65 < 3 – low risk level ; ≈ 3,5 – acceptable risk level (in România) < 4 – average risk level

The partial risk levels by risk factors for the workplace: "*metrological measurements analyst*" are graphically represented by the histogram in Figure 5, and the risk control measures located in the intolerable risk area are included in Table 3.

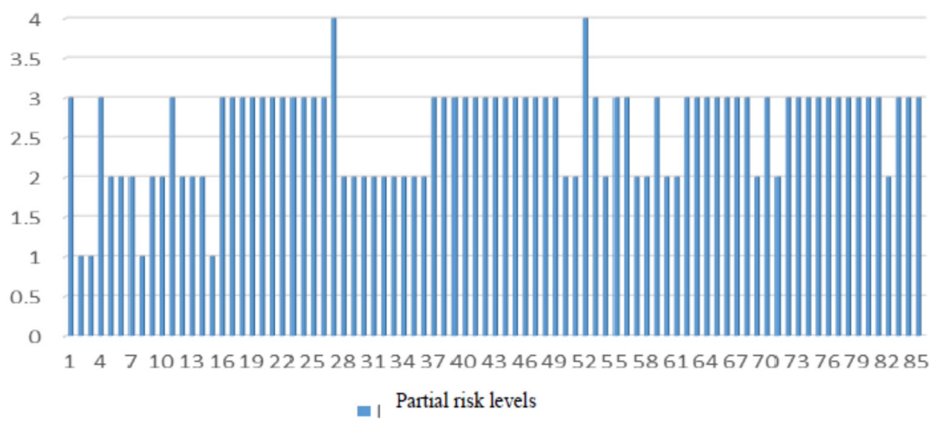

Figure 5. Histogram giving a depiction of the risk landscape in the working place

Table 3. Synthesis of proposed measures to control unacceptable risks

Risk factor	Risk level	Propesed measures
F27: Fires/explosions in the vicinity, the tank farm or installations within the oil platform, which may affect the laboratory building.	4	***Technical:*** - Repair and installation of all protective devices. ***Organizational:*** - Training workers and checking how safety rules are respected; -Providing workers with technical data sheets of products, substances and chemical mixtures involved in their activity and detailed knowledge of the work environment; -Entry with ignition sources (open fire), with inappropriate clothing or footwear is prohibited; -Working with fire will only be done based on a work permit and under strict supervision;
F52: Dynamic effort when handling large masses (packaging	4	***Technical:*** - Medical recommendation (occupational medicine) for alternating working positions (rest, sitting and movement) – establishing time intervals at which this is recommended; ***Organizational:***

laboratory equipment for shipment to the supplier in the calibration process).		- Equipping workplaces with spaces for body relaxation and chairs where the worker can sit periodically to prevent risks associated with vicious, forced positions, etc. -Respecting the breaks necessary for body relaxation and prevention of back and neck disorders. -Respecting the recommendations of the occupational medicine doctor for the prevention of back and neck disorders; - Benefit packages granted by the employer to employees (subscriptions to gyms, swimming pools, medical treatment facilities)

The global risk level calculated for the job "Metrological Measurements Analyst" is equal to 2.65, a value that places it in the category of jobs with a low risk level. The result is supported by the "Evaluation Sheet", from which it is observed that out of the total of 85 risk factors identified, only 2 exceed, as a partial risk level, the value 3, falling into the category of medium risk factors. The 2 risk factors that are in the unacceptable range are:

- **F27**: Fires/explosions in the vicinity, the tank farm or installations within the oil platform, which may affect the laboratory building – ***partial risk level 4;***
- **F52**: Dynamic effort when handling large masses (packaging laboratory equipment for shipment to the supplier in the calibration process).- ***partial risk level 4.***

In order to reduce or eliminate the 2 risk factors (which are in the unacceptable range), the generic measures presented in the "Proposed Measures Sheet" are necessary. The result is supported by the "Workplace Evaluation Sheet", from which it is observed that out of the total of 85 risk factors identified, 62.35% (53) may have irreversible consequences on the performer. Regarding the distribution of risk factors by generating sources, the situation is as follows:

- 32 %, factors specific to the means of production/work equipment;
- 17%, factors specific to the work environment;
- 18%, factors specific to the work task;
- 33%, factors specific to the human errors.

Based on the application of the same tool for analysis and evaluation of risk factors for occupational accidents and illnesses, within the research undertaken at the investigated company, the risks were also assessed for the jobs "Laboratory Manager" and "Technical Unit Coordinator". In accordance with the provisions of the national legislation in the field, harmonized - of course - with the acquis communautaire of the European Union, a prevention and protection plan was developed, from which an extract is presented regarding the three jobs studied in table 4.

Table 4. Prevention and protection plan intended to minimize/control unacceptable risks identified at the assessed workplaces

Risk	Technical measures	Organizational measures	Deadline	Responsible person
Movement of means of transport - hitting by means of transport while walking	Carrying out technical inspections within the deadlines established in the maintenance plan	Checking how personal protective equipment is used	Permanent	Workplace manager OHS Supervisor
Movements under the effect of gravity - sliding, rolling, overturning, free fall	Checking the correct way of storing and placing goods - fixing shelves	Marking and signaling of dangerous areas (prohibition and mandatory signs)	Permanent/ When appropriate	Workplace manager
High temperature of objects or surfaces of activity.	Granting PPE	Verification of knowledge and compliance with occupational safety requirements	Permanent	OHS Supervisor
Electric current / direct and indirect contact (defective sockets, stripped cables, unenclosed equipment, etc.).	Covering with materials, closing with electrically insulating housings	Checking the work environment and equipment before, during and after the work schedule	Permanent	Workplace manager Electrician Technical service
Natural disasters (earthquakes, etc.), flooding	-	Training workers on OSH requirements	Monthly	Workplace manager
Working in an orthostatic position with overloading of the lumbar and cervical spine and upper limbs; dynamic effort when handling goods during loading/unloadin g, as well as when placing	Providing appropriate PPE	Equipping workplaces with spaces intended for body relaxation and chairs on which the worker can sit periodically to prevent risks caused by dynamic effort	Permanent/ According to planning	Workplace manager

them on storage shelves				
Failure to use protective equipment	-	Checking knowledge of occupational safety requirements	Monthly	OHS Supervisor
Virus contamination due to the spread of various forms of Coronavirus (Sars Cov-2)	-	Personnel training on the risks caused by coronaviruses; Training with specific procedures/internal orders; Provision and maintenance of stocks of hygienic and sanitary materials		Workplace manager
Fall from the same level - by slipping, tripping, losing balance	Providing appropriate PPE (shoes with non-slip soles)	Marking and signaling of dangerous areas (prohibition and mandatory signs)	Permanent/ When appropriate	OHS Supervisor
Fall from height - by stepping on something, slipping, tripping or losing balance	Providing standardized/approved means of access to heights (ladders, platforms or platforms).	Checking knowledge of occupational safety requirements	Monthly	OHS Supervisor
Carrying out operations unforeseen by the workload / traveling and staying in dangerous areas	-	Checking knowledge of occupational safety requirements Periodic medical control	Monthly	OHS Specialist
Non-synchronization of operations / delays, advances	-	Periodic OHS training of workers regarding compliance with assigned work tasks.	Periodic	Workplace manager
Psychological demand – high work pace depending on	-	Checking the health of employees, ensuring	Permanent	Workplace manager

the day or busy periods		additional rest breaks		
Forced or vicious working positions	-	Proper organization of the work schedule (breaks included)	According to planning	Workplace manager

4. CONCLUSIONS

This work aimed at assessing the risks to the safety and health of laboratory personnel who carry out their productive activity within a representative and well-known company nationally in the field of laboratory analyses carried out in order to establish the quality of products delivered/produced by refineries in our country. The analyzed company is "leading edge" in terms of technical facilities, laboratory equipment used and the implementation of established procedures confirmed by certified bodies. The results obtained from the risk assessment were summarized in the "*Job Evaluation Sheet*" and the "*Proposed Measures Sheet*" for each analyzed job. The list of evaluated jobs is shown in Table 5.

Table 5. List of jobs evaluated in the investigated company

Crt.no.	File no.	Workplace	Overall risk level
1	F01	Metrological Measurements Analyst	2.65
2	F02	Head of Laboratory	2.78
3	F03	Technical Unit Coordinator	2.65

The overall risk level for the 3 jobs is:

$$N_{Sg} = \frac{\sum_{i=1}^{3} r_i \cdot Ng_i}{\sum_{i=1}^{3} r_i} = 2{,}69$$

The ranking of work places, depending on the overall risk level, is shown in table 6.

Table 6. Hierarchy of jobs, depending on the overall risk level calculated for each job

Crt.no.	File no.	Workplace	Overall risk level
1	F02	Head of Laboratory	2.78
2	F03	Technical Unit Coordinator	2.65
3	F01	Metrological Measurements Analyst	2.65

In accordance with the previous hierarchy, it is evident that in their completeness, the jobs subject to the analysis fall within the acceptable risk level (which is lower than the value of 3.5). These fall within the category of jobs with a low to medium risk level. The value of the aggregate global risk level per company NgS = 2.69 determines its classification in the category of those with a low to medium risk level. Whether it is a workplace, a department or a laboratory, the analysis allows the hierarchy of risks according to them and we can also size the efficient allocation of resources for prioritizing measures.

The final conclusion is that the main objective of any assessor in the operation of carrying out the assessment of occupational disease and injury risks is to eliminate the risk at source where possible. The company's overall strategy follows the assessment of OSH risks through various methods that do not depend on the size of the organization, but on the hazards associated with the activities, process-based approaches, hazard identification and risk assessment.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

THE ROLE OF SUSTAINABLE INVESTMENTS IN INCREASING ORGANIZATIONAL COMPETITIVENESS

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Abstract: *The article analyzes the role of sustainable investments in increasing organizational competitiveness in the context of global economic transformations and the intensification of pressures for the adoption of ESG (Environmental, Social, Governance) criteria. The main concepts associated with sustainable investments and their relationship with the economic, reputational and operational performance of firms are examined. The theoretical analysis is complemented by case studies on Romanian and international companies, highlighting the positive impact of ESG strategies on energy efficiency, social productivity and governance risk reduction. The results indicate that green investments represent an essential driver of innovation and competitive differentiation, in an economy marked by rapid changes and regulatory pressures. The general conclusion is that the responsible and strategic integration of sustainable investments becomes a determining pillar of long-term competitiveness, both at national and global levels.*

Key words: *sustainable investments, organizational competitiveness, ESG, competitive advantage, economic performance*

1. INTRODUCTION

In the context of global economic transformations and increasing pressures regarding environmental protection and social responsibility, sustainable investments have become a central element of modern organizational strategies. Internationally, the adoption of ESG (Environmental, Social, Governance) principles is increasingly influencing the development directions of companies, the way they attract capital and their ability to remain competitive in an environment characterized by uncertainty and intense competition [3]. In Romania, the trend is supported both by market requirements and by European regulations regarding the green transition and sustainable innovation.

The interest in the topic of sustainable investments is justified by their demonstrated impact on the economic and reputational performance of organizations. International studies show that companies that integrate environmental, social and governance dimensions in the investment process benefit from competitive advantages such as cost reduction, better access to financing and increased stakeholder trust [4]. At the same time, Romanian literature emphasizes the need for companies to align with global trends in order to maintain their sustainability and competitiveness in the long term [16].

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The objective of this article is to analyze how sustainable investments contribute to increasing organizational competitiveness, by correlating theoretical data with practical examples and with the perspective of emerging trends in the economy.

To this end, it begins by providing the conceptual framework necessary for the development of further analysis, integrating theoretical elements and arguments from the specialized literature, with the aim of highlighting that sustainable investments are not just a temporary trend, but an essential condition for the competitiveness of modern organizations.

2. CONCEPTUAL AND THEORETICAL FRAMEWORK OF SUSTAINABLE INVESTMENTS

2.1. Sustainable investments, social responsibility, sustainable development

The concept of sustainable investments has evolved progressively in recent decades, as the business and academic community have become aware of the profound impact of economic activities on the environment, society and corporate governance. In the specialized literature, sustainable investments are defined as capital allocation processes that simultaneously consider traditional financial criteria and non-financial factors integrated within the ESG – Environmental, Social and Governance framework [10]. This type of investment differs from classic investments in that it seeks to create a balance between economic performance and social-ecological impact, thus representing a holistic approach to financial management.

The relationship between sustainable investment and corporate social responsibility (CSR) is direct and fundamental. CSR is a set of ethical practices and strategies through which organizations assume responsibility for the consequences of their actions on society and the environment, going beyond the obligations strictly imposed by law. Carroll [1] defines CSR through the famous "Pyramid of Responsibility", which includes the following dimensions: economic, legal, ethical and philanthropic responsibility (figure 1). This perspective highlights the fact that organizations have a duty to generate profit in a way that respects ethical principles and actively contributes to social well-being. Sustainable investment is found at the top of this pyramid, as it circularizes financial resources towards projects that bring long-term value to communities and the environment.

Another fundamental concept for understanding sustainable investment is that of sustainable development, officially introduced by the Brundtland Report [18]. Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This principle has been the basis of all modern policies regarding environmental protection, responsible use of resources and mobilisation of investments towards eco-efficient activities. From this perspective, sustainable investment can be interpreted as the economic mechanism through which the principles of sustainable development are translated into organisational practices.

Figure 1. Carrol's Pyramid of CSR

The interconnection of the three concepts — sustainable investment, corporate social responsibility and sustainable development — is widely recognized in contemporary literature. Elkington [5] proposes the Triple Bottom Line model, which brings together the three essential dimensions: profit (economic), people (social) and planet (ecological). In this framework, sustainable investment becomes a central element for achieving the overall performance of the firm, contributing to strengthening governance, reducing risks, improving energy efficiency and creating a sustainable competitive advantage.

In conclusion, sustainable investments represent the result of the convergence between the moral imperative of social responsibility and the strategic objective of sustainable development. They can no longer be viewed as a passing trend, but as a fundamental pillar of organizational competitiveness, economic stability and contemporary social progress.

2.2. The correlation between sustainability and economic performance

The correlation between sustainability and economic performance has become a topic of major interest in the literature of the last decade, with numerous studies highlighting the fact that the integration of social responsibility and environmental protection principles can generate sustainable competitive advantages. Sustainable investments contribute to improving economic performance by reducing operational costs (through energy efficiency, optimizing resource consumption, reducing losses), by strengthening the organization's reputation and by increasing its attractiveness to investors and consumers. In addition, companies that adopt sustainable strategies benefit from a lower level of risk in the long term, as they are better prepared to respond to regulatory pressures, technological changes and behavioral developments in the market. The literature confirms that organizations with strong environmental, social and governance (ESG) policies often record superior financial performance, due to both operational efficiency and preferential access to capital and international markets [4] (figure 2).

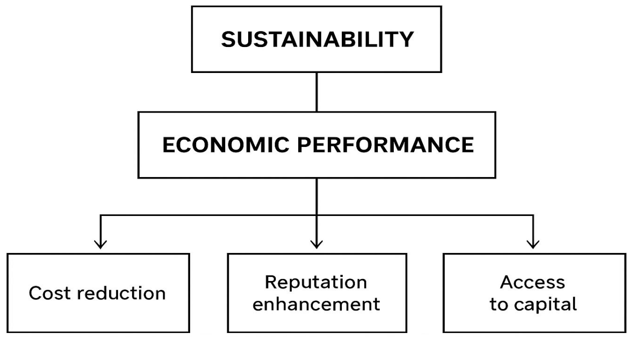

Figure 2. Sustainability-economic performance relationship

Thus, sustainability is not just a moral obligation, but an economic strategy that supports long-term resilience, profitability, and competitiveness.

2.3. Theoretical models regarding the relationship between green investments and firm competitiveness

The literature has developed several theoretical models that explain how green investments contribute to increasing the competitiveness of firms. One of the most influential is the Porter Model of Competitive Advantage through Regulation, according to which well-designed environmental policies stimulate innovation, causing firms to develop more efficient technologies and cleaner processes, which translates into cost reductions and increased productivity [13]. In this sense, green investments act as a catalyst for innovation, generating a "double win": high environmental performance and superior economic results.

A second relevant theoretical framework is the Resource-Based View (RBV), according to which green investments allow firms to develop valuable, rare, inimitable and difficult-to-substitute resources and capabilities – such as eco-efficient technology, sustainable innovation skills or green reputation. These resources become strategic sources of competitive advantage, strengthening the firm's position in the market. In particular, competencies related to environmental management and eco-innovation are viewed as intangible assets that create competitive barriers for rivals.

A third theoretical model is the Triple Bottom Line (TBL) Theory, which argues that sustainable competitive performance derives from the balance between economic, social and environmental objectives. Green investments contribute to operational efficiency, attract employees with superior skills, improve community relations and reduce reputational risks – factors that translate into long-term competitive advantages [5].

The ESG (Environmental, Social, Governance) model also highlights the direct relationship between investments in sustainable practices and financial performance (figure 3). According to it, companies with high ESG scores benefit from a positive perception from investors, easier access to capital, lower financing costs and increased resilience in times of economic volatility. These effects strengthen the competitiveness of the company in both domestic and international markets.

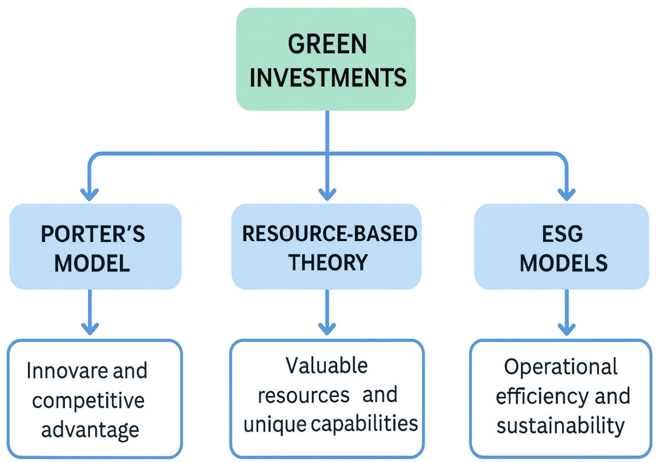

Figure 3. Green investment and financial performance

Overall, theoretical models converge towards the idea that green investments are not just responses to regulatory pressures or societal expectations, but can constitute genuine strategies for strengthening competitiveness, through innovation, operational efficiency, risk reduction and the creation of distinctive resources that differentiate the company from competitors.

3. ANALYSIS OF THE IMPACT OF SUSTAINABLE INVESTMENTS ON ORGANIZATIONAL COMPETITIVENESS

3.1. Competitiveness measurement indicators (financial, environmental, reputational)

Assessing the impact of sustainable investments on organizational competitiveness involves the use of a diverse set of indicators, which capture both financial performance and non-financial dimensions, associated with social responsibility and environmental performance. In the specialized literature, competitiveness is conceptualized as the ability of the firm to obtain and maintain advantages in domestic and international markets through efficiency, innovation, reputation and strategic adaptability [13]. In the context of green investments, measuring competitiveness requires integrated indicators, because the impact of these investments is manifested not only in immediate economic results, but also in the firm's reputation, resource efficiency and compliance with ESG (Environmental, Social, Governance) standards.

Financial indicators are the traditional form of competitiveness assessment and include elements such as profitability, return on invested capital (ROI), operating margins, asset productivity and turnover growth. Studies show that companies that integrate sustainability principles tend to benefit from reduced operational costs, improved access to capital and superior long-term financial stability [2]. For example, investments in energy-efficient technologies or recyclable materials can generate significant savings, thus improving financial performance indicators.

Environmental indicators are essential in the analysis of competitiveness in the context of the green economy. They include: CO_2 emission reduction, energy efficiency, recycling rate, water consumption, use of renewable resources and the degree of circularity of production processes. According to research conducted by the OECD [11], environmental performance is an important determinant of competitiveness, as companies with positive results in this area benefit from reduced costs, lower compliance risks and the ability to access new markets oriented towards sustainable products.

Reputational indicators, although more difficult to quantify, are crucial for competitive advantage. They include ESG scores, ratings by rating agencies, consumer trust levels, positive media visibility and positioning in rankings such as the Dow Jones Sustainability Index. Organizational reputation directly influences customer loyalty, investor appeal and the ability to attract and retain talent. Fombrun [6] highlights that reputation is a critical intangible asset for competitive performance, as firms with a strong image benefit from lower opportunity costs and more advantageous strategic partnerships.

Therefore, competitiveness analysis in relation to sustainable investments must simultaneously use financial, environmental and reputational indicators, in an integrated assessment framework. This holistic approach allows capturing the complex impact of sustainable strategies on organizational performance in the short and long term.

3.2. Case studies - Romanian and international companies

The analysis of the impact of sustainable investments on organizational competitiveness can be deepened by studying companies that have implemented green strategies and achieved significant improvements in economic, reputational and operational performance. These case studies highlight how investments in sustainability can generate tangible and intangible competitive advantages, confirming the conclusions present in the specialized literature. [10], [14]

International examples

Unilever – integrating sustainability into the business model

Unilever is one of the best-known examples of fully integrating sustainability into corporate strategy. Through the Unilever Sustainable Living Plan, the company has invested heavily in energy efficiency, emission reduction and the use of certified raw materials. These investments have led to reduced operational costs, increased productivity and a strengthened global reputation [17]. According to the company's reports, brands with high ESG performance have generated growth 69% faster than the rest of the portfolio.

Tesla – green investments as a vector of innovation and competitive advantage

Tesla is often used as a case study for how green investments can redefine industry competitiveness. The company has invested in electric vehicle technologies, batteries, and charging infrastructure, driving a global structural shift. These investments have increased market value, strengthened the brand, and accelerated the industrial transition to low emissions [7].

IKEA – investments in renewable energy and circular economy

IKEA has allocated over 2.5 billion euros in renewable energy, becoming energy-independent globally [8]. Investments in recyclable materials and circular design have reduced logistics and production costs, while improving reputation and consumer satisfaction indicators.

Romanian examples

OMV Petrom – energy transition and investments in clean technologies

OMV Petrom, the largest energy producer in Romania, has invested significantly in technology modernization, emission reduction and energy efficiency projects. The "Zero Waste" program and the transition to renewable energy contribute to improving ESG ratings and strengthening competitiveness on the European market [12].

Ursus Breweries – energy efficiency and water consumption reduction

The company has implemented technologies to streamline processes and reduce water consumption, achieving a reduction of over 30% in recent years. These investments have reduced operational costs and improved environmental scores, contributing to a better positioning in the market [19].

Dedeman – investments in energy efficiency and social responsibility

As a leader in the retail of building materials, Dedeman has invested in photovoltaic panels, smart lighting systems and CSR programs focused on education and sports. The impact of these investments is reflected in the reduction of energy costs, customer loyalty and brand consolidation [21].

Table 1. Comparative analysis of companies

Company	Types of sustainable investments (ESG)	Impact on economic performance	Impact on reputation/ public image	Relevant indicators reported
Unilever	Emission reduction, energy efficiency, sustainable raw materials, waste management	Reducing operational costs; increasing profitability of the "Sustainable Living Brands" lines	Improved global image; high consumer loyalty	Sustainable brands grew 69% faster than the rest of the portfolio
adze	Investments in green technology (electric vehicles,	Market capitalization growth; dominant	Positive perception as an innovator;	EV sales increase; battery costs per kWh decrease

	batteries), renewable energy	position in the EV market	increased global notoriety	
IKEA	Renewable energy, circular economy, recyclable materials	Reduction of logistics and production costs; operational efficiency	Strong association with sustainability; solid reputation	Energy independence through investments >2.5 billion EUR
OMV Petrom	Technology modernization, emission reduction, clean energy projects	Reducing compliance risks; optimizing costs	Improved perception as a responsible partner in the energy transition	Significant decrease in emissions reported in ESG Reports
Ursus Breweries	Reducing water consumption, energy efficient technologies	Reducing operational costs; streamlining processes	Positive reputation as a responsible producer	Water consumption reduced by >30%
Dedeman	Photovoltaic panels, smart lighting, CSR programs	Energy savings; improved operational performance	Brand strengthening; increasing consumer trust	Expanding investments in green energy and CSR

In conclusion, the examples analyzed show that sustainable investments contribute to competitiveness by:

- cost reduction,
- increasing innovation,
- improved access to financing,
- increasing brand attractiveness,
- reducing compliance risks

confirming the positive relationship between sustainability and organizational performance.

3.3. The role of ESG strategies in strengthening competitive advantage

The integration of ESG (Environmental, Social, Governance) strategies into the business model has become a determining factor of competitive advantage in an economic environment characterized by regulatory pressures, accelerated technological changes and increased consumer awareness. ESG strategies directly influence the financial performance and strategic positioning of companies, as they allow for the reduction of operational risks, cost optimization, stakeholder loyalty and access to new markets and sources of financing [4].

From the perspective of its components, the E (Environmental) strategy contributes to increasing the efficiency of processes by reducing energy and resource consumption, reducing emissions and eliminating waste. These measures translate into cost savings and a faster transition to low-carbon production models, a key advantage in an economy geared towards climate neutrality [10]. At the same time, companies that adopt robust environmental policies are better prepared to respond to future regulations, reducing exposure to sanctions and reputational risks.

The S (Social) component strengthens competitive advantage by promoting responsible practices towards employees, the community and consumers. Social responsibility programs, investments in employee well-being and ensuring ethical supply chains contribute to increasing the productivity, loyalty and public image of the organization. Studies show that organizations with high social scores benefit from an increased level of team performance and superior talent retention, critical aspects in a context of global competition [15].

Dimension G (Governance) ensures transparency, accountability and integrity in decision-making processes. Strong governance is associated with reduced cost of capital, preferential access to green financing and increased trust from institutional investors. According to MSCI studies, companies with effective governance achieve superior financial results and exhibit lower volatility in stock market performance [9].

The integration of the three ESG components creates a synergistic effect, transforming sustainability from a compliance element into a source of strategic differentiation. Companies that successfully implement ESG strategies become more resilient, more innovative and more attractive to all categories of stakeholders – investors, employees, consumers and local communities. Therefore, ESG strategies are an essential catalyst for strengthening long-term competitive advantage.

Figure 4. ESG as a generator of competitive advantage

It can be argued that the coordinated integration of these three dimensions — E, S and G — favors the creation of a sustainable competitive advantage, difficult to replicate by competitors. Therefore, ESG strategies become not just a complementary element, but a central strategic component of modern competitiveness.

4. CONCLUSIONS

Sustainable investments have transformed from a strategic option into a fundamental necessity for organizations seeking to maintain and strengthen their long-term competitiveness. The analysis highlighted that the integration of ESG (Environmental, Social, Governance) criteria into corporate strategies generates quantifiable effects on the economic, reputational and operational performance of companies, regardless of the sector in which they operate.

The research results demonstrate that green investments contribute to improving resource efficiency, reducing operational costs and developing innovative processes, thus strengthening the position of organizations in domestic and international markets. At the same time, the social component – reflected in improving working conditions, increasing employee satisfaction and strengthening social responsibility – can produce direct effects on workforce productivity and loyalty, which further contributes to competitive advantage.

The comparative analysis of companies resulting from the case studies shows that companies that have adopted coherent and measurable ESG strategies are better positioned to attract investment, adapt to legislative changes, and respond to the increasing demands from consumers and business partners. In addition, robust corporate governance, based on transparency and risk reduction, is becoming an essential catalyst for increasing investor confidence and financial stability.

Overall, the conclusions of the article confirm the central hypothesis that sustainable investments represent a strategic pillar of organizational competitiveness, and ignoring this global trend can generate significant vulnerabilities. Thus, it is recommended that companies – whether Romanian or international – continue to develop and implement integrated ESG policies, based on measurable indicators and a long-term vision.

Sustainable investments must be seen not just as a response to external pressures, but as a fundamental opportunity for transformation, innovation and differentiation in an ever-changing global market.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

UTILIZING VARIOUS INDUSTRIAL WASTES IN THE CONSTRUCTION MATERIALS SECTOR WITHIN THE FRAMEWORK OF CIRCULAR ECONOMY

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Abstract: *In the field of construction materials, especially in the manufacturing of thermal and sound insulation products with or without additions of mechanical foams, alongside the need to optimize energy costs, the idea of using so-called "inexpensive materials" is gaining momentum. The chemical-mineralogical similarity of certain industrial wastes, which can only be partially valorized in other technical fields, represents a favorable premise for the partial replacement of material resources while achieving products with comparable characteristics. This approach simultaneously reduces operational expenses and consequently preserves these resources. The objective of the research is to provide solutions for effectively utilizing waste generated from diverse industrial activities, with a focus on achieving the best possible outcome from both economic and environmental standpoints. Furthermore, the paper aims to maintain all available resources within the production-utilization-recycling cycle, ultimately aiming to convert waste into valuable by-products that serve as inputs in production processes.*

Key words: *circular economy, industrial waste, thermal power plant ashes, construction materials*

1. INTRODUCTION

The global community is grappling with an unparalleled crisis of waste and pollution, marked by an annual generation of approximately 2.01 billion metric tons of municipal solid waste (World Bank, 2018). This immense statistic underscores the critical necessity for pioneering approaches to diminish waste and foster sustainable progress.

There is also a significant pressure on policy makers to design and implement policies that can effectively and swiftly contribute to the transition towards sustainability, proposing solutions to reduce burdens and addressing trade-offs. [7]

Overall, to circumvent these problems, a long-envisaged paradigm shift is urgently required. Waste should be treated as a valuable resource rather than as an undesirable by-product of economic activity, in line with the notion of *Circular economy*. The 2030 Agenda, a comprehensive framework adopted by the United Nations in 2015, highlights in many regards the importance of adopting a circular model.[2]

The circular economy is a new economic paradigm that plans to reduce waste

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and pollution, maintain products and materials in use, and restore natural systems. A circular economy may positively impact the environment, public health, and economy. For instance, it may reduce greenhouse gas emissions, enhance resource efficiency, create new business opportunities, protect human health, as well as foster social inclusion. [14]

The specific remit of the circular economy is to use the same resources over and over again to eliminate, or at least reduce, the need to use virgin resources, increasing eco-efficiency in the process. [9]

The paper presents the research undertaken to valorize various types of industrial waste. By understanding the processes that occur during the burning of coal in furnaces [17] and the chemical and mineralogical properties of the ashes [4], the idea of using this industrial waste, together with other wastes, in the construction materials industry was advanced.

Processing these wastes and obtaining valuable products is an important issue - at least quantitatively, both nationally and globally. [13, 18]

The efficient utilization of ashes in various fields takes into account the compatibility between the physico-chemical and mineralogical properties of the ashes and the requirements imposed by specific usage conditions, whether in their original form or after processing. The utilization of coal combustion by-products has been demonstrated in numerous applications, including concrete, soil stabilization, controlled low-strength materials, highway road base and subgrade, soil amendments for agricultural uses, waste stabilization, extenders in plastics and paints, and the manufacture of products such as cement, insulating materials, lightweight building block, brick, and other construction materials. [19]

In academic literature, the primary fields where coal ash from power plants is utilized include: [3, 5, 8, 10, 11, 20]:

The field of construction materials:

- As an additive in cement manufacturing;
- As an additive in concrete preparation;
- In the production of lightweight aggregates such as granulite or agloporite;
- In the manufacturing of bituminous cardboard;
- In the production of lightweight bricks or autoclaved bricks;
- In the preparation of masonry and plaster mortars;
- For thermal insulation of residential building roofs.

The field of road construction:

- As fill material for embankment construction;
- For improving the particle size distribution of local materials (ballast, sand, etc.) used for road foundation construction;
- In the production of insulating road substrates;
- As a filler in asphalt mixtures;
- As an anti-skid material during winter.

Utilization in the agricultural sector:

- For soil improvement in acidic soils;
- For soil fertilization by blending ashes with industrial waste, household waste, etc.;

- As a substrate for cultivating certain species of agricultural and forestry plants.

Utilization for wastewater treatment:
- pH neutralization treatment
- Heavy metal adsorption
- Filtration and separation
- Organic substance adsorption
- Treatment and removal of nutrients

Utilization as a source of raw materials in the extractive industry:
- For alumina extraction;
- For iron recovery.

In the mining industry:
- As fill material;
- As a binder in cemented fills.

A wide range of studies on circular economy and the built environment highlighted that circular economy contributed various tangible and intangible benefits to this sector.

The built environment is leading in raw materials usage, greenhouse gas emissions, and waste generation. This sector is facing a significant problem due to the scarcity of raw resources, while the growing amount of construction and demolition waste (CDW) causes problems for landfill management, the environment, and climate. [12]

2. RESEARCH METHODS

In approaching the research, the aim was to develop new non-autoclaved aerated concrete (NAAC) ceramic materials with reduced volumetric weight and superior thermal, acoustic, and insulation properties. This involved incorporating into the manufacturing recipe, alongside conventional materials, various solid residues predominantly sourced from the mining and energy industries. These may include various types of slag, flotation tailings from the settling pond at Moldova Nouă, thermal power plant ash, as well as wood chips, PET (polyethylene terephthalate) bottles, polystyrene, among others.

Industrial waste continues to accumulate in ever-increasing quantities, posing economic and environmental challenges in terms of their removal and storage.

For this purpose, several recipes for lightweight cellular concrete based on cement, thermal power plant ash, expanded granulated polystyrene, hydrated lime, as well as strips and granules obtained from PET bottles, mechanical foam, and water are proposed, adjusted as needed until the desired consistency is achieved.The qualitative characteristics obtained (porosity, bulk density, compressive strength), as well as the thermal and acoustic insulation properties, recommend the use of these products in special thermal and acoustic insulation works. They can successfully replace conventional cellular concretes due to their mechanical strengths [1, 6].

It is known that cellular concretes have a structure composed of mineral aggregates within a hydraulic matrix based on Portland cement and hydraulic additives such as thermal power plant ash, hydrated lime powder, and mechanical foam.The waste materials under study and also subject to an invention are [15]: ash from solid fuel-based thermal power plants, specifically using energy-grade coal, appropriately granulated expanded polystyrene, primarily used as packaging material, and granules as well as strips derived from PET bottles, commonly used as containers for soft drinks, alcoholic beverages, and other substances, excluding fatty ones.

The use of these materials allows, under certain conditions, the production of products with characteristics comparable to those obtained from conventional raw materials, while simultaneously reducing expenses associated with prospecting, exploiting, and processing natural deposits, thereby conserving them. Utilizing ash from thermal power plants stored in settling ponds or directly collected from the producing facility in the composition of concretes enables the reuse of storage lands and reduces the waste/environmental factors interface (water, air, soil). At the same time, it is well known that packaging materials such as expanded polystyrene and PET bottles are abundant in the surrounding environment and are non-biodegradable.

2.1. Determination of composite material characteristics

Characteristics of power plant ash

The proportion of ash as a composite material in BCfA cannot exceed certain values, even if technologically it would improve the technical-economic and qualitative indicators.

Special attention has been given to the addition of thermal power plant ash in the study because this composite material has multiple effects that are reflected in the changes in the physical, mechanical, and chemical properties of the concrete [17].

The addition of thermal power plant ash has several effects

- Reduces heat of hydration;
- Decreases shrinkage and deformation under long-term load;
- Increases resistance to corrosive waters and chemical agents;
- Lower cost due to partial substitution of cement and fine aggregates with ash.

Starting from these premises and considering the characteristics of the ashes, which recommend them as materials with very good hydraulic hardening properties, a series of trials were conducted to produce BCfA type bricks. The Paroşeni ashes fall into the silico-aluminous type.

Physical and mechanical analyses have shown that the ash from the Paroșeni Thermal Power Plant appears as compact powders, microporous spheres, or compact or cavernous glassy spheres. The fineness of grinding is 68% at the -0.074 mm class, with high abrasion resistance, low permeability, and high magnetic susceptibility. The fineness of grinding of the coal used for combustion in the hearths is also 68% at the -0.074 mm class [4].

Following the conducted research, it was concluded that the specific surface area, and thus implicitly an advanced fineness of grinding, is not an essential condition for the use of ash as an additive in cements and concretes. This is why ash from ash dumps can be used, eliminating the need for grinding, with unfavorable technical and economic consequences. Ash, being hydrophilic, easily retains water and exhibits a higher degree of compaction than sands. Additionally, it is characterized by low permeability.

Characteristics of slag resulting from the combustion of Valea Jiului coal

This type of waste has been used in various proportions and combinations. By adding certain materials, the aim was to ensure a porosity and bulk density as close as possible to the targeted brick type, such as: polyurethane foams, sawdust from sawmills, and mechanical foam.

Physical characteristics of different types of sand

Sand is a fundamental component in the structure of construction materials; therefore, grain size distribution, density, average size, and specific surface area are important parameters to be monitored. The grain size distribution curves of the two types of sand: quartz sand from Făget and ordinary sand from the gravel pit, are shown in figures 1 and 2.

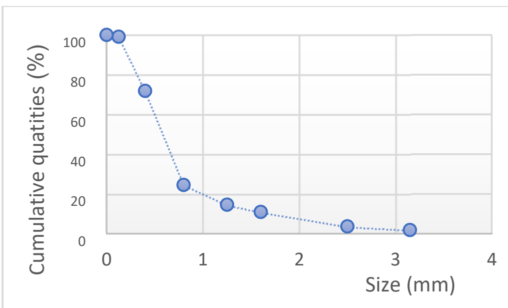

Figure 1. Cumulative refusal curve for ordinary sand (class - 3.15 mm)

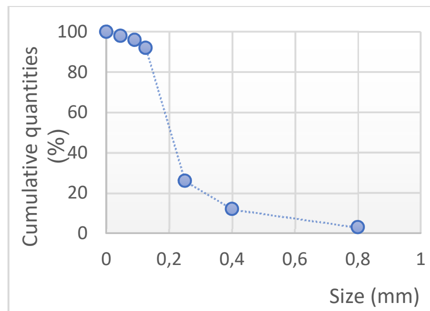

Figure 2. Cumulative refusal curve for quartz sand from Făget

In table 1, the bulk densities determined for the composite materials that constitute the structure of non-autoclaved cellular concretes, which are the subject of study of this article, are presented.

Table 1. Bulk densities for composite materials

Type of material	***Density [t/m³]***
Sand 0-3 mm	1.60
Portland cement 32.5	1.36
Thermal power plant slag + 3.25 mm	0.80
Thermal power plant slag - 3.25 mm	0.55
Thermal power plant ashes	0.90
Quartz sand from Făget	1.50
Lime	0.53
Expanded polystyrene	0.01
Plastic granules	0.80
Sawdust from spruce	0.24
Water	1.00
Foam	1.19

2.2. Results and discussions

Establishing correlations between the contents of composite materials in lightweight cellular concretes

To establish the influence of specific consumption of composite materials on the qualitative results of lightweight cellular concretes, the correlation and regression method was applied, statistically processed using correlation analysis in EXCEL.

Correlation between the specific consumption of cement and other composite materials (ash, PET, lime, polystyrene) was studied, focusing on compressive strength and density as response functions. [4]

The specific consumption of cement influences both the compressive strength and the density of lightweight cellular concretes, in an increasing sense, with the influence of this composite material being insignificant (figures 3 and 4).

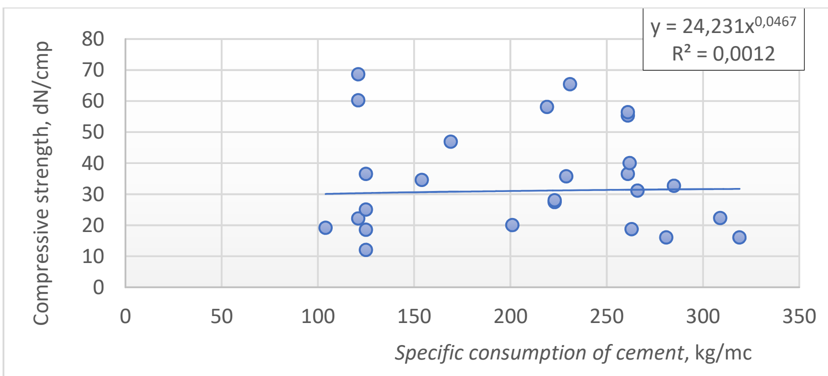

Figure 3. The correlation between the specific consumption of cement and compressive strength

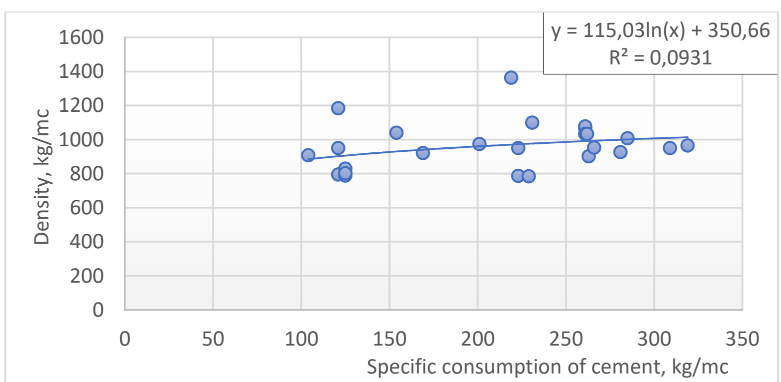

Figure 4. The correlation between the specific consumption of cement and density

In figure 5, the correlation between the specific consumption of ash and the compressive strength of lightweight cellular concretes is presented. From the diagram, it is observed that up to a specific consumption of ash of 380 kg/m3, the compressive strength increases with the increase in ash content. Beyond this consumption, the compressive strength decreases.

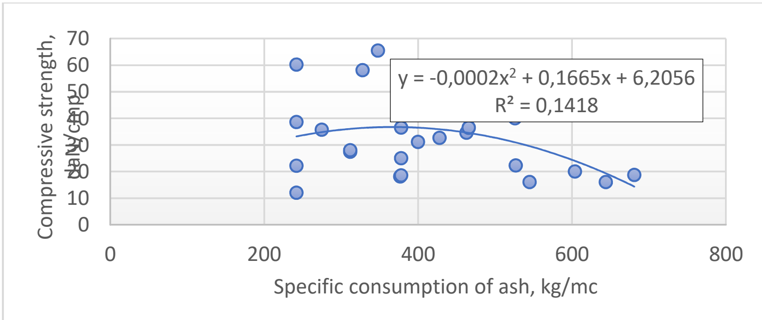

Figure 5. The correlation between the specific consumption of ash and compressive strength

Figure 6 illustrates the correlation between the consumption of ash and density. The influence of this composite material on density is insignificant and decreasing.

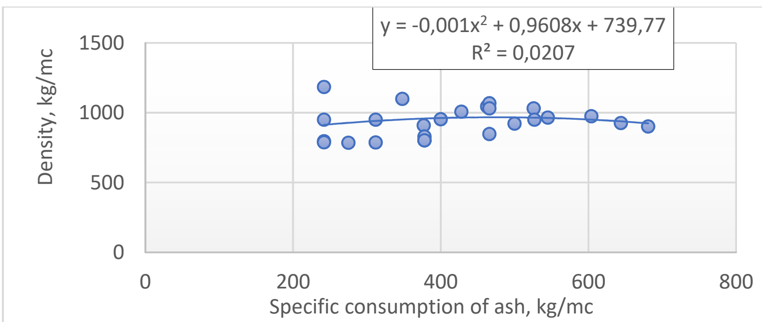

Figure 6. The correlation between the specific consumption of ash and density

Figure 7 illustrates the influence of the cement/ash ratio on compressive strength. This introduced synthetic parameter demonstrates the influence of this ratio on compressive strength, which is weak and linear.

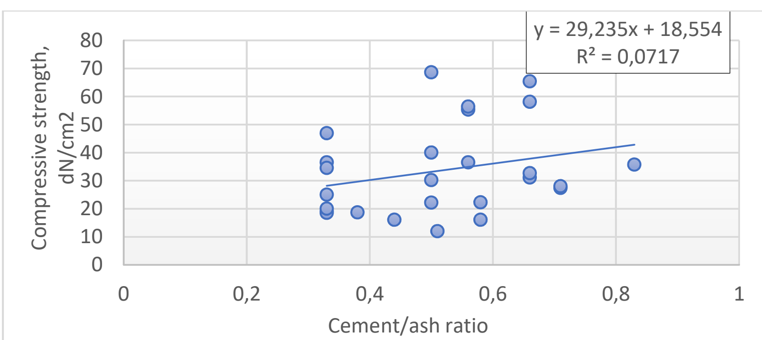

Figure 7. The correlation between the cement/ash ratio and compressive strength

The influence of lime consumption on compressive strength and density is presented in Figures 8 and 9. This composite material has an insignificant and decreasing influence on these qualitative parameters.

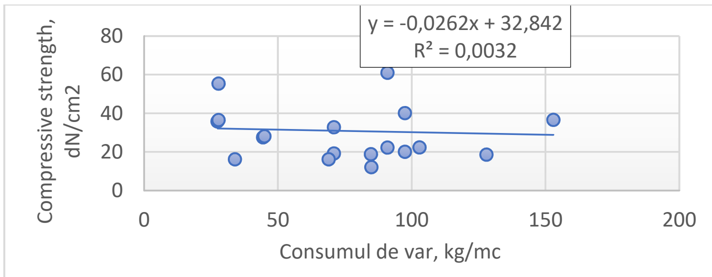

Figure 8. The correlation between the specific consumption of lime and compressive strength

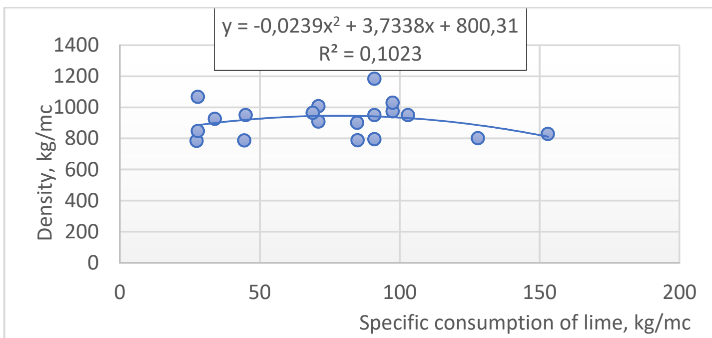

Figure 9. The correlation between the specific consumption of lime and density

The influence of specific consumption of PET bottles on the qualitative parameters of lightweight cellular concretes is presented in Figures 10 and 11. It is observed that the influence of this composite material on compressive strength and density is very significant, with the caveat that the number of experiments conducted with this composite material was relatively small.

It was also observed during the compression tests that the specimens cracked along the plane delimited by the PET spheres.

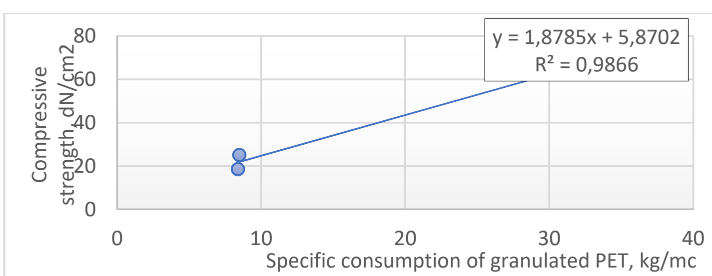

Figure10. The correlation between the specific consumption of granulated PET and compressive strength

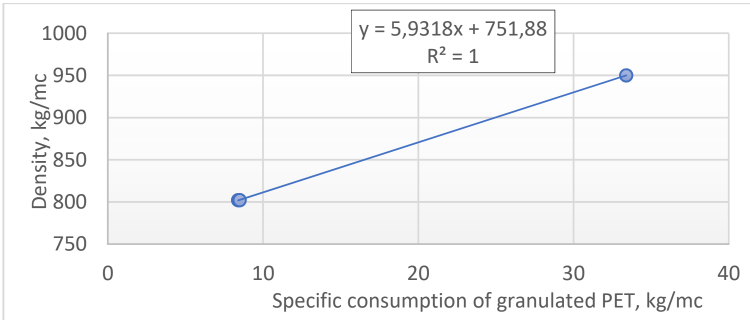

Figure 11. The correlation between the specific consumption of granulated PET and density

The utilization of PET in strip form also had a notable impact, particularly regarding compressive strength and density in relation to the specific consumption of PET strips, as illustrated in Figures 12 and 13.

Figures 14 and 15 depict how polystyrene affects compressive strength and density. The specific consumption of polystyrene notably affects compressive strength, whereas density shows a slight decrease with increasing specific consumption of polystyrene.

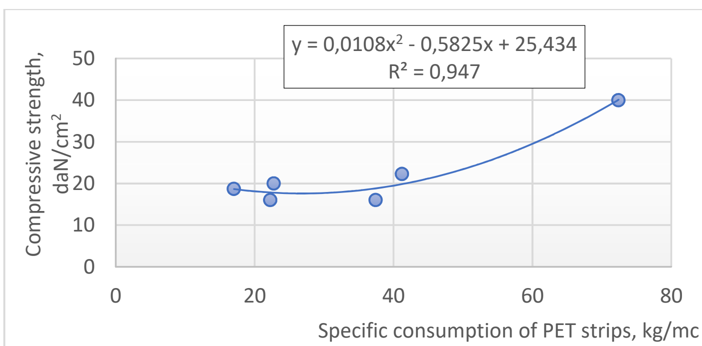

Figure12. The correlation between the specific consumption of PET strips and compressive strength

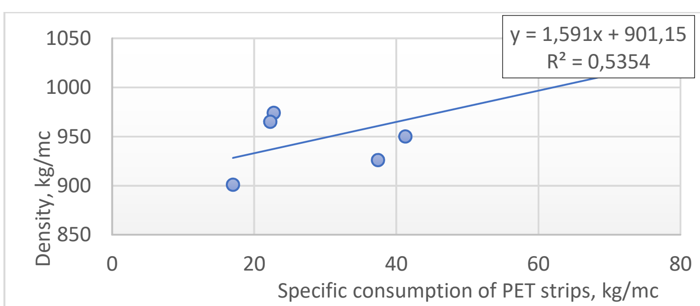

Figure13. The correlation between specific consumption of PET strips and density

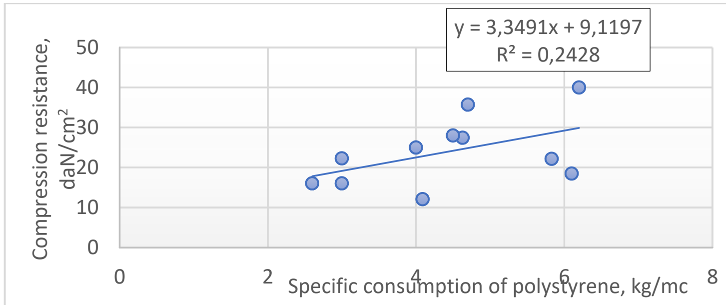

Figure14. The correlation between specific consumption of polystyrene and compression resistance

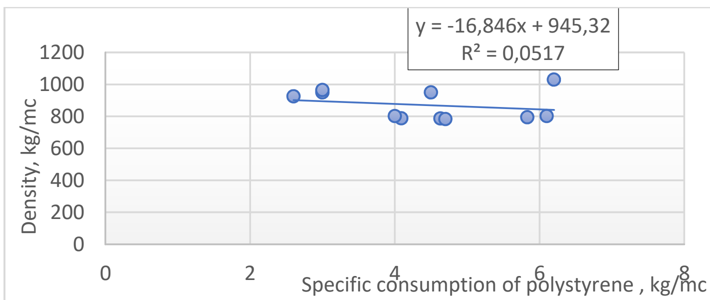

Figure15. The correlation between specific consumption of polystyrene and density

Conclusions derived from analyzing the relationships among various consumption rates of composite materials are:

- The specific consumption of cement influences the compressive strength and density of lightweight cellular concrete, with both parameters qualitatively increasing as the specific consumption increases.
- Increasing the specific consumption of ash has a positive impact on compressive strength and density up to a certain value, after which these parameters decrease with further increases in ash consumption.
- Lime has a decreasing influence on both compressive strength and density.
- Both PET strips and granulated PET have a significant influence on these two qualitative parameters, with their values increasing as the specific consumption of these composite materials increases.
- Increasing the specific consumption of polystyrene leads to increased compressive strength of lightweight cellular concrete and reduced density of these products.

Establishing the optimal recipe for lightweight cellular concrete bricks using the gradient method

The method used to determine the optimal consumption of composite materials for the production of AAC blocks correlated with compressive strength, bulk density, and porosity was the gradient method or ascent along the steepest slope of the response surface.

The experimental trials carried out following the programmed matrix considered, in establishing the baseline, the correlations existing between the composite materials utilized in the manufacturing formulations and their impact on the qualitative attributes of lightweight cellular concretes, as previously discussed in correlations.

Through the experiments conducted, the aim was to use a higher proportion of materials currently considered waste, such as ash from power plants, PET (polyethylene terephthalate), and polystyrene. As a response measure, the goal was to achieve a compressive strength around 35 daN/cm². Figure 16 shows the variation in compressive strength depending on the quantities of ash and PET.

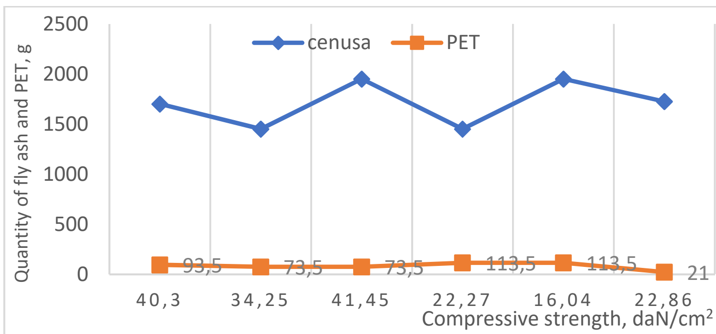

Figure16. The variation of compressive strength as a function of the quantity of fly ash and PET

In conclusion, considering the obtained results and the field of application of these products, the manufacturing recipe chosen achieved a compressive strength of 34.25 daN/cm^2. It includes the following composite materials: 0.848 kg of cement, 1.45 kg of fly ash, 73.5g of PET, 0.315 kg of lime, and 0.0348 g of foaming agent.

3. CONCLUSIONS

The ash deposits from thermal power plants represent a viable source that could be used with good results in the field of construction materials, with favorable ecological effects in the Jiu Valley area.

The specific characteristics of thermal power plant ashes (especially the vitreous mass) have a beneficial effect on the hydraulic hardening capacity of NAAC -type blocks - which represent a very good construction material. The qualitative properties of these products recommend them for thermal and acoustic insulation works.

The correlations established between the various contents of composite materials and their influence on compressive strength and density served as the starting point in determining the optimal recipe for manufacturing lightweight cellular concrete.

Taking into account the results obtained and the field of application of these products, the manufacturing recipe was chosen for which a compressive strength greater than 34.0 daN/cm^2 was achieved.

By implementing the proposed procedure, the following advantages are achieved:

- Utilization of industrial and household waste in the manufacturing process of lightweight non-autoclaved cellular concrete, inertizing them in a hydraulic matrix to achieve environmental elimination.
- Production of products with characteristics comparable to conventional ones.
- The obtained products, due to their ensured characteristics, can be used for thermal and acoustic insulation works.
- Reduction of manufacturing costs by partially replacing cement and sand with fly ash from thermal power plants and other composite materials.
- Cellular concretes do not contain aluminum powders.
- Good compatibility with any type of plaster.
- Very good load-bearing capacity.
- Environmental protection through the recycling of non-degradable materials.

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THE COMPETITIVENESS OF ROMANIAN ENERGY COMPANIES WITH DOMESTIC CAPITAL AND THEIR ROLE IN STRENGTHENING NATIONAL ENERGY SECURITY

Diana Cornelia CSIMINGA[1]

Abstract: *The main objective of this article is to examine the competitiveness of Romanian energy companies with domestic capital and assess their role in ensuring national energy security. The research is exploratory and descriptive in nature, aiming to analyze the determinants of competitiveness in the Romanian energy sector and identify the structural limitations that influence market performance. A comparative qualitative-quantitative approach based on financial indicators for the period 2023-2024 is also used. The conclusions of the analysis thus highlighted a dual market structure, dominated economically by state-owned companies but supported operationally by private actors.*

Key words: *Energy sector; Competitiveness; Energy security; Romanian energy companies; State-owned enterprises; Market structure.*

1. INTRODUCTION

The energy sector is an essential element in the functioning of any country's economy, being closely linked to the level of development, the resilience of critical infrastructure, and the ability of countries to respond effectively to crises that may arise. In recent decades, the energy sector has undergone major structural changes, moving towards a more competitive framework, closely supervised by regulatory authorities. The pace and scope of reforms vary depending on the initial conditions of each market and the particularities of the domestic environment [5]. Energy systems around the world are undergoing a profound transformation, driven by the need to achieve decarbonization targets, keep consumption growth under control, accelerate the modernization and digitization of electricity networks, and address the challenges posed by geopolitical instability. The European Union's electricity market aims to support the transition to clean energy sources and strengthen energy security across EU countries. At the same time, it facilitates energy accessibility by promoting competition, developing long-term markets, and giving consumers the freedom to choose their energy suppliers [23].

In this context, national energy security has become a priority for both policymakers and energy companies. Romania, endowed with significant natural resources and a consolidated infrastructure of state-owned enterprises, occupies a strategic position in the regional energy landscape.

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Energy policy has become an increasingly important area of interest in economic and environmental research, and competition in the energy sector is one of the main topics analyzed. Until the 1990s, in most European Union countries, the electricity, natural gas, and oil sectors were organized as vertically integrated monopolies owned by the state, but now policies and efforts are focused on developing liberalized and competitive energy markets [4, 5, 7, 16]. Since the 1990s, international electricity markets have been and continue to be subject to extensive institutional and economic restructuring processes, through which traditional monopolistic structures have been transformed into partially decentralized markets characterized by competitive mechanisms. The literature highlights the fact that these reform processes are complex, involve transition costs, and are accompanied by significant economic, technical, and regulatory risks [1, 6, 9]. Romania's energy market has undergone a gradual liberalization process since the 2000s, accelerated under the influence of European legislation, becoming formally liberalized in 2021, but effective liberalization has been partially limited by state intervention, particularly through indirect price control mechanisms.

In other words, although Romania has liberalized the energy market from a legislative point of view, by transposing European Union directives and eliminating regulated prices for end consumers, the effective functioning of the market cannot be considered fully liberalized. The literature emphasizes that liberalization requires not only institutional and legislative changes, but also the existence of functional market mechanisms based on real competition and free price formation [11, 21]. Painuly (2001) considers that the liberalization of the energy sector requires the adoption of policies aimed at restructuring it and stimulating competition, such as the separation of production and distribution activities in the electricity sector, facilitating access and participation of private sector companies, or eliminating existing control mechanisms [12].

In this context, state interventions through electricity and natural gas price capping and compensation schemes have distorted price signals and reduced the role of competition in the efficient allocation of resources, an issue frequently highlighted in the analysis of liberalized energy markets [8].

Thus, there is a clear difference between formal liberalization, as reflected in the regulatory framework, and effective liberalization, as determined by the actual conditions of the market. The European Commission points out that prolonged administrative intervention in prices can undermine the objectives of the internal energy market, even in Member States that have formally implemented the necessary structural reforms [17]. Consequently, the case of Romania illustrates the incomplete nature of the liberalisation process, highlighting the persistence of an active role for the state in a strategic sector with significant economic and social implications.

Although the Romanian energy market is dominated numerically by private companies, the most influential corporations in terms of revenue, assets, and systemic relevance remain state-owned companies [10]. On the one hand, these companies ensure the operation and e of critical infrastructure, the provision of a stable energy mix, and a significant contribution to national resilience. At the same time, private companies—

including new market entrants—play an increasingly important role in distribution, supply, and technological innovation processes.

2. COMPETITIVENESS IN THE ENERGY SECTOR

Competitiveness is one of the most analyzed topics in contemporary economic literature, with implications at both the microeconomic and macroeconomic levels, but it does not have a single, precise definition. Depending on the objectives of the analysis, the term is often adapted, which explains the diversity of approaches in the literature. In general, competitiveness reflects the ability of an economic actor—a firm, sector, or economy—to maintain and evolve in a competitive environment by offering high-quality products or services at efficient costs. According to classical literature, competitiveness is determined by the capacity for innovation, the efficient use of resources, market structure, and the intensity of competition [9, 13]. Rebega (2022) summarizes three perspectives on competitiveness [14]:

- The first approach associates competitiveness with comparative advantage, although, as Siggel (2006) points out, this interpretation depends on the level of analysis—microeconomic, macroeconomic, national, or international [15].
- A second perspective focuses on performance evaluation through trade and price indices, providing a way to compare firms, sectors, or countries.
- A third approach, inspired by Porter [13], uses the concept to determine competitive advantage and develop indirect performance indicators, such as internal resource costs, social cost-benefit ratio, or production costs. Thus, competitiveness becomes a multidimensional tool, applicable both in structural analysis and in the evaluation of comparative economic performance at various levels.

In the energy sector, the concept of competitiveness involves a combination of operational efficiency, financial performance, innovation capacity, and strategic adaptability. It can be defined by two dimensions [15, 22, 23]:

- economic performance (profitability, costs, asset utilization, added value),
- structural performance (access to resources, market position, systemic role).

In the context of utility industries, competitiveness takes on a special dimension, as these industries are characterized by the existence of essential infrastructures, often considered natural monopolies. Thus, the analysis of competitiveness cannot be separated from the degree of regulation, access to infrastructure, the market power of dominant players, or state intervention.

2.1. Competitiveness in regulated sectors: general characteristics

In network industries, such as electricity and natural gas, the market is not "free" in the classical sense. Transportation and distribution require fixed, costly, non-fragmentable, and difficult-to-replicate infrastructure ( ), which creates natural barriers to entry into these markets. For these segments, competition cannot function without the intervention of regulatory authorities.

The literature distinguishes two fundamental mechanisms through which competition can be introduced into regulated sectors [3]:

- Liberalization of competitive segments (such as production, supply, etc.);
- Regulation of monopolistic segments (transport, distribution) through transparent tariffs and non-discriminatory access to networks.

As mentioned by numerous academic and institutional sources [11, 17,18,19, 21, 22, 23], competitiveness in energy depends on several factors, including:

- the degree of functional and legal separation (unbundling);
- equal access to infrastructure;
- the degree of market transparency;
- incentives for investment;
- the existence of a stable legislative framework.

Regulation in this case is essential to prevent opportunistic behavior by dominant players and to protect consumers, without stifling market mechanisms.

2.2. Specific features of competitiveness in the energy sector

The energy sector is defined by a set of fundamental characteristics that directly influence the degree of competitiveness, such as market structure, competitiveness determinants, and, last but not least, the role that renewable energy plays in this sector.

Of the four major segments of the energy market—production, transmission, distribution, and supply—we can talk about competitiveness especially for the production and supply segments, because the transmission and distribution segments remain strictly regulated areas, as replicating networks is economically inefficient.

With regard to the key factors of competitiveness, the literature highlights that excessive concentration in the sector reduces competition and amplifies the market power of dominant players [11]. Legislative predictability is vital, as regulatory instability discourages investment and limits the entry of new market participants [21, 22]. Non-discriminatory access to energy networks and infrastructure is also a fundamental condition for the functioning of a competitive market. In addition, the expansion of renewable energies, characterized by marginal costs close to zero, significantly changes the price formation mechanisms and economic logic of energy markets [17]. In fact, the evolution of renewable technologies has led to a decrease in marginal costs and the entry of new, smaller players, reducing market concentration and diversifying the energy mix. At the same time, renewable energies are characterized by volatility, requiring additional balancing and storage capacities, which raises new competitive challenges.

3. ANALYSIS OF THE ENERGY MARKET IN ROMANIA FROM A COMPETITIVENESS PERSPECTIVE

The energy market in Romania is subject to interdependent factors that directly influence the competitiveness of the sector and the efficiency of its operation. These factors include structural, institutional, and technological elements that determine price dynamics, the level of competition, and the ability to adapt to changes in the regional and international markets**.** Among these,

- the production mix is an essential element, as the combination of hydro, nuclear, thermal, and renewable sources determines the marginal costs and flexibility of the energy system.
- The structure of the energy sector
- The role of state-owned companies is also significant: these entities account for a large share of production, providing stability but often limiting dynamism and the intensity of competition.
- The level of transparency and legislative predictability affects investment attraction and the functioning of the free market, while regulatory instability or delays in the settlement of subsidies generate uncertainty.

Overall, the competitiveness of the Romanian energy market is the complex result of all these factors, and in order to understand the sector's performance, it is necessary to assess them in an integrated manner, an analysis which I present summarily below.

3.1. Energy dependence and production mix

Romania has a diversified energy mix, including hydro, nuclear, coal-fired and natural gas thermal power, as well as a growing share of renewable sources, as shown in Figure 1. Dependence on energy and fuel imports directly influences competitiveness by increasing exposure to international price volatility and, last but not least, to geopolitical risks. At the same time, the production mix affects both marginal costs and the flexibility of the energy system, which are considered key elements in assessing competitiveness.

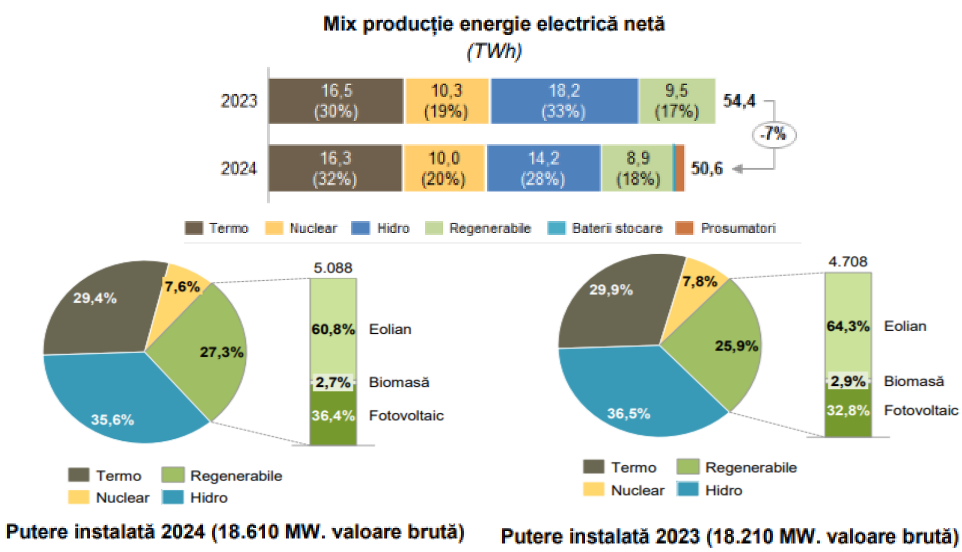

Figure 1.

Source: [24 p.31]

3.2. Structure and degree of concentration of the energy sector in Romania

The structure of the energy sector in Romania shows a predominance of private companies, most of which are controlled by non-state shareholders. However, the distribution of economic performance across the industry indicates a significant concentration of added value and production capacity among companies with majority state ownership. In terms of turnover, state-controlled enterprises continue to represent the core of national energy production.

A relevant indicator of this structural polarization is the absence of private electricity producers that have exceeded the threshold of one billion lei in annual turnover [20]. This suggests that strategic investments, critical assets, and large-scale production capacities remain concentrated in the portfolio of state-owned companies, reflecting a market architecture specific to sectors considered essential for energy security.

A study conducted by Mihail Bușu on the evolution of market concentration in Romania revealed a direct correlation between concentration, innovation, and competitiveness [2]. Concentration in the energy production segment is considered to be quite high, with three major producers accounting for over 60% of installed capacity. The Herfindahl-Hirschman index calculation shows values that indicate a moderately concentrated market, with a potential risk of price influence. The dominance of state-owned companies limits the entry of other competitive producers into this market, while new projects face multiple administrative barriers**.**

According to data provided by the Termene.ro platform, in 2023 the electricity production sector consisted of 6,984 economic agents [28]. This dispersion in the number of entities, coupled with the concentration of turnover among a few dominant companies, outlines a dual structural profile: a large number of small operators coexisting with a small segment of strategic players who exert a disproportionately large influence on the performance and stability of the entire energy system.

In fact, the role of the state is essential, given that many strategic assets (production, transport, storage) are owned and coordinated at national level, and ANRE (National Energy Regulatory Authority) regulations and market mechanisms directly influence margins and investments.

3.3. The role of state-owned companies

The market is fragmented in terms of the number of entities, but economically concentrated around a few large state-owned companies:

- hydro production (Hidroelectrica),
- nuclear production (Nuclearelectrica),
- energy transmission (Transelectrica),
- natural gas (Romgaz).

These state-owned companies account for a significant share of energy production. This indicates short-term stability, but may reduce legislative dynamism, as these companies benefit from certain financial and legislative advantages from the state. Moreover, their decisions are influenced in some situations by government policies and are not necessarily based on economic criteria.

3.4. Level of legislative transparency and predictability

Legislative predictability and transparency in decision-making are essential factors both in attracting investment and for the functioning of the free market. Frequent changes to renewable energy support schemes, combined with price regulations and delays in the settlement of subsidies, create uncertainty and financial risks for both suppliers and investors. This lack of stability is one of the main reasons why new players are discouraged from entering the market and why existing players are struggling.

Legislative instability is also a major constraint on competitiveness. Frequent changes to support schemes, price interventions, changes in taxation, and ad hoc regulations create uncertainty for investors. Added to this are the difficulties reported by supply companies due to delays in settlements, raising problems in cost management and cash flow balancing.

At the same time, the modernization of transmission and distribution networks, the development of interconnections and investments in renewable energy capacities are key factors for competitiveness, while wholesale market liquidity and consumer mobility in the retail market are additional factors that determine the actual level of competition. As is well known, a liquid market promotes competition and efficient pricing, while low liquidity limits trading options and can create market volatility. In the retail segment, liberalization allows consumers to choose their supplier, but mobility is still limited due to switching costs and the complexity of offers, which affects the actual level of competition.

4. ANALYSIS OF THE COMPETITIVENESS OF DOMESTIC ENERGY COMPANIES

The analysis of the competitiveness of domestic companies in the Romanian energy sector is carried out using a comparative approach, structured around two categories of economic actors: companies with majority state ownership and private companies with majority Romanian ownership. The methodology is based on a functional delimitation of the energy value chain, including the segments of base energy production, primary resource exploitation, transport and distribution, and supply, trading, and development of renewable energy capacities. For each category of companies, relevant competitiveness elements were analyzed, such as control of strategic resources, market positioning, energy portfolio diversification, ability to adapt to the energy transition, and level of integration into the regulatory and institutional framework.

Comparability between the actors analyzed is ensured by using standardized quantitative indicators, namely market share and installed capacity, supplemented by qualitative indicators regarding the systemic role and economic function of each entity. The data used comes from official public sources (company annual reports, ANRE statistics, and the National Trade Register Office (ONRC)), and is analyzed in aggregate to highlight the structural complementarity between state-owned and private companies.

This approach allows for the assessment of the balance between the systemic stability provided by state-owned companies and the competitive dynamics induced by private firms, providing a coherent framework for interpreting the results obtained.

Table 1. Competitiveness factors in the energy sector

Competitiveness elements	Companies contributing to energy security	Estimated market share*	Strategic impact
Control over critical infrastructure	S.P.E.E.H. Hidroelectrica S.A	~30–33% of electricity production	Ownership of nuclear and hydroelectric power plants, gas fields, and transport and distribution infrastructure ensures security of supply, influences prices, and positions companies as key players in the market
	S.N.Nuclearelectrica S	~18–20% of electricity production	
	SNGN Romgaz S.A	~45–50% of domestic natural gas production	
	CNTEE Transelectrica SA	100% electricity transmission	
Operational and technological experience	S.P.E.E.H. Hidroelectrica S.A S.N.Nuclearelectrica S.A	>50% cumulative base energy production	Know-how accumulated in power plant operation and investments in renewables, digitization, and predictive maintenance increase operational efficiency and reduce costs , offering an advantage that is difficult to replicate
	Electrica S.A (distribution & supply)	~40% electricity distribution	
Access to domestic energy resources	SNGN Romgaz S.A	~45–50% of domestic natural gas production	Reduces dependence on imports and price volatility
	CE Oltenia	~11% of domestic energy production	
Strategic market positioning	S.P.E.E.H. Hidroelectrica S.A., SNGN Romgaz S.A., Electrica Furnizare S.A C.E. Oltenia S.A.	>60% cumulative production + supply	Control of a significant share of production and distribution facilitates contract negotiations and influences market price developments
	Tinmar Energy (largest private energy supplier)	~5–7% energy supply	
Diversified portfolio and energy mix	S.P.E.E.H. Hidroelectrica S.A	Hydropower dominant + renewable investments	The combination of conventional (nuclear, gas, hydro) and renewable sources reduces the risks associated with price fluctuations and ensures
	SNGN Romgaz S.A	Natural gas + power plants + offshore	
	S.N. Nuclearelectrica S.A.	Low-emission energy	

			flexibility in the energy transition
Ability to adapt to the energy transition transition	Electrica Furnizare S.A	~15% energy supply	Investments in renewables, digitalisation and storage increase long-term resilience, reduce regulatory and carbon risks, and facilitate access to sustainable financing.
	Nova Power & Gas S.R.L	National leader in battery storage capacity, with 240 MWh operational.	
	S.P.E.E.H. Hidroelectrica S.A	~30–33% of electricity production	

*Estimates are based on data published in companies' annual reports and statistics from the National Energy Regulatory Authority.

Quantitative analysis indicates a high concentration of market share (including installed capacity) among companies with majority state ownership, which dominate base load power generation and critical infrastructure. In contrast, private companies with Romanian capital have smaller shares in total production but are competitive in the supply, renewable, and energy services segments, contributing to the flexibility and dynamics of the energy transition.

Table 2 shows the situation of the best-performing state-owned companies.

Table 2. Top state-owned companies contributing to energy security

No. No	**Companies contributing to energy security**	**Turnover (lei)**		**Profit (lei)**	
		2023	**2024**	**2023**	**2024**
1	SPEEH Hidroelectrica SA	12,342,326,973	9,659,879,145	6,352,326,530	4,071,551,582
2	CNTEE Transelectrica SA	4,631,408,019	7,639,092,966	213,611,306	585,924,311
3	Romgaz S.A.	8,619,285,676	7,531,970,469	2,649,276,775	3,090,696,860
4	SN Nuclearelectrica SA	7,469,308,958	4,680,533,991	2,506,518,832	1,708,188,496
5	CE Oltenia S.A.	6,318,628,834	3,266,120,740	1,027,332,808	317,505,919

The data was taken from the companies' annual reports and officially published statements [24-31].

According to financial data for 2023-2024, the Romanian energy sector is characterised by high profitability and economic dynamics superior to other sectors, with performance concentrated mainly among companies with majority state ownership. A comparative analysis of the main public operators highlights their role in generating significant revenues, as well as their contribution to the stability and functioning of the national energy system.

Hidroelectrica S.A. ranks first among state-owned energy companies, reporting a turnover of over 9.6 billion lei and a net profit exceeding 4 billion lei in 2024. Although turnover contracted by approximately 22% year-on-year, the high level of profitability indicates superior operational efficiency and confirms the company's strategic role in the Romanian energy market. In second place is the National Electricity Transmission Company Transelectrica S.A., which recorded an annual increase of approximately 65% in turnover, reaching a level of over 7.6 billion lei in 2024. The reported net profit of over 580 million lei reflects the company's ability to ensure the operational stability of the transport infrastructure, despite the volatility of the economic environment and regulatory pressures. Romgaz S.A. ranks third, with a turnover of over 7.5 billion lei and a net profit exceeding 3 billion lei. Although the company recorded an annual decline in turnover of approximately 12.6%, its financial performance suggests a high capacity to adapt to market conditions and manage the risks associated with the natural gas sector. Nuclearelectrica S.A. ranks fourth, reporting a turnover of over 4.6 billion lei and a net profit of approximately 1.7 billion lei in 2024. The annual reduction in turnover, estimated at around 37%, did not significantly affect the company's position in the ranking of state-owned companies, highlighting its systemic role in ensuring the of basic electricity production and maintaining energy security.In fifth place is Complexul Energetic Oltenia S.A., which, despite a decrease of approximately 48% in turnover, reported revenues of over 3.2 billion lei and a net profit of 317 million lei. These results reflect the company's ability to maintain its economic viability in a context characterized by structural pressures and the demands of the energy transition.

At the same time, the most representative private companies with domestic capital can be seen in Table 3.

Electrica Furnizare S.A. is an important domestic player, but not a state-owned majority shareholder. In the case of this company, the decline in turnover in 2024 (−19.7%) and the shift from profit to loss are the consequences of regulatory pressures and high costs specific to the supply and distribution segments, despite the company's systemic role in the energy transition

Table 3. Top representative Romanian private companies contributing to energy security

No.	**Companies contributing to energy security**	**Turnover (lei)**		**Profit (lei)**	
		2023	**2024**	**2023**	**2024**
1	Electrica Romania SA (supply and distribution)	10,846,176,909	8,708,109,254	64,882,909	-354,837,176
2	NOVA POWER & GAS S.R.L.	2,821,622,868	2,621,129,595	335,595,273	228,401,467
3	Electrocentrale Bucharest SA	3,075,575,686	2,506,399,064	122,362,122	434,574,235
4	Tinmar Energy SA	3,114,071,978	1,475,497,375	311,095,018	388,230,752

The data was taken from the companies' annual reports and officially published statements [28-31].

If we look at the ranking of the most profitable companies in the energy sector for 2024 (Table 4), we see that public companies dominate in terms of profitability, even though a private company with majority foreign capital ranks first.

Table 4. Top most profitable companies in the energy sector in 2024

No.	Companies	Profit in 2024	Source of capital
1	OMV Petrom	**4,143,914,310**	private with majority foreign capital
2	Hidroelectrica	4,071,551,582	state
3	Romgaz	3,090,696,860	state
4	Nuclearelectrica	1,708,188,496	state
5	Transelectrica	585,924,311	state
6	CE Oltenia	317,505,919	state
7	Nova Power & Gas	228,401,467	Private with domestic capital
9	Premier Energy	16,110,563	Private with majority foreign capital
10	Delgaz Grid	16,008,397	Private with majority foreign capital

Source: [24-31].

5. CONCLUSIONS

Romania's energy market has undergone a gradual liberalization process since the 2000s, accelerated under the influence of European legislation. The main factors influencing competitiveness in Romania are energy dependence and the production mix, the role played by state-owned companies, the degree of legislative predictability, and investments in infrastructure and support for renewable energies.

It should be noted that the energy production segment is dominated by a few large, mostly state-owned companies (Hidroelectrica, Nuclearelectrica, CE Oltenia), while the supply segment has been completely liberalized, allowing consumers to choose their supplier.

The main conclusions drawn from the research show that:

- Domestic energy companies play a decisive role in Romania's energy security.
- State-owned companies are the most profitable and strategically important.
- Private companies also have a role to play, being dynamic and contributing to market diversification, particularly in the area of supply and new technologies (such as digitization).
- Financial indicators show solid performance for the period 2023–2024, especially for Hidroelectrica, Romgaz, and Nuclearelectrica, representative state-owned companies.

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SPECTRAL ANALYSIS OF PLASTIC TYPES IN THE BED OF THE EASTERN JIU RIVER

Angelica-Nicoleta GAMAN[1*], Marius KOVACS[1]

Abstract: *Plastic waste represents a global problem, their presence in the environment, particularly along riverbanks and in oceans caused by discharge of various types of waste, being well-known. However, documented analysis of these plastics can contribute to understanding and raising awareness of the risks they pose to the aquatic environment and human health. Macro-sized plastic materials of various dimensions and shapes that reach the water system, gradually degrade and break down into smaller fragments as they are transported and, over time, become microplastics in other rivers, streams, and oceans. The purpose of this study is to identify microplastics present in the bed of the Eastern Jiu River basin using Fourier-transform infrared spectroscopy (FTIR), which provides a qualitative spectral analysis of absorption or emission, followed by cartographic analysis allowing classification of microplastics found, based on size and type of contaminant (polyester, polypropylene, polyvinyl chloride, polystyrene). Therefore, six types of plastic materials from the Eastern Jiu River bed were explored, and the applied FTIR method provided high identification precision, significant time savings compared to other techniques, and easy implementation by inexperienced operators. Our results have shown that infrared spectral analysis of plastic types is a powerful and versatile technique, offering detailed and valuable information on composition and characteristics of plastic materials. Moreover, this study aims to advance understanding of the processes related to plastic waste affecting aquatic life and, consequently, human health.*

Key words: *plastics, microplastics, environment, water pollution, infrared spectrometry*

1. INTRODUCTION

During the meeting held in Nairobi, Kenya between February 28th and March 2nd 2022, the United Nations Environment Assembly agreed to launch negotiations on a legally binding global agreement to combat plastic pollution. As outlined in the European Green Deal and the Circular Economy Action Plan, the EU emphasized the need for a circular, lifecycle-based approach to plastics as the basis for a new legally binding global agreement. The solution lies in prevention, proper design and production of plastic materials, as well as their efficient use, followed by sound management when they become waste. The treaty, titled "Ending Plastic Pollution: Pathway to an International Legal Agreement," aims not only to address plastic production and use in packaging but also the management of plastic masses as waste. Thus, actions to protect,

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sustainably manage, and restore natural ecosystems simultaneously provide environmental, social, and economic benefits and contribute to building resilience.

Plastic (Figure 1.) is one of the materials that has fundamentally changed the packaging industry, being used both as the main element (products packaged or bottled in plastic bags or bottles) and as a secondary element (plastic films, bubble wraps, ESD bags).

Figure 1. Plastic materials regularly used by population

In 1988, the Plastics Industry Society established Resin Identification Codes (RIC) for each type of plastic, enabling quick identification of materials for recycling and sorting items according to their resin type. Globally, seven standard classifications for plastic materials and information regarding their recycling and reuse were established, namely: Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), Other types of plastic materials (e.g., polycarbonates). [1, 12].

Microplastics are plastic pieces smaller than 5 mm, which appear in the environment as a consequence of plastic pollution.[2] Microplastics are present in a variety of products, from cosmetics to synthetic clothing, plastic bags, and bottles. Many of these products easily enter the environment because of improper waste recycling.

Common plastic materials for which usage should be limited include: food packaging and containers, bottle caps and lids, plastic bags, straws and stirrers, beverage bottles (PETs), polystyrene package containers. [6, 10].

2. MATERIALS AND METHODS

Fourier-transform infrared spectroscopy (FTIR) is a fundamental analytical tool in the analysis of plastic and polymer materials, used for quality control, competitive reverse engineering, and troubleshooting plastic product manufacturing issues.[5] Infrared spectral analysis of plastic types is a complex and essential process, widely employed in industry and research to identify and characterize the chemical composition of these materials. The technique relies on the careful study of the infrared absorption spectra of plastics, which reflect how specific functional groups interact with infrared radiation. By interpreting these spectra, a detailed picture of the material's molecular structure can be obtained, thus facilitating the identification of the plastic type and determination of its chemical composition. In addition to identifying the plastic type, infrared spectral analysis can provide information on other material characteristics, such as degree of polymerization, presence of contaminants or additives, or even mechanical or thermal properties of the material. Therefore, this technique is essential in development and quality control of plastic materials used in a variety of industrial and commercial applications.

For the identification of plastic types using the FTIR method, attenuated total reflection (ATR) was employed. The ATR method involves placing the sample on a high refractive index prism (ZnSe) and measuring the spectrum using infrared light that is totally internally reflected within the prism. The ATR technique is highly convenient and fast, as it requires almost no sample preparation.[7] Measurements performed using the Shimadzu IR Tracer 100FTIR spectrometer were conducted in absorbance in the range of 600-4000nm, and peak deconvolution was estimated using the least squares method at a resolution of 2 cm-1.

The process of sampling plastic materials of various sizes and shapes (Fig. 2) was carried out within the bed of the Eastern Jiu River, these being considered representative samples of the daily consumption of population in the Eastern Jiu Valley. Research conducted to identify and classify types of plastic materials was performed using the FTIR spectrometer.

Figure 2. Types of plastic materials found in the Eastern Jiu River

Based on the IR spectrum obtained, the plastic materials identified in the representative sample were classified according to the "Resin Identification Codes (RIC)" recycling symbols as follows: Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), and other types of plastic (polyurethane, polycarbonate, ABS) [4, 9].

The interpretation of FTIR (Fourier-transform infrared) spectra involves identifying and analysing characteristic bands in the obtained spectrum. [3, 11, 8, 5] The main steps in interpreting an FTIR spectrum are:

a. Identification of characteristic bands: firstly, characteristic bands in the FTIR spectrum are identified. These are regions where infrared absorption is significant and indicate the presence of certain functional groups or chemical bonds.

b. Assignment of bands: the characteristic bands are correlated with the corresponding functional groups or chemical bonds in the compound or material analysed. This is done based on knowledge of organic chemistry and IR spectroscopy.

c. Analysis of band shape and intensity: research is conducted on the shape and intensity of the characteristic bands. The shape of the bands can provide information about the environment, and intensity can be correlated with the concentration or crystallinity state of the material.

d. Comparison with reference spectra: for confirmation, the obtained spectrum is compared with available reference spectra for similar compounds or materials. This helps in the proper identification of functional groups and confirmation of chemical composition.

e. Detailed interpretation: in some cases, detailed interpretation may involve analysing sub-bands and subtle changes in the spectrum depending on experimental or processing conditions.

3. RESULTS AND DISCUSSION

For the advanced analysis of IR spectra for the identified plastic materials, Shimadzu LabSolutions software was used, which enables the identification and assignment of characteristic bands.

Spectral analysis of plastic types

1. The analysis of the IR spectrum for polyethylene terephthalate (PET) (Fig. 3) involves the identification and interpretation of characteristic bands in its IR spectrum.

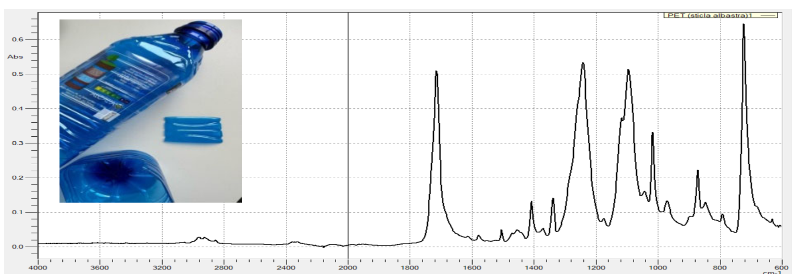

Figure 3. IR spectrum of polyethylene terephthalate (PET)

The infrared spectrum analysis for polyethylene terephthalate, showed several characteristic bands, as follows:

• Carbonyl group stretching: PET contains ester functional groups (-COO-) in its structure, generating a strong absorption band around 1710-1735 cm^{-1}, corresponding to the stretching vibration of the carbonyl group (C=O).

• C-H bond stretching: stretching vibrations of methylene (CH2) and methyl (CH3) groups commonly appear in the region of 2800-3000 cm^{-1}.

• C-O bond stretching: the etheric bond (C-O-C) of PET can produce a weak absorption band in the region of 1100-1300 cm^{-1}, corresponding to the stretching vibration of the C-O bond.

• Aromatic C=C bond stretching: PET contains aromatic rings in its structure, generating characteristic absorption bands around 1600-1615 cm^{-1}, corresponding to the stretching vibrations of the aromatic C=C bonds.

• Amorphous vs. crystalline regions: PET can exist in both amorphous and crystalline forms, and the relative proportions can affect the spectrum. The amorphous phase generally exhibits broader and less intense bands compared to the crystalline phase.

2. The analysis of the IR spectrum for high-density polyethylene (HDPE) (Fig. 4), known for its excellent strength-to-density ratio and chemical resistance.

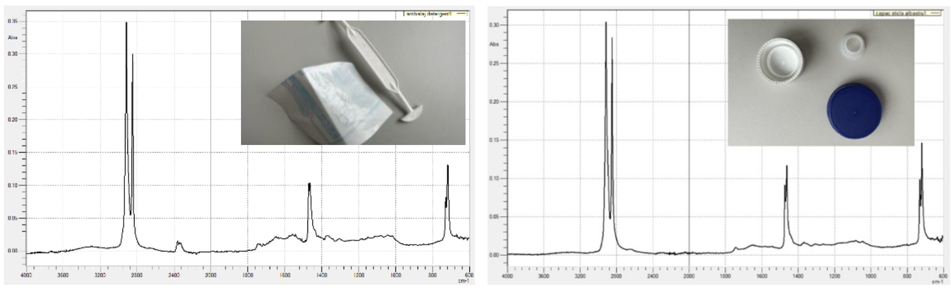

Figure 4. IR spectrum of high-density polyethylene (HDPE)

The analysis of the infrared spectrum for high-density polyethylene (HDPE), showed several characteristic bands, as follows:

• CH2 and CH3 stretching: stretching vibrations of methylene (CH2) and methyl (CH3) groups appear in the region of 2800-3000 cm^{-1}. These bands are usually broad and intense due to the presence of multiple CH bonds.

• CH2 deformation: deformation vibrations of methylene (CH2) groups typically appear as bands in the region of 1300-1470 cm^{-1}.

• C-H bending: bending vibrations of CH2 and CH3 groups produce bands in the region of 1350-1470 cm^{-1}.

• C-C stretching: stretching vibrations of carbon-carbon (C-C) bonds are usually observed around 1000-1100 cm^{-1}.

• Out-of-plane C-H bending: bending vibrations of CH2 and CH3 groups perpendicular to the main chain typically appear as bands in the region of 700-750 cm^{-1}.

• Crystalline and amorphous regions: similar to PET, HDPE can exist in both crystalline and amorphous forms, which can affect the spectrum. Crystalline regions may exhibit more pronounced bands compared to the broader bands of the amorphous phase.

3. The analysis of the IR spectrum for polyvinyl chloride (PVC) (Fig. 5) involves the identification of characteristic bands and their assignment to the functional groups and chemical bonds present in PVC materials.

The infrared spectrum analysis for polyvinyl chloride (PVC), showed several characteristic bands, as follows:

• C-H stretching band: in the region of 2800-3000 cm^{-1}, stretching bands of CH groups from the alkyl side chain can be observed. These are present due to the presence of methyl and methylene groups in the structure of PVC.

• C-Cl stretching band: around 700-800 cm^{-1}, stretching bands of C-Cl bonds can be identified. This band is one of the most distinctive for PVC, as it reflects the presence of chloride groups in the polymer structure.

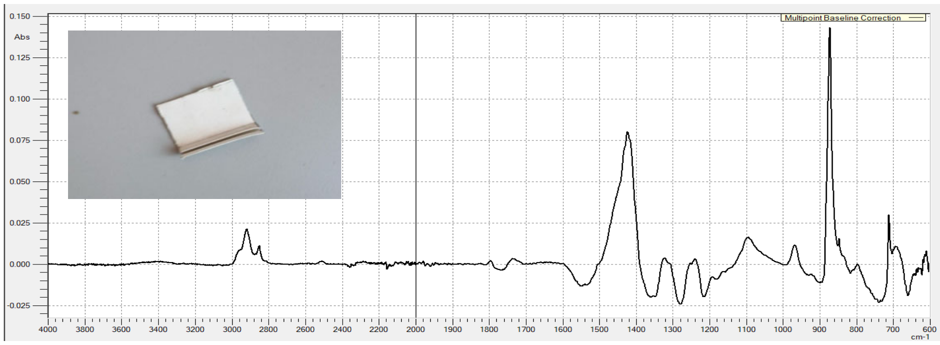

Figure 5. IR spectrum for polyvinyl chloride (PVC)

• C-H bending (out-of-plane bending) band is a CH groups' band of bending and can be observed in the region of 900-1000 cm^{-1}.

• C-C stretching band observed in the region of 1000-1200 cm^{-1}, appears as a stretching band of C-C bonds, which is or can be more intense in the case of unchlorinated PVC.

• Other characteristic bands: depending on the production processes and additives used, other characteristic bands may appear, such as those corresponding to vinyl groups or bands associated with stabilizers, plasticizers, or other additives.

Interpretation of the IR spectrum for PVC is useful for identifying and characterizing this polymer in various applications, including in the chemical industry, in the production of plastic materials, and in recycling. Comparing the PVC spectrum with reference spectra or with spectra of other polymers can help confirm the identity of PVC and evaluate its quality and composition.

4. The analysis of the infrared spectrum for low-density polyethylene (LDPE) (Fig.6) involves identifying characteristic bands and assigning them to the functional groups and chemical bonds present in the identified plastic materials.

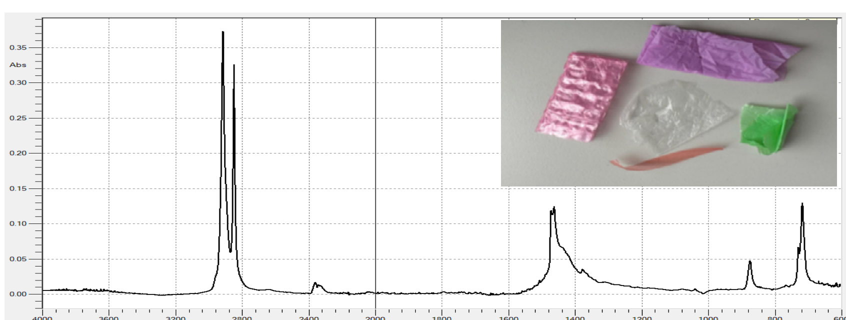

Figure 6. Infrared spectrum for low-density polyethylene (LDPE)

The infrared spectrum analysis for low-density polyethylene (LDPE), showed several characteristic bands, as follows:

- C-H stretching: characteristic bands for stretching of methyl (CH3) and methylene (CH2) groups appear in the region of 2800-3000 cm^{-1}. These bands are broad and intense due to the presence of multiple C-H bonds.
- C-H deformation: in the region of 1300-1470 cm^{-1}, deformation bands of methylene (CH2) groups can be observed.
- C-H bending: bending vibrations of methylene and methyl groups can be identified in the region of 1350-1470 cm^{-1}.
- C-C stretching: Stretching of carbon-carbon (C-C) bonds can be observed in the region of 1000-1100 cm^{-1}.
- Additional bands are observed depending on the production process and additives used; other characteristic bands associated with additives or stabilizers used in manufacturing may also appear.

Amorphous and crystalline regions: LDPE can exist in both amorphous and crystalline regions, and the relative proportions of these can affect the appearance of the spectrum; crystalline regions may exhibit more pronounced bands than amorphous regions.

Infrared spectral analysis of LDPE is important for identifying and characterizing this polymer in various applications, such as in the packaging industry, film production, and other fields. Comparing the LDPE spectrum with reference spectra or with spectra of other polymers can help confirm the identity of LDPE and evaluate its composition and quality.

5. The analysis of the IR spectrum for polypropylene (PP) (Fig. 7) is characterized by specific absorption bands associated with various modes of vibration and rotation of polypropylene molecules. Polypropylene is a thermoplastic polymer that is commonly used in various applications such as packaging, textiles, automotive components, and many others.

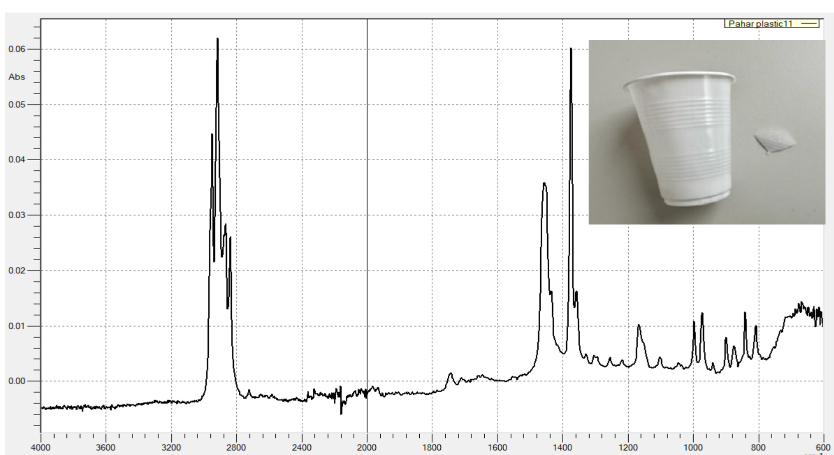

Figure 7. IR spectrum for polypropylene (PP)

The infrared spectrum analysis obtained for polypropylene (PP), showed several characteristic bands, as follows:

- Absorption band of methyl groups (CH3): this appears in the region of 2950-2970 cm^{-1}. This band is associated with the asymmetric and symmetric vibration of methyl groups (CH3) present in the structure of polypropylene.

- Absorption band of methylene groups (CH2): this appears in the region of 2850-2930 cm^{-1}. This band is associated with the asymmetric and symmetric vibration of methylene groups (CH2) in the structure of polypropylene.

- Absorption band of carbonyl group (C=O): polypropylene may contain impurities or terminal groups containing carbonyl groups (C=O), so an absorption band for this group may appear in the region of 1715-1750 cm^{-1}.

- Absorption band of the double bond C=C: in case polypropylene contains double bonds (such as in unsaturated polypropylene), an absorption band for these bonds may appear in the region of 1600-1660 cm^{-1}.

6. The analysis of the IR spectrum for polystyrene (PS) (Fig. 8) provides important information about its molecular structure and the functional groups present. Polystyrene is a widely used polymer in the plastics industry and is primarily composed of styrene monomer units.

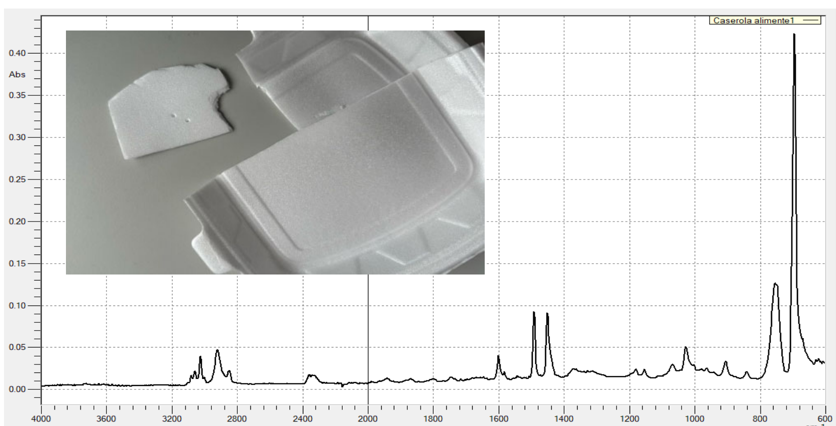

Figure 8. IR spectrum for polystyrene (PS)

The infrared spectrum analysis for polystyrene (PS), showed several characteristic bands, as follows:

- Absorption band of C-H bonds: this appears in the region of 3000-3100 cm^{-1} and is associated with the asymmetric and symmetric vibrations of the C-H bonds within the methyl and methylene groups in the structure of polystyrene.

- Absorption band of aromatic C=C groups: appears in the region of 1450-1600cm^{-1} and is associated with the vibrations of the double bonds C=C in the aromatic ring of styrene. This band is often intense and broad.

- Absorption band of C-C bonds: this appears in the region of 1000-1200 cm^{-1} and is associated with the vibrations of the single C-C bonds in the structure of polystyrene.

- Absorption band of the phenyl group (C6H5): appears in the region of 700-750cm^{-1} and is associated with the deformations of the phenyl aromatic ring in the structure of polystyrene.
- Absorption band of the methyl group (CH3): Depending on the manufacturing process and possible impurities, sometimes an absorption band of the methyl group can be observed in the region of 2800-2950 cm^{-1}.
- Absorption band of the carbonyl group (C=O): if there are impurities or added functional groups such as ester groups (COO-), an absorption band for the C=O bond may appear in the region of 1700-1750 cm^{-1}.

4. CONCLUSIONS

Plastic waste, continuously accumulating both on vegetated riverbanks and in waters, is persistent and has an extended lifespan, threatening both the natural environment and human health. For this purpose, various types of plastics such as polystyrene, polypropylene or other polymers have been analysed using the FTIR method, a complex process involving detailed analysis of multiple spectral characteristics. To confirm identification, the IR spectrum of the sample/specimen was compared with reference spectra of known polymers. Interpreting the spectrum is essential for evaluating the chemical composition, purity and any impurities or structural changes in the plastic material, especially when these types of waste are intended for capitalisation and need to undergo certain technological processes. Furthermore, integrating the data obtained from the IR spectrum within the specific context of plastic material applications is crucial for understanding their behaviour and performance in various environments and reuse conditions. Thus, FTIR analysis conducted on plastic materials in this study highlights a high sensitivity in terms of characterization and identification of each sample. However, validating the results using other complementary analytical techniques such as Raman spectroscopy or thermogravimetric analysis can strengthen the identification process and provide a more comprehensive understanding of the composition and properties of plastic materials.

The FTIR method can be applied in various industries and applications and often serves as the first step in the qualitative analysis process of various types of materials, both organic and inorganic, by examining chemical bonds and composition. In this context, the choice of using FTIR in this research is the first step in identifying types of plastics, thus enabling more detailed research on microplastics. Consequently, the research can be continued with a mapping analysis, performed using an infrared microscope coupled with FTIR, which can map secondary microplastics from water samples, experimentally taking a section of surface water.

Acknowledgements
The current paper was carried out through the Nucleu Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. PN 23 32 01 01 and IOSIN PCDIEX.

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Annals of the University of Petrosani, Mining Engineering, 26 (2025)

DEVELOPMENT OF A METHODOLOGY FOR SIMULTANEOUS ANALYSIS OF PESTICIDE RESIDUES IN WATER BY GAS CHROMATOGRAPHY-MASS SPECTROMETRY (GC-MS/MS)

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Abstract: *Residues of pesticides in water can have significant implications for aquatic and terrestrial ecosystems, as these residues may stem from agricultural runoff, improper disposal, or accidental spills. Therefore, it is imperative to develop precise analytical methodologies to identify and quantify the complex array of pesticide compounds in water. Through the appliance of this analytical methodology, researchers can markedly reduce the cost of pesticide analysis while augmenting the likelihood of accurately identifying the specific pesticide involved. This method enables the simultaneous identification and quantification of as many as 38 highly toxic pesticides, thereby offering a comprehensive and efficient approach to pesticide analysis. Furthermore, in this paper, the methodology was validated, considering specificity, selectivity, linearity, sensitivity (LOD, LOQ), accuracy, precision, robustness, matrix effect, and stability of analytes. To bring matters to a close, the developed method, combined with suitable materials and instrumentation, offers a dependable and efficient approach for analyzing pesticide residues in water. This contribution significantly enhances water quality monitoring and risk assessment strategies by facilitating the identification of pollution sources, the evaluation of exposure levels, and the formulation of effective mitigation measures aimed at safeguarding human health and the environment from the adverse effects of pesticide residues.*

Key words: *gas chromatography, mass spectrometry, MRM, pesticides, water*

1. INTRODUCTION

Residues of pesticides in water ecosystems present significant ecological and human health concerns, stemming from multiple sources including agricultural activities, industrial processes, and accidental releases [1,2,3]. The persistent presence of these chemical residues necessitates the development of precise and reliable analytical methodologies capable of identifying and quantifying a diverse spectrum of pesticide compounds. Effective monitoring and assessment of pesticide residues in water are crucial for comprehending their distribution, persistence, and potential impacts on aquatic and terrestrial organisms, as well as on human populations. In response to these challenges, this study introduces an advanced analytical methodology designed to concurrently identify and quantify up to 34 highly toxic pesticides in water samples. The

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methodology combines analytical techniques with robust validation protocols to ensure accuracy, precision, and reliability in pesticide analysis. Key parameters such as specificity, selectivity, linearity, sensitivity (including limits of detection and quantification), accuracy, precision, robustness, matrix effects, and analyte stability were systematically evaluated to establish the method's suitability for routine environmental monitoring and regulatory compliance [4].

The validation process involved testing aliquots of water sample conditions to assess the methodology's performance and reproducibility. By meeting validation criteria, the methodology demonstrates its capacity to provide precise measurements of pesticide residues, thereby enhancing the effectiveness of water quality monitoring programs and supporting evidence-based decision-making in environmental management [4,5]. Moreover, the validated methodology contributes to broader environmental protection efforts by facilitating the identification of pollution sources, evaluating exposure levels, and formulating targeted mitigation strategies [1,4]. By improving our understanding of pesticide distribution and behavior in aquatic environments, the methodology strengthens risk assessment frameworks aimed at minimizing environmental contamination and safeguarding ecosystem health.

Effective monitoring and assessment of pesticide residues in water are crucial for comprehending their distribution, persistence, and potential impacts on aquatic and terrestrial organisms, as well as on human populations. The integration of this comprehensive analytical methodology with state-of-the-art instrumentation and rigorous quality assurance practices represents a significant advancement in pesticide residue analysis. This approach enhances scientific understanding, facilitates regulatory compliance, and strengthens management strategies concerning pesticide pollution in water systems [5,6].

Moreover, by enabling precise and reliable measurement of pesticide residues, this methodology supports sustainable water resource management practices. It underscores the economic importance of proactive environmental stewardship by minimizing the potential economic costs associated with pesticide contamination, such as impacts on agriculture, fisheries, and public health [2,7]. This integrated approach promotes efficient resource allocation and decision-making, thereby contributing to long-term environmental sustainability and safeguarding ecosystems and human health from the adverse effects of pesticide residues.

2. MATERIALS AND METHODS

Chemicals and Reagents:

Analytical grade standards of pesticide compounds including 508.1 Calibration Mix 1 (Lot nr. A0184460), 508.1 Calibration Mix 2 (Lot nr. A0165566) and 508.1 Calibration Mix 3 (Lot nr. A0176006) were obtained from Restek, USA. Acetonitrile, Acetic Acid (CH_3COOH), Methanol (CH_3OH), Formic Acid (CH_2O_2), extraction salts (Magnesium sulfate ($MgSO4$), sodium chloride ($NaCl$)), and SPE purification purchased from Phenomenex.

Water Sample Preparation

Water samples were prepared by adding calibration mixes of different concentrations in ultra-purified water.

QuEChERS Extraction:

Phase Separation: A 15 mL sample of filtered water was carefully transferred into a 50 mL centrifuge tube, to which 15 mL of acetonitrile/acetic acid (99/1) mixture was added [8,9]. The tube was then promptly placed into a freezer set to -15°C for 15 minutes to facilitate phase separation. Following this step, 4 grams of magnesium sulfate ($MgSO_4$) and 1 gram of sodium chloride were meticulously added to the tube [8,9].. The tube was securely capped and vigorously shaken for 1 minute to ensure thorough mixing of all components. Subsequently, the sample was subjected to centrifugation at 4000 rpm for 5 minutes to separate the phases effectively.

Cleanup Procedure: A 500 µL aliquot of pretreated sample mixed with buffer in a 1:1 ratio was applied onto a solid phase extraction (SPE) cartridge. A vacuum (2-5 mmHg) was applied until the liquid was no longer visible above the top frit, ensuring optimal retention on the cartridge. The cartridge was then washed with 600 µL of methanol in water to remove impurities and enhance analyte recovery. Subsequently, elution of the analytes was achieved using 0.1% formic acid in a mixture of acetonitrile and methanol (90:10). Elution was performed under vacuum (2-5 mmHg) for 1 minute, allowing efficient transfer of analytes into the elution solvent for downstream analysis or further processing.

Instrumental Analysis: Triple-quad GCMS-TQ8050 (Shimadzu Corporation, Japan) was used for the determination of pesticide residues. The instrument was equipped with a Shimadzu AOC-30i autosampler, the injector temperature was set at 250°C with a 1 µL injection volume in splitless mode, using helium as the carrier gas at a flow rate of 1 mL/min. SH-I-5MS used a silica column, 30 m length × 0.25 mm id. × 0.25 µm film thickness, sourced from Shimadzu Corporation, Japan, was used.

The oven temperature program began at 105°C (held for 3 minutes), ramped to 130°C at 10°C/min, then to 200°C at 4°C/min, and finally to 290°C at 8°C/min, held for 6 minutes. For MS/MS analysis, the ion source temperature was set to 230°C and the transfer line temperature to 280°C, utilizing electron ionization (EI) with multiple reaction monitoring (MRM) for data acquisition. Table 1 provides detailed retention times (RT), precursor ions, collision energies (Coll En), and product ions for various pesticide compounds.

Table 1. Transitions and collision energies for each pesticide residue

Compound	RT (min)	First transition (m/z)	Coll En (V)	Second transition (m/z)	Coll En (V)	Third transition (m/z)	Coll En (V)
Etridiazole	10,062	210.90>182.90	10	182.90>139.90	18	210.90>139.90	22
Chloroneb	12.011	206.00>191.00	12	206.00>141.00	20	193.00>113.00	18
Propachlor	13,839	120.00>77.00	20	176.10>57.00	8	120.00>92.00	8
Trifluralin	15,655	306.10>264.10	8	264.10>160.10	18	264.10>206.10	8
alpha-BHC	15,916	180.90>144.90	16	218.90>144.90	8	218.90>144.90	20

Hexachlorobenzene	16,251	283.80>248.90	24	283.90>213.90	32	285.80>250.80	22
Simazine	16,965	201.10>173.10	15	201.10>186.10	15	186.10>173.10	15
gamma-Lindane	17,216	180.90>144.90	16	218.90>144.90	8	218.90>144.90	15
Atrazine	17,253	215.10>58.00	14	215.10>173.10	6	200.10>104.10	15
beta-Lindane	17,489	180.90>144.90	16	218.90>144.90	8	218.90>144.90	15
delta-Lindane	18,642	180.90>144.90	16	218.90>144.90	8	218.90>144.90	15
Chlorothalonil	18,891	263.90>168.00	24	263.90>228.80	18	265.90>168.00	15
Heptachlor	20,865	271.80>236.90	15	273.80>238.90	15	271.80>117.00	15
HCPD	21,102	237.00>119.00	18	237.00>143.00	22	237.00>141.00	15
Alachlor	21,102	188.10>160.10	10	188.10>132.10	18	160.10>132.10	10
Aldrin	22,456	262.90>191.00	32	262.90>193.00	30	292.90>219.00	26
Metolachlor	22,788	162.10>133.10	16	238.10>162.10	12	238.10>133.10	26
Chlorthal-dimethyl	23,264	298.90>220.90	24	300.90>222.90	26	300.90>272.90	14
HEE	24,277	352.80>262.90	12	352.80>316.90	20	352.80>316.90	10
trans-Chlordane	25,213	374.80>265.90	26	372.80>263.90	28	372.80>265.90	22
cis-Chlordane	25,781	374.80>265.90	26	372.80>263.90	28	372.80>265.90	22
Endosulfan 1	25,781	194.90>160.00	8	194.90>125.00	24	194.90>123.00	22
4,4'-DDE	26,422	246.00>176.00	30	317.90>248.00	20	246.00>211.00	14
Dieldrin	26,541	276.90>241.00	12	262.90>193.00	32	262.90>228.00	24
p,p'-DDD	26,595	246.00>176.00	14	317.90>248.00	16	246.00>211.00	12
Endrin	27,232	262.90>191.00	30	262.90>193.00	28	244.90>173.00	32
Endosulfan 2	27,521	194.90>160.00	8	194.90>125.00	24	194.90>123.00	22
Chlorobenzilate	27,657	139.00>111.00	16	251.00>139.00	18	139.00>75.00	26
p,p'-DDT	27,896	235.00>165.00	24	237.00>165.00	28	235.00>199.00	16

Endrin aldehyde	28,119	249.80>214.90	26	344.90>244.90	14	344.90>242.90	14
Methoxychlor	28,651	227.10>121.10	12	121.10>78.00	16	121.10>91.00	18
Endosulfan sulfate	28,816	271.80>236.90	16	386.80>252.90	12	386.80>288.80	10
cis-Permethrine	32,801	183.10>153.10	14	183.10>168.10	14	183.10>165.10	10
trans-Permethrine	32,968	183.10>153.10	14	163.10>127.10	6	183.10>168.10	14

Method validation: The method was validated following Eurachem guide, The Fitness for Purpose of Analytical Methods, which included evaluation of selectivity and specificity, linearity, limits of detection (LOD) and quantification (LOQ), matrix effect, accuracy and precision.

3. RESULTS AND DISCUSSION

Developing Multiple Reaction Monitoring (MRM) methods standards in Gas Chromatograph Mass Spectrometry (GC-MS) for multicomponent simultaneous analyses. Traditionally, creating MRM methods involves programming the analysis time based on the retention times of target compounds. However, when dealing with multiple components, substantial time and effort are required for standard analysis and retention time calculation. Thus, the procedure includes preparing a Smart Database file containing retention indices and measuring a mixed standard pesticide mix solution to refine the retention times registered in the database. The Smart Pesticides Database provided by Shimadzu pre-registers transitions and retention indices for approximately 480 pesticide components, streamlining MRM method creation without the traditional need for detailed method development. This approach optimizes data acquisition specifically at elution times, ensuring sensitive and precise analyses, even for multiple components analyzed concurrently.

Calibration mixes 1 (Lot Nr. A0184460), 2 (Lot Nr. A0165566), and 3 (Lot Nr. A0176006), sourced from Restek, were sequentially injected. The resulting chromatogram exhibited distinct peaks (Figure 1) corresponding to a range of pesticide compounds. This comprehensive analysis enabled precise identification and quantification of each compound present, ensuring reliable data for further analytical assessments.

During MRM (Multiple Reaction Monitoring) analysis, the mass spectrometer selectively monitors predetermined quantification and confirmation ions for each pesticide compound. This focused monitoring approach enhances sensitivity and reduces background noise by specifically analyzing targeted ions. By comparing the observed intensity of the quantification ion against calibration standards, precise concentrations of individual compounds can be accurately determined. Additionally, confirmation ions, which exhibit similar retention times and relative intensities to the quantification ion, provide further evidence of compound presence.

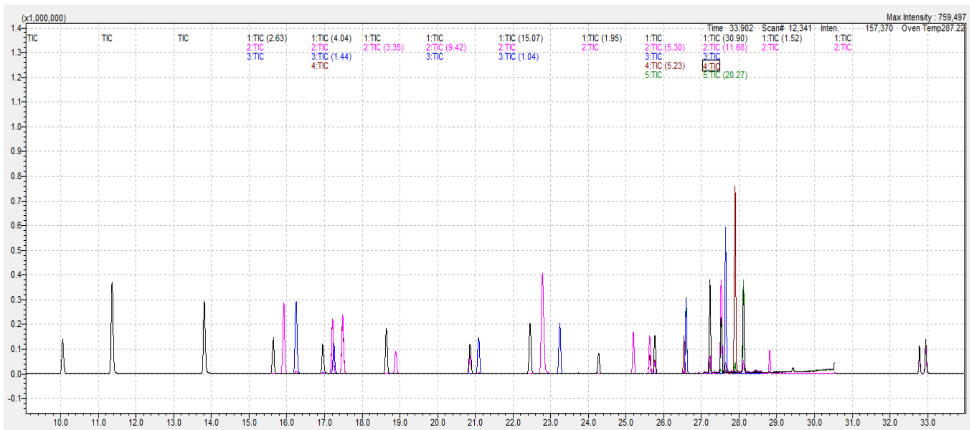

Figure 1. Retention time of the identified pesticide compounds

Transitioning from scan mode to MRM mode and utilizing specific ions for both quantification and confirmation optimize the analysis for detecting and quantifying the targeted pesticides. This method enhances selectivity, sensitivity, and efficiency in the detection and quantification process, particularly beneficial for monitoring the targeted nine phenolic compounds.

Linearity. The method's linearity was evaluated by constructing calibration curves (Figure 2- Figure 3) through single injections across a range of concentrations for the tested pesticides (10, 25, 50.0, 100.0, and 200.0 µg/L). The calibration parameters, including correlation coefficients (R²), ranged from 0.9802 to 0.9998, as detailed in Table 2.

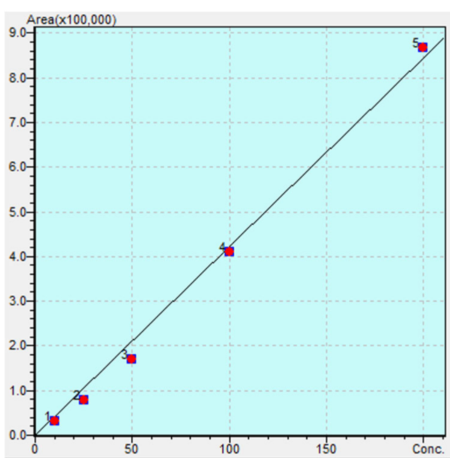

Figure 2. Calibration curve of Etridiazole (R^2=0,9982)

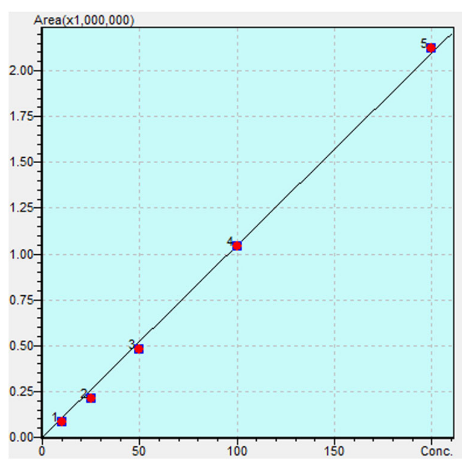

Figure 3. Calibration curve of gamma BHC (R^2=0,9996)

Limit of Detection (LOD) was determined using a signal-to-noise ratio of 3.3:1, achieved by progressively injecting lower concentrations of the compound until the signal (peak area) met three times the average baseline noise level. Equation 1 was used to calculate the lowest concentration meeting this LOD criterion:

$$LOD = \frac{3.3 \times SD\ of\ Blank\ Signal}{Slope\ of\ Calibration\ Curve} \quad (1)$$

Limit of Quantification (LOQ) was calculated with a signal-to-noise ratio of 10:1, where the signal (peak area) was ten times greater than the average baseline noise level. Equation 2 was employed to determine the lowest concentration meeting the LOQ criterion:

$$LOQ = \frac{10 \times SD\ of\ Blank\ Signal}{Slope\ of\ Calibration\ Curve} \quad (2)$$

The standard deviation of the blank signal was based on the average baseline noise level measured from blank samples, while the slope of the calibration curve was derived from linear regression analysis. These parameters provide crucial insights into the method's sensitivity and detection limits for each compound. To evaluate the recovery of pesticide compounds, spike solutions containing known concentrations of these compounds were prepared and added to the sample matrix. These solutions covered a range of concentrations to assess recovery at 25 µg/L and 100 µg/L, added to representative samples from the same matrix type as those being analyzed. The recovery (%) was calculated by comparing the measured concentrations in spiked samples with the known spike concentrations, using Equation 3:

$$Recovery\ (\%) = \frac{\text{Concentration in spiked sample}}{\text{Known spike concentration}}\ x\ 100 \quad (3)$$

This approach not only ensures accurate quantification of pesticide compound concentrations but also serves as a robust measure of the method's precision and reliability in complex sample matrices. By systematically comparing the observed intensities of quantification ions with established calibration standards, the method validates its ability to precisely determine the exact concentrations of each pesticide compound present. This quantitative assessment is crucial for evaluating the method's accuracy across various sample types and matrices, affirming its capability to deliver reliable results consistently.

Table 2. Validation parameters for analysis of pesticide compounds in water

Compound	RT (min)	R^2	LOD (µg/L)	LOQ (µg/L)	Recovery (%)		RSD (%) - 25 µg/L	
					25 µg/L	100 µg/L	Intra-day	Inter-day
Etridiazole	10,062	0,9982	5,044	11,813	99,62	97,60	7,31	8,45
Chloroneb	12.011	0,9995	1,897	9,754	100,87	98,52	4,11	9,47
Propachlor	13,839	0,9995	1,395	8,963	97,12	98,02	3,03	6,38

Trifluralin	15,655	0,9971	4,874	9,854	95,33	102,59	7,90	9,08
alpha-BHC	15,916	0,9997	2,153	7,597	96,94	100,82	7,24	8,32
Hexachlorobenzene	16,251	0,9996	2,674	7,854	99,78	98,71	6,30	7,24
Simazine	16,965	0,9984	3,574	9,751	100,46	100,98	7,40	8,51
gamma-Lindane	17,216	0,9996	2,098	7,865	100,55	100,75	8,01	9,21
Atrazine	17,253	0,9987	4,874	12,549	97,33	100,68	5,19	5,96
beta-Lindane	17,489	0,9996	2,049	7,357	99,54	102,23	5,70	6,51
delta-Lindane	18,642	0,9992	2,187	7,942	97,27	101,59	7,29	8,38
Chlorothalonil	18,891	0,9802	7,662	13,859	98,47	97,59	9,11	11,47
Heptachlor	20,865	0,9982	4,182	8,847	96,68	97,22	9,15	10,52
HCPD	21,102	0,9973	4,362	7,597	100,99	102,95	6,71	7,71
Alachlor	21,102	0,9991	3,260	9,574	99,42	100,41	8,36	9,61
Aldrin	22,456	0,9966	6,424	12,178	97,06	100,85	8,81	12,98
Metolachlor	22,788	0,9983	4,873	8,559	99,27	97,99	6,05	6,95
Chlorthal-dimethyl	23,264	0,9987	5,413	10,742	98,13	101,45	9,06	10,44
HEE	24,277	0,9991	5,301	10,608	96,97	102,60	6,07	6,98
trans-Chlordane	25,213	0,9987	4,781	9,835	95,46	97,50	7,05	10,87
cis-Chlordane	25,781	0,9986	3,788	7,389	95,88	102,71	8,76	10,07
Endosulfan 1	25,781	0,9998	3,905	6,527	99,90	97,59	5,22	6,38
4,4'-DDE	26,422	0,9996	2,207	7,893	98,24	97,07	9,26	10,64
Dieldrin	26,541	0,9993	2,167	4,858	96,08	98,50	6,37	7,32
p,p'-DDD	26,595	0,9996	2,151	5,841	97,55	97,95	7,66	8,89
Endrin	27,232	0,9919	4,591	4,854	95,88	97,50	7,77	8,93
Endosulfan 2	27,521	0,9998	1,169	5,982	99,19	99,34	8,55	9,83
Chlorobenzilate	27,657	0,9991	3,178	6,987	96,38	102,34	5,59	6,42
p,p'-DDT	27,896	0,9984	5,811	10,581	98,05	97,41	5,47	6,29
Endrin aldehyde	28,119	0,9948	5,581	10,945	98,78	102,38	5,42	6,23
Methoxychlor	28,651	0,9991	2,172	5,871	98,18	100,26	8,02	9,22

Endosulfan sulfate	28,816	0,9945	6,997	12,873	98,80	102,99	8,16	9,38
cis-Permethrine	32,801	0,9966	5,037	11,351	99,09	98,98	6,28	7,22
trans-Permethrine	32,968	0,9802	3,388	9,584	100,76	100,02	7,22	8,33

Retention times (RT) for the compounds range from 10.062 to 32.968 minutes, indicating variability in their chromatographic behavior. High R^2 values, ranging from 0.9802 to 0.9998, indicate strong correlation and reliability of the calibration curves used for quantification. Limits of detection (LOD) range from 1.169 to 7.662 µg/L, with corresponding limits of quantification (LOQ) ranging from 4.854 to 13.859 µg/L, highlighting the sensitivity of the method.

The compounds exhibit high recovery rates at both 25 µg/L and 100 µg/L concentrations, demonstrating efficient extraction and quantification methods. Intra-day and inter-day relative standard deviations (RSD), ranging from 3.03% to 9.26% and 5.42% to 12.98%, respectively, indicate acceptable precision and reproducibility of the analytical method.

In our research, we employed GC-MS/MS to analyze a panel of 34 pesticides in environmental and agricultural samples. The method's selectivity was demonstrated by utilizing multiple reaction monitoring (MRM), where each pesticide compound was targeted based on specific precursor and product ion transitions. This approach allowed for the simultaneous detection of multiple pesticides with high sensitivity and selectivity, even in complex matrices such as soil and water.

The specificity of our method was verified through rigorous validation procedures. Matrix-matched calibration curves were constructed to account for potential matrix effects, ensuring accurate quantification of pesticides at trace levels. Moreover, the chromatographic separation achieved with a specialized column and optimized conditions minimized interference from co-eluting compounds and matrix components. Blank samples analyzed alongside spiked samples consistently showed negligible signals at the retention times and MRM transitions corresponding to the target pesticides, affirming the method's capability to distinguish analytes of interest from background noise.

Overall, our study underscores the robustness of GC-MS/MS for comprehensive pesticide analysis in water, providing reliable data crucial for environmental monitoring, regulatory compliance, and risk assessment in agricultural practices.

4. CONCLUSIONS

In conclusion, the pervasive occurrence of pesticide residues in water ecosystems presents a critical ecological and public health challenge, primarily emanating from agricultural activities, industrial processes, and accidental releases. The persistent nature of these chemical contaminants necessitates the development and application of robust analytical methodologies capable of accurately quantifying a diverse array of pesticide compounds in environmental matrices.

This study introduces an advanced analytical framework leveraging the QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) method coupled with gas chromatography-tandem mass spectrometry (GC-MS/MS). QuEChERS, renowned for its efficiency and reliability, facilitates the rapid extraction and cleanup of pesticides from complex matrices such as water samples. This integrated approach enables simultaneous detection and quantification of up to 34 highly toxic pesticides with exceptional sensitivity and specificity.

The methodology's validation followed stringent Eurachem guidelines, encompassing assessments of selectivity, linearity, sensitivity (including limits of detection and quantification), accuracy, precision, matrix effects, and analyte stability. These validation parameters were rigorously evaluated to ensure the method's reliability and suitability for routine environmental monitoring and regulatory compliance.

For instance, the calibration curves constructed for each pesticide compound exhibited high linearity (R^2 ranging from 0.9802 to 0.9998), demonstrating robust quantification capabilities across a wide concentration range (Figure 2 and Figure 3). Limits of detection (LOD) ranged from 1.169 to 7.662 μg/L, with corresponding limits of quantification (LOQ) ranging from 4.854 to 13.859 μg/L, underscoring the method's sensitivity to trace levels of contaminants in water samples (Table 2).

Moreover, the methodology's application of QuEChERS streamlined sample preparation by combining a straightforward extraction procedure with efficient cleanup steps using sorbent materials. This approach effectively minimized matrix interferences while optimizing analyte recovery rates, thereby enhancing the method's robustness and reproducibility across diverse water sample types.

Furthermore, the implementation of QuEChERS with GC-MS/MS not only facilitated the accurate determination of pesticide residues but also provided critical insights into contamination levels and distribution patterns within aquatic environments. The precise quantification of pesticide concentrations supports evidence-based decision-making processes aimed at mitigating environmental impacts and protecting ecosystem health.

In summary, the integration of QuEChERS with GC-MS/MS represents a significant technological advancement in pesticide residue analysis, contributing substantially to scientific knowledge and environmental management practices. By improving our understanding of pesticide behavior and persistence in water ecosystems, this methodology empowers stakeholders to implement proactive measures to minimize environmental contamination and safeguard public health effectively.

Acknowledgements
The current paper was carried out through the Nucleu Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of MCID, project no. PN 23 32 01 01 and IOSIN PCDIEX.

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INDEX OF AUTHORS

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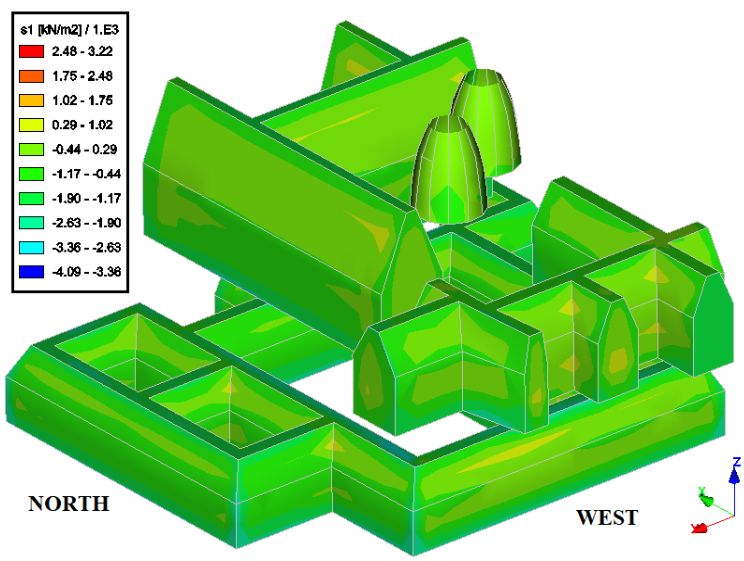

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3. CONCLUSIONS

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4. REFERENCES

[1]. Author, Paper title, Publisher (year) – TNR, 10p

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