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AN INTEGRATED ASSESSMENT OF GEOMECHANICAL AND ENERGY PARAMETERS FOR DEEP PIT RECLAMATION VIA REGENERATIVE CONVEYORS: A KRYVYI RIH CASE STUDY

The object of research is the technological process of rock mass handling. During active mining, this process required moving the overburden from the pit to surface terrain dumps. Once extraction was completed, the operation shifted to mine reclamation through in-pit dumping. At that stage, the stored rock mass was relocated from external dumps back into the mined-out space using regenerative conveyor systems. The main problem to be solved involved reducing the energy footprint of such reclamation operations without sacrificing the geomechanical stability of the dump slope. Conventional haulage methods relied heavily on fossil fuels, leading to carbon emissions and high operating costs. This economic and environmental burden demanded a shift toward technologies capable of capturing the gravitational potential energy of the relocated rock mass.

The research combined limit equilibrium analysis for slope stability evaluation with numerical modeling of the interconnected energy and geomechanical balance. To pinpoint exactly where gravity acted on each rock volume, a step-by-step vertical discretization of the benches was applied, coupled with the geometric centroid method.

Modeling of the reclamation system designed for a 500-meter-deep pit in Ukraine's Kryvyi Rih region proved that regenerative conveyors are capable of accumulating up to 542.36 million kWh of energy (1.24–1.34 kWh/m^3). Calculations revealed a 6.9% technological gap from the theoretical limit. The centroid method yielded zero mathematical error, whereas the area bisection technique underestimated the energy potential by 11.7%.

These findings offered a practical framework for designing reclamation and decarbonization strategies at deep open-pit mines. By leveraging the patented technological solution (Ukrainian Patent No. 158796), mining operators could transform standard environmental cleanup operations into a revenue-generating energy asset.

Keywords: *reclamation, open-pit, conveyor, regeneration, geomechanics, efficiency, dumping, recovery, decarbonization, modeling.*

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1. Introduction

The vast majority of operational iron ore open-pits in the Kryvyi Rih Basin reached critical depths, with design limits frequently exceeding 300 meters and, in several instances, descending to 600 meters or beyond. Restoring the ecological equilibrium at these sites through in-pit dumping necessitated the relocation of hundreds of millions of cubic meters of overburden. At such extreme depths, reliance on conventional truck hauling led to prohibitive operational costs, driven by excessive fuel consumption and a corresponding surge in greenhouse gas emissions. Transitioning to regenerative conveyor systems offered a direct technical solution to these challenges. Beyond the optimization of transportation expenditures, these systems harnessed the gravitational potential energy of descending rock masses to generate electricity, effectively aligning mining operations with global industrial decarbonization mandates.

The regulatory and technical framework for the safe design of in-pit dumping and industrial waste disposal within Ukrainian iron ore quarries was governed by the relevant sectoral Regulations of the Ministry of Industrial Policy [1]. Specific parameters for forming such internal dumps within the mined-out space of deep open-pits were extensively investigated by [2]. Furthermore, the fundamental theoretical principles of surface mining, alongside the geomechanical aspects of slope and highwall stability for both quarries and dumps, were detailed in the seminal textbook [3]. Global best practices and modern quarry reclamation technologies, specifically focusing on UK sites, were analyzed in a critical review by [4]. In turn, innovative technological solutions for the ecological restoration and reclamation of dump slopes and mined-out voids were proposed in the research by [5].

Recent publications in international journals focused on the application of regenerative braking in industrial drives [6, 7] and the optimization of continuous and combined (truck-and-conveyor) mining technologies [8, 9]. However, a critical analysis of the existing literature revealed a lack of integrated "energy – geomechanical balance" models. Most authors treated slope stability and energy recovery as two independent systems. Consequently, the quantitative impact of the mined – out void's geometric configuration on the theoretical and technological limits of energy efficiency during overburden relocation remained unresolved. Furthermore, there was a distinct absence of methodologies for accurately estimating energy generation based on the shifting centers of gravity during the transfer of overburden from external to internal dumps.

The distinctive features of the obtained results lay in the formulation of an integrated energy-geomechanical balance for deep pit reclamation, which interconnected the geomechanical stability thresholds of dump slopes with the theoretical and operational limits of electricity generation. This approach allowed for the quantification of the spatial displacement of overburden mass centers using a step-by-step geometric centroid method, thereby identifying the mathematical limitations inherent in conventional area-bisection techniques. Furthermore, the structural difference between pure physics and operational mining layouts was mathematically substantiated, linking the technological efficiency gap directly to the explicit geometric constraints of the transport infrastructure.

The object of research: the research focused on the cyclical technological process of rock mass handling. During active mining, this process required moving the overburden from the pit to surface terrain dumps. Once extraction was completed, the operation shifted to mine reclamation through in-pit dumping. At that stage, the stored rock mass was relocated from external dumps back into the mined-out space using regenerative conveyor systems.

The aim of this research was to provide a comprehensive substantiation of the geomechanical and energy parameters for a reclamation technology that ensured pit slope stability while maximizing the conversion of overburden potential energy into electricity.

To achieve this aim, the following objectives were addressed:

1. To perform a geomechanical assessment of the stress-strain state of the dump slope under the loading conditions imposed by an inclined conveyor complex.
2. To develop a mathematical model for calculating potential energy based on the iterative shifting of mass centroids.
3. To establish dependences between the degree of quarry backfilling and the intensity of energy generation to identify the technological gap in energy efficiency.

2. Materials and Methods

2.1. Methods

A comprehensive geomechanical and energy assessment of the deep quarry reclamation process was performed by integrating analytical, mathematical, and numerical modeling methods. The methodological framework comprised the following approaches:

- *Limit Equilibrium Analysis (LEA)*: used to assess the stability of pit slopes and benches. This involved calculating the Factor of Safety (F_s) values for dynamically changing geometric configurations during the iterative backfilling process within the quarry;
- *Analytic Geometry and Mathematical Modeling*: used to define the centroids of the relocated rock mass and to establish theoretical limits for energy efficiency. This approach involved a comparative assessment between the traditional area-bisection method and the geometric centroid method. Core algorithms were developed using Python (Python Software Foundation, USA);
- *Finite Element Modeling (FEM)*: performed in the MIDAS GTS NX software (Midas IT, South Korea) to assess dump stability under loading from the conveyor system;
- *Comparative Analysis*: used to compare the efficiency of different calculation methods.

2.2. Geomechanical modeling and parameters

The research tools and the sequence of the research stages were defined within this section. The methodology for the first objective comprised the following steps:

1. Designing the calculation scheme for the quarry and the dump.

Geometric modeling was performed for a deep open-pit mine at a steeply dipping magnetite quartzite deposit. Model parameters:

- Overburden thickness: $H_{overburden} = 50$ m;
- Horizontal thickness of the ore body: $m = 200$ m;
- Parameters of the final open-pit contour: slope angle $\alpha = 40°$; depth $H_1 = 500$ m; bottom width $L_1 = 40$ m; total bottom length $L_S = 1$ km;
- Typical bench height: $H_{bench} = 15$ m (for the upper horizon, $H = 5$ m is assumed).

In the model, the open-pit floor is shaped like a rectangle with two semicircular ends of radius of $L_1/2$. The length of the rectangular part was calculated as follows

$$L_2 = L_S - L_1, \text{ m.} \quad (1)$$

Excavation volumes and geometric parameters were calculated using an algorithm developed in Python (Python Software Foundation, Delaware, USA). The calculated volumes and mass characteristics were as follows:

1) Total rock mass volume (V_{total}): 510.48 million m^3;

2) Total overburden and waste rock volume ($V_{waste\ total}$): 379.26 million m^3, including:

- Overburden: 110.27 million m^3 ($\gamma = 17658$ N/m^3);
- Hard waste rock ($V_{waste\ hard\ rock}$): 269.00 million m^3 ($\gamma = 24525$ N/m^3);
- Ore body volume ($V_{ore\ total}$): 131.22 million m^3;
- Stripping ratio ($K_{stripping\ ratio}$): 0.876 m^3/t.

The total weight of the waste rock to be moved is $Q_{waste\ total} = 8.5442 \cdot 10^{12}$ N.

2. External dump parameters and stability conditions.

An external dump was designed to accommodate the waste rock with the following characteristics:

- Dump tier slope angle: $\beta = 20°$;
- Waste rock swell factor: $K_L = 1.15$;
- Top platform parameters: width $D_1 = 100$ m, length $D_S = 300$ m;
- Calculated dump height (H_{dump}): 195.02 m;
- Working tier height: 20 m (15 m for the upper lift).

3. Geomechanical stability assessment (Midas GTS NX)

The critical section was selected to study the impact of the conveyor system on dump stability. The following system was modeled: "*man-made rock mass – conveyor foundation – moving rock mass*".

The model focuses on a dump slope at its maximum height (195 m) with an angle of 20°. The dump rests on a 50-meter overburden layer, which is underlain by bedrock. The physical and mechanical properties of the materials, typical for the Kryvyi Rih Iron Ore Basin in Ukraine, are listed in Table 1.

Table 1

Physical and mechanical properties of the rocks for modeling

Parameter name	Dump	Overburden	Bedrock
Elastic modulus (E), N/m^2	$1.2 \cdot 10^8$	$4.5 \cdot 10^7$	$4.5 \cdot 10^9$
Poisson's ratio ν	0.25	0.32	0.20
Unit weight (γ), N/m^3	24525	17658	33000
Ko determination	Automatic	Automatic	Automatic
Damping ratio (for dynamic)	0.05	0.05	0.01
Cohesion (C), N/m^2	$6.0 \cdot 10^4$	$3.2 \cdot 10^4$	$1.0 \cdot 10^9$
Frictional angle (φ), degree	40	18	36

Slope stability was analyzed using MIDAS GTS NX (Midas IT, South Korea). The calculations were performed via the Finite Element Method combined with the Strength Reduction Method (*FEM-SRM*) to determine safety factors and potential failure surfaces.

The linear load from the conveyor onto the dump surface was set at 100 kN/m.

2.3. Energy potential modeling methodology and mass recovery algorithms

In the second stage of the research, numerical-analytical modeling of the potential energy conversion process during the displacement of rock mass into the mined-out space was implemented. The proposed energy balance methodology was based on the use of regenerative systems. Their design and technological features were protected by Ukrainian Patent No. 158796, "Method for reclamation of exhausted open-pit mines" [10].

The calculations were based on the law of conservation of mechanical energy. During the descent of waste rock with mass m from an external dump to the lower horizons of the open-pit (height change ΔH), the volume of generated energy (ΔE) was determined by the formula

$$\Delta E = m \cdot g \cdot \Delta H \cdot \eta_{syst},\ \text{J}, \tag{2}$$

where g – the acceleration of gravity (9.81 m/s^2); η_{syst} – the complex efficiency coefficient, which accounts for mechanical losses in conveyor components, belt resistance, and the efficiency of the generator unit.

Calculation algorithm architecture: the simulation model was developed in Python, utilizing a matrix analysis for volume distribution (Matrix Balancing). The model operated with discrete elements, where dump lifts served as sources and open-pit benches acted as receivers.

The designed algorithm replicated the following technological cycle: the dismantling of the dump was initiated from the upper lifts, while the open-pit backfilling (internal dump formation) was simultaneously performed, starting from the lowest horizons and progressing upward.

Gravity center determination methodology: the core task of the developed model was to precisely calculate the coordinates of the centers of gravity for discrete rock mass volumes. Discrete elements were defined as spatially separated and clearly characterized elementary volumes of overburden rock, each possessing fixed geometric and mass parameters. These elements represented the external dump materials that were relocated by the conveyor into the mined–out open–pit space for subsequent internal dumping. To accomplish this task, two distinct approaches were implemented:

1. *Area Bisection Method (simple engineering approach):* under this approach, the height h_{eq} was determined, which divided the profile (the transverse vertical cross-section of the tier) into two zones of equal area

$$h_{eq} = \frac{a \cdot H - \sqrt{H^2 \cdot \dfrac{a^2+b^2}{2}}}{a-b},\ \text{m}, \tag{3}$$

where H – the cross-section height (trapezoid), m; a, b – the lengths of the trapezoid bases, m.

2. *Geometric Centroid Method:* this approach involved determining the application height of the gravitational force by calculating the geometric center of the trapezoidal cross-section

$$vh_c = \frac{H}{3} \cdot \frac{a+2b}{a+b},\ \text{m}, \tag{4}$$

where H – the cross-section height (trapezoid), m; a, b are the lengths of the trapezoid bases, m.

Logistics and energy parameters calculation: for each individual element within the displacement matrix (i, j) corresponding to a specific discrete volume of rock mass, the following metrics were calculated:

– *Transport distance of discrete elements* ($L_{\Delta V}$): this parameter accounts for the spatial position of the cargo and the actual track configuration

$$L_{\Delta V} = \frac{h_{low} \cdot K_1 + h_{up} \cdot K_2 + K_3}{1000},\ \text{km}, \tag{5}$$

where h_{low}, h_{up} – the displacement heights relative to the surface level, m; K_1, K_2, K_3 represent technological track coefficients.

– *Freight turnover* (W)

$$W = m_i \cdot L_{ij},\ \text{t} \cdot \text{km}, \tag{6}$$

where m_i – the mass of the i-th discrete rock volume being relocated, t; $L_{i,j}$ – the transport distance between the i-th source (dump lift) and the j-th receiver (open-pit bench), km.

– *Potential energy* (E): determined by the difference in heights of the mass centers of gravity in the dump and the open-pit

$$E = m \cdot g \cdot \Delta H,\ \text{J}, \tag{7}$$

where

$$\Delta H = \left(H_{surface} + H_{gravity\_dump}\right) - \left(H_{surface} - H_{gravity\_pit}\right),\ \text{m}. \tag{8}$$

Output data structure: the modeling results were systematized into four structured datasets:

1. *Displacement matrix*: the logic of the reclamation sequence.
2. *Operational indicators:* energy taking into account real transport routes and freight turnover.
3. *Total theoretical potential:* an idealized physical model between centroids, serving as a benchmark for energy efficiency.
4. *Summary balance:* integral project indicators for the technical and economic feasibility research.

This methodology allows for the optimization of regenerative system parameters and the minimization of energy costs for reclamation works at the design stage.

3. Results and Discussion

3.1. Geomechanical assessment of the slope stress-strain state under complex conveyor loading

The numerical modeling of the dump slope stability was performed in the MIDAS GTS NX software package using a finite element simulation model configured with a hybrid (Tri + Quad) mesh generated via the Delaunay triangulation method. The geomechanical stability was evaluated for two boundary states: the initial un-loaded profile (Fig. 1) and the profile subjected to an external conveyor load with a linear intensity of 10000 N/m (Fig. 2). The analysis of the total displacements (TZX Translation) for the un-loaded slope in Design Case 1 yielded a baseline stability factor (K_{st}) of 1.48, outlining the initial configuration of the failure zone (Fig. 3). Upon activating the external load from the conveyor complex in Design Case 5, the critical slip surface shifted, resulting in a decrease of the K_{st} value to 1.45 (Fig. 4). This 2% reduction in geomechanical stability confirmed that the structural framework of the slope retained sufficient load-bearing capacity under operational stress.

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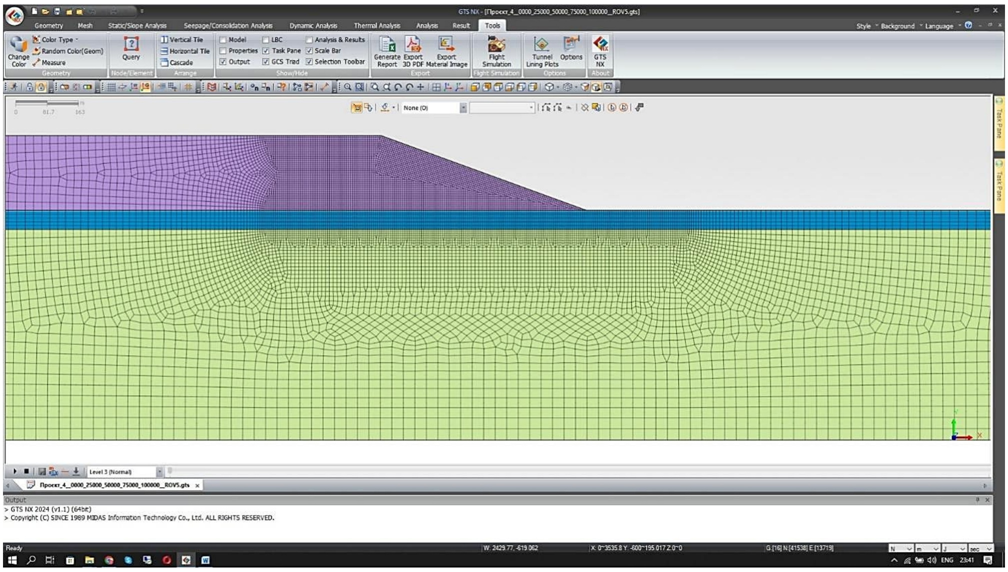

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Output
> GTS NX 2024 (v1.1) (64bit)
> Copyright (C) SINCE 1989 MIDAS Information Technology Co., Ltd. ALL RIGHTS RESERVED.
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Fig. 1. Finite element simulation model of the un-loaded dump slope with a hybrid (Tri + Quad) mesh generated via the Delaunay triangulation method (Design Case 1)

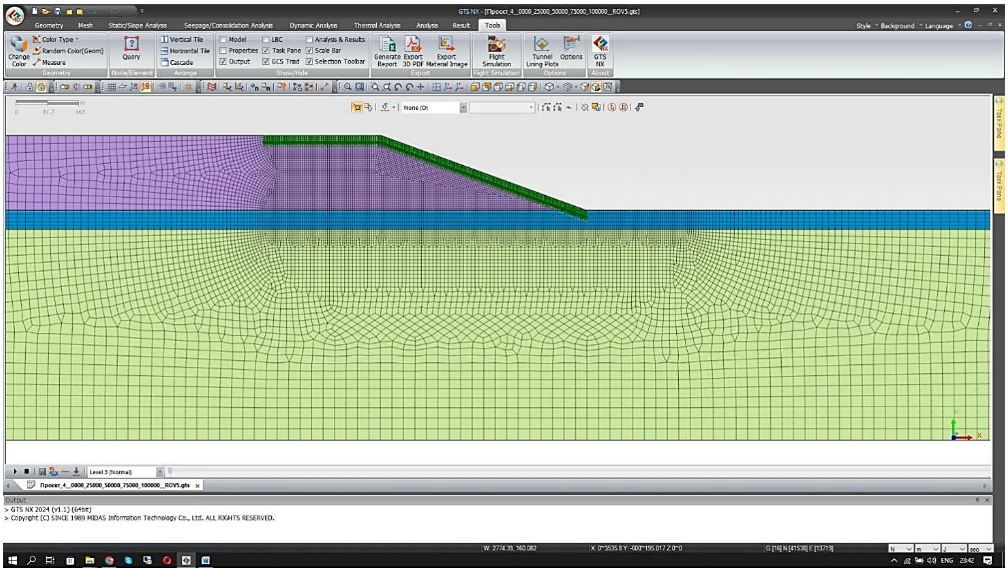

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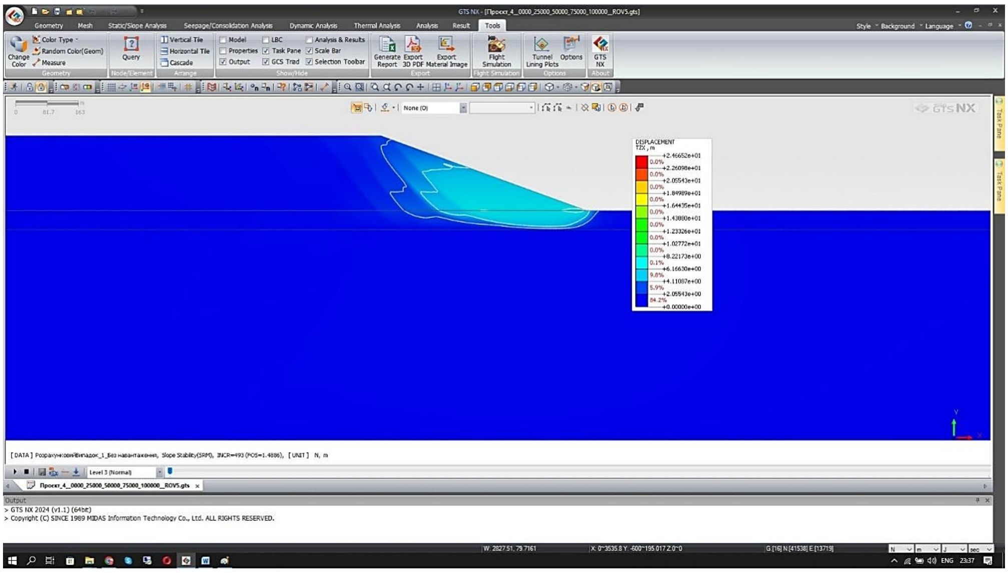
Fig. 2. Finite element simulation model of the dump slope under an external linear load of 10000 N/m from the conveyor complex (Design Case 5)



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Output
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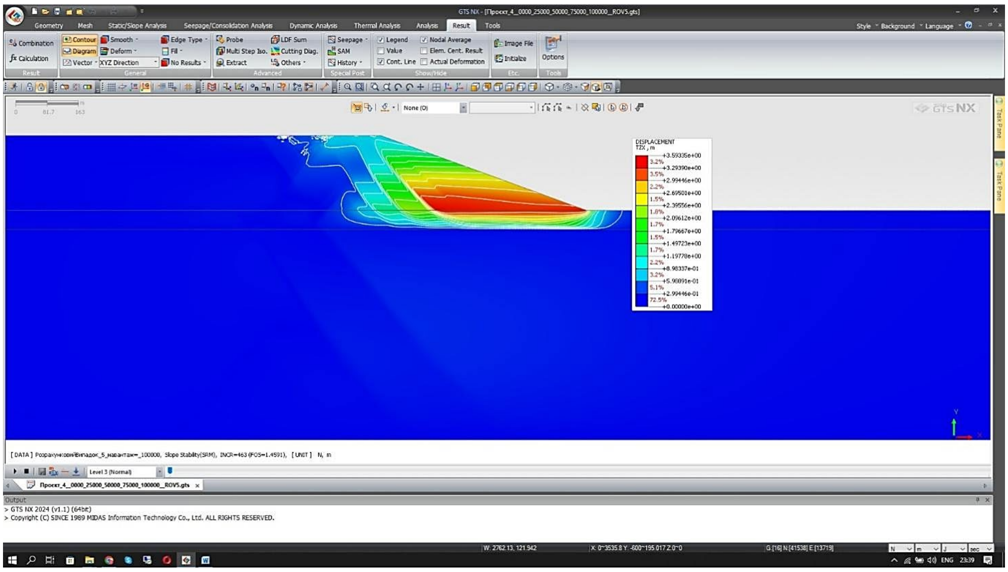
Fig. 3. Contour plot of total displacements (TZX Translation) and the critical slip surface for the un-loaded slope profile in Design Case 1 (K_{st} = 1.48)



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> GTS NX 2024 (v1.1) (64bit)
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Fig. 4. Contour plot of total displacements (TZX Translation) and the critical slip surface under maximum conveyor loading in Design Case 5 ($K_{st} = 1.45$)

3.2. Mathematical modeling of potential energy conversion into electricity

3.2.1. Input data and parameters

The modeling parameters included the physical and mechanical properties of the rock mass, the geometric characteristics of the open-pit mine, and the logistical transportation conditions (Table 2).

3.2.2. Volume-mass balance and geometric verification

The calculated mass balances and the spatial coordinates of the center of gravity determined by different methods were summarized in Table 3.

Based on the vertical discretization of the dump mass, the total weight of the waste rock was calculated as $8.544 \cdot 10^{12}$ N, requiring a final external dump volume of 436.15 million m^3. The height of the total dump gravity center was fixed at 70.12 m using the geometric centroid method, compared to 61.90 m obtained via the area bisection method.

3.2.3. Divergence of calculation methodologies

The step-by-step mathematical verification of the gravity center coordinates across individual dump lifts and the total dump structure was presented in Table 4.

The data in Table 4 demonstrated that the geometric centroid method weighted by cross-sectional area ensured zero mathematical deviation, providing perfect consistency between the individual tier movements and the total mass displacement.

Table 2

Input data for energy-geomechanical balance modeling

Category	Parameter	Symbol	Value	Units
Physical properties of the massif	Density of sedimentary rocks	γ_{sed}	1800	kg/m^3
	Unit weight of sedimentary rocks	$\gamma_{sed(N)}$	17658	N/m^3
	Density of waste hard rock	γ_{waste}	2500	kg/m^3
	Unit weight of waste hard rock	$\gamma_{waste(N)}$	24525	N/m^3
	Density of ore	γ_{ore}	3300	kg/m^3
	Unit weight of ore	$\gamma_{ore(N)}$	32373	N/m^3
Deposit parameters	Depth of the ore body roof	H_3	50	m
	Horizontal thickness of the deposit	m	200	m
Open-pit parameters	Open-pit slope angle	α	40	degrees
	Open-pit bottom width	L_1	40	m
	Bottom length along the strike	L_S	1000	m
	Design depth of the open-pit	H_1	500	m
	Working bench height	h_{pit_bench}	15	m
External dump parameters	Bulking factor of the rock mass	K_L	1.15	–
	Resultant dump slope angle	β	20	degrees
	Upper platform width	D_1	100	m
	Upper platform length	D_S	3000	m
	Dump lift height	h_{dump_bench}	20	m
Logistics (Track)	Track elongation coefficient (dump/pit)	K_{1_dump}/K_{2_pit}	3.9/3.9	–
	Length of the main surface track	K_{3_surf}	1900	m

Table 3

Results for volume-mass balance

Parameter	Value	Units
Total weight of all waste rock (W_{waste_total})	$8.544 \cdot 10^{12}$	N
Required dump capacity (V_{dump})	436.15	million m^3
Height of the dump gravity center (centroid method)	70.12	m
Height of the dump gravity center (bisection method)	61.90	m

Table 4

Comparison of methods for calculating the center of gravity

Method	Variable	Center of gravity, m	Deviation, m	Deviation, %
Calculation based on lift indicators:				
Area bisection	Weighted average by volume	67.06	–3.06	–4.37
Area bisection	Weighted average by cross-sectional area	69.98	–0.14	–0.20
Centroid	Weighted average by volume	67.19	–2.93	–4.18
Centroid	Weighted average by cross-sectional area	70.12	0	0
Calculation based on total dump indicators:				
Total center (area bisection)	Weighted average by volume	61.90	–8.22	–11.72
General center (baseline, centroid)	Weighted average by cross-sectional area	70.12	0	0

3.3. Establishing dependences in quarry backfilling to identify the technological gap in energy efficiency

3.3.1. Waste rock movement: technology and logistics

The simulation of the reclamation cycle established that the available external dump volume (436.15 million m^3) was sufficient to fill 93.4% of the pit's height, which corresponded to 85.4% of its total volume. The final backfill level was located 32.86 m below the pit crest.

3.3.2. Energy efficiency of regeneration

The operational energy generation indicators calculated across 10 distinct dump lifts during the top-down dismantling process were accumulated in Table 5.

Table 5

Energy indicators and conveyor system turnover

Dump lift	Total volume, million m^3	Average arm ΔH, m	Freight turnover, million t · km	Energy, million kWh
10 (upper)	6.39	637.8	56.02	22.19
9	14.67	566.4	120.41	45.23
8	22.06	496.3	168.95	59.58
7	29.82	428.8	212.75	69.60
6	37.96	362.7	251.29	74.94
5	46.49	297.7	284.16	75.32
4	55.39	233.6	310.93	70.42
3	64.67	170.4	331.17	59.96
2	74.33	107.9	344.47	43.64
1 (lower)	84.37	46.8	350.86	21.48
TOTAL	436.15	228.5 (avg.)	2 431.00	542.36

The highest output occurs at tier 5, where energy production hits a peak of 75.32 million kWh. The total energy generated through the actual operational path amounted to 542.36 million kWh. In contrast, the net theoretical potential energy calculated strictly via total gravity center displacement amounted to 582.80 million kWh. The absolute difference between the theoretical limit and operational layout was 40.44 million kWh, which identified a fixed technological efficiency gap

$$\{(582.80 - 542.36)/582.80\} \cdot 100\% = 6.94\%.$$

3.4. Discussion

The results proved that the regenerative conveyor transport transforms deep open-pit mine reclamation from an environmental expenditure into an energy-generating asset. The modeling quantified that the specific energy generation under the theoretical scenario reached 1.336 kWh/m^3, while real-world mining technology constraints reduced this figure to 1.244 kWh/m^3, establishing a 6.94% technological gap.

Conventional analytical methods, such as the 2D limit equilibrium methods described by Drizhenko [3], tend to overestimate the negative impact of transport infrastructure on slope stability.

Traditional mining calculations often relied on the "area-split" method or simple volume averages. However, as demonstrated in Table 4, splitting the area into two equal parts underestimated the center of gravity height by 11.72% (–8.22 m) for the total dump. In terms of energy potential, this indicated that standard methods significantly undervalued the baseline potential energy.

Prior to this research, the development of steep-dipping iron ore deposits through open-pit mining primarily focused on the reclamation and greening of external dumps, despite the significant potential of these dumps for electricity generation. Conventional conveyor system designs focused exclusively on energy consumption by transport components. In contrast, this research quantified that even with a 100% efficient regenerative drive, approximately 7% of the net potential energy was lost due to mining technology constraints.

The main limitation of the formulated models was the assumption that the rock mass, rock types, and density within the external dump were relatively homogeneous, utilizing a simplified geometric shape. It was also assumed that the foundation properties and conveyor system characteristics remained completely uniform throughout the model.

In real-world conditions, factors like rock mass heterogeneity, variations in moisture content, and localized settling over time could shift the actual center of mass.

The calculated technological gap depended on the height of the dump tiers. Consequently, variations in mining parameters could alter the efficiency gap. Furthermore, this calculation did not account for electromechanical losses within the conveyors, such as recuperation efficiency constraints.

Future researches will focus on assessing the long-term strength of the dump rocks. Specifically, modeling the stability factor variations over time under continuous dynamic loading from the conveyor is intended. This will include accounting for rock creep, degradation of cohesion parameters, and shifting boundary conditions during seasonal freeze-thaw cycles.

The next stages will account for heterogeneous rock distribution by integrating Python scripts with 3D geological block models of the dump. This approach will enable the tracking of center-of-mass shifts within non-uniform rock masses.

The primary direction involved the combination of this efficiency assessment model with actual conveyor system data. This integration aimed at determining the final volume of commercial electricity for direct supply back to the local power grid of the Kryvyi Rih mining region in Ukraine.

To scale up the practical applicability of Ukrainian Patent No. 158796, future research will focus on assessing the long-term strength of dump rocks under continuous dynamic loading, accounting for rock creep and seasonal freeze-thaw cycles. The mathematical model will be integrated with 3D geological block models and actual electromechanical conveyor efficiency data to determine the precise volume of commercial electricity suitable for direct supply back to the regional power grid.

4. Conclusions

1. The data proved that the combined static and dynamic impact of the infrastructure (conveyor system) reduced the stability factor by less than 2%. Such a negligible shift confirmed the system stayed well within safe operational margins throughout the entire reclamation cycle.
2. Modeling the relocation of 379.26 million m^3 of rock (436.15 million m^3 considering a 1.15 bulking factor) established a baseline physical potential of 582.80 million kWh. Using area-weighted mass centroids proved vital; simple averaging led to significant errors in gravity center determination, which was precisely fixed at 70.12 m.
3. Simulating a workflow of 10 dump tiers and 32 pit benches yielded an actual energy output of 542.36 million kWh at a mean depth of 228.5 m. Due to inherent technological constraints, the output was 6.94% (40.44 million kWh) lower than the theoretical maximum. Thus, the expected specific energy yield was established at 1.244 kWh per cubic meter of relocated mass.

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Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors strictly followed the journal's editorial policy and limits on artificial intelligence. While working on this paper, the Gemini (Google) language model under close human supervision was used. The tool was never used to write text; its involvement was limited to debugging original Python scripts and generating literature search queries. The authors thoroughly cross-checked and independently verified all code. Standard engineering workflows were used throughout. The tool acted purely as a technical aid to speed up data processing and had no influence on our hypothesis, geomechanical interpretation, or final conclusions. This research is entirely the original work of the authors.

Authors' contributions

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