Performance Evaluation of Heading-and-Winning Machines in the Conditions of Potash Mines

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Abstract: The authors focus on the process of potash ore production by a mechanized method. They show that currently there are no approved procedures for assessing the performance of heading-and-winning machines operating in the conditions of potash mines. This causes difficulties in determining the field of application of heading-and-winning machines, complicates the search for implicit technical solutions for the modernisation of existing models of mining units, prohibits real-time monitoring of the stability of stope-based technological processes and makes it difficult to assess the performance of the services concerning mining enterprises. The work represents an aggregate assessment of the performance of heading-and-winning machines for potash mines by determining complex indicators describing the technological and technical levels of organising the work in stopes. Such indicators are the coefficients of productivity and energy efficiency, respectively. Experimental studies have been carried out in the conditions of the potash mine of the Verkhnekamskoye potassium-magnesium salt deposit to assess the performance of the latest and most productive Ural-20R heading-and-winning machines manufactured in Russia. Using the above methodological approaches, this paper shows that the unsatisfactory technological performance of the studied machine is due to the low productivity of the mine district transport. The average productivity coefficient was 0.29. At the same time, high values of the energy efficiency coefficient show that the productivity of the machine is on par with design conditions.

Keywords: heading-and-winning machine; performance evaluation; specific energy consumption; productivity; potash mining

1. Introduction

Companies from Russia and the Commonwealth of Independent States (hereinafter CIS) engaged in the extraction of potash and magnesium ores widely use room-and-pillar mining with strip pillars to mine productive formations, which involves sets of mining and transporting machines referred to as mechanized combine complexes. Each mechanized complex includes the mining unit, which is a heading-and-winning machine; a storage capacity, which is a feeder-breaker; and the delivery vehicle, which is a self-propelled car [1–4].

At Russia’s potash mines, the most widely used mining units are the Ural heading-and-winning machines (Figure 1) manufactured by Kopeysk Machine-Building Plant JSC (Chelyabinsk Region). Continuous work on improving the design of Ural combines, carried out by the manufacturer, has ensured high reliability indicators (MTBF (mean time between failures), maintainability) and adaptability of the combines to the conditions of potash enterprises in Russia and CIS countries. Comparative tests with similar heading-and-winning machines manufactured in Western Europe and North America have shown higher average annual productivity of Ural combines in fracturing of sticky or strong potash ores of the Verkhnekamskoye deposit [5]. Ural-20R units are used in rooms with...
height $H = 3.1 \text{ m}$ and a cross-sectional area of $15.75 \text{ m}^2$. The rated power of each of the actuator engines is $160 \text{ kW}$ in relative motion; the rotary actuator has a power of $75 \text{ kW}$.

![Figure 1. Ural-20R-11 Combine (general view).](image)

A comparative assessment of the performance of each heading-and-winning machine in the course of operating in the conditions of potash mines is necessary in order to determine their field of application, develop technical solutions for the modernisation of existing models, control the stability of technological processes in the stope and evaluate the performance of the services on mining enterprises.

2. Performance Evaluation Procedures for Heading-and-Winning Machines in Potash Mines

The task of assessing the efficiency of the use of heading machines for potash mines is possible through the development and implementation of automated on-board systems that monitor the operating parameters of mining machines. Such systems should be based on scientifically grounded methods of collecting and analyzing recorded data, aimed at ensuring trouble-free operation and increasing the productivity of mining equipment [6–22].

The technical literature indicates that the most informative and simple method of monitoring the performance of mining combines is continuous monitoring of the load on the drive motors, carried out by measuring currents, voltages and active and full capacity. It is also necessary to monitor the movement, feed rate and productivity of the combine and relate these indicators to absolute time.

It is known that the performance of extracting machines in real operating conditions can be reliably evaluated by correlating the basic (nominal) and actual values of energy indicators describing their operation. For combines operating in potash mines, one such indicator is the specific energy consumption for the potash ore mining process $H_{wb}$ [23–26].

The basic value of the specific energy consumption for the destruction of the potash formation by the combines’ cutters and for ore loading is calculated by the formula:

$$H_{wb} = \frac{\sum P_r}{60Q},$$  (1)
where \( H_{wb} \) is the base value of specific energy consumption for the destruction of the potash formation by the combine’s cutters and for ore loading, kWh/t; \( \Sigma P_r \) is the rated power of actuating units of the combine’s final elements, kW; \( Q \) is the combine’s technical performance, t/min.

For example, according to the results of calculations carried out for latest and most productive domestic combines Ural-20R with a productivity \( Q = 8 \) t/min and ore cutting resistance \( A_c = 450 \) kN/m, the base value of specific energy consumption for the extraction of potash ore is \( H_{wb} = 1.16 \) kWh/t.

The index of potash ore cutting resistance \( A_p \) is related to the ultimate compression/shear strength of the ore by empirical dependences

\[
f_c = 0.09 A_c; \quad (2)
\]

\[
\tau = 0.33 f_c, \quad (3)
\]

where \( A_c \) is the cutting resistance of potash ore, kN/m; \( f_c \) is the ultimate compression strength of potash ore, MPa; \( \tau \) is the ultimate shear strength of potash ore, MPa [5].

The actual values of the specific energy consumption for the analysed time period \( T \) of the combine operation are based on the data on the energy consumption and the mass of ore mined during this period:

\[
H_{wa} = \frac{T \Sigma P_a G}{T}, \quad (4)
\]

where \( H_{wa} \) is the actual value of the specific energy consumption for the extraction of potash ore during the operation of the combine in the analysed time period, kWh/t; \( T \) is the duration of the controlled period of the combine’s operation, h; \( \Sigma P_a \) is the sum of the average values of the effective power of the combine’s electric motors over the controlled period \( T \), kW; \( G \) is the mass of mined ore, t.

The ratio of the base value of specific energy consumption to the actual value is used to calculate the energy efficiency coefficient of the heading-and-winning machine \( k_{e,ef} \):

\[
k_{e,ef} = \frac{H_{wb}}{H_{wa}}, \quad (5)
\]

The specific energy consumption for the extraction of potash ore is determined taking into account the specifics of the operation of the heading-and-winning machines in real operating conditions. For example, when the combine executes undercutting of the seam (the operation uses a partial section of the final element), the specific energy consumption takes on greater values due to the uneven and incomplete loading of the combine’s electric actuators. The minimal (out of the possible range) values of the specific energy consumption are provided when the combine is operating on a full face, with a nominal capacity [7,27].

The duration of the combine’s operation at a mine is determined by the expression:

\[
T_l = \sum T_{p,l} + \sum T_{t,l} + \sum T_{l,l} + \sum T_{s,m} + \sum T_{u,r}, \quad (6)
\]

where \( T_l \) is the total time of use of the combine at the mine, h; \( \Sigma T_{p,l} \) is the productivity time of the combine, hours; \( \Sigma T_{t,l} \) is the total time for performing auxiliary operations, hours; \( \Sigma T_{l,l} \) is the total time of routine breaks, hours; \( \Sigma T_{s,m} \) is the total time of scheduled repairs, hours; \( \Sigma T_{u,r} \) is the total time of unscheduled repairs caused by sudden failures, hours.

The level of organisation of mining operations in the stope can be estimated by the productivity coefficient \( k_{p,r} \), which is defined as the ratio of the time of the combine’s productive work to the overall time the machine is being deployed:

\[
k_{p,r} = \frac{\sum T_{p,r}}{\sum T_{p,r} + \sum T_{t,l} + \sum T_{l,l}} = \frac{\sum T_{p,r}}{T_l - \sum T_{s,m} - \sum T_{u,r}}. \quad (7)
\]
The quantitative values of the coefficients for productivity and energy efficiency define, respectively, the technological and technical levels of organisation of the potash ore mining process. Comparison of the quantitative values of the considered complex indicators provides for a cumulative assessment of the performance of heading-and-winning machines, taking into account the specifics of their functioning conditions [7,24].

Let us set the range of possible values of complex performance indicators by the coordinate plane, where the ordinate describes the values of the energy efficiency coefficient, and the abscissa shows the productivity coefficient (Figure 2).

Let us take the conditional values of the coefficients \( k_{p.r.u} \) and \( k_{e.ef.u} \) and divide the coordinate plane into four zones.

Conditional values \( k_{p.r.u} \) and \( k_{e.ef.u} \) can be determined, respectively, as the average values of performance coefficients \( k_{p.r} \) and energy efficiency \( k_{e.ef} \) of the operation of the combine miners (plant, enterprise), the work of which is analyzed in a given period of time. Reasonable correction of national values \( k_{p.r.u} \) and \( k_{e.ef.u} \) is possible based on technical and economic feasibility.

If the values of the efficiency indicators are in Zone 1, the work of the combine can be described as ineffective. The low value of the productivity coefficient determines the poor organisation of works in the stope: The period of the combine’s productive work is much shorter than the routine breaks. Low values of the energy efficiency factor determine high specific energy consumption for separating the ore from the potash massif, which, when the combine is operating at full capacity, is a consequence of low productivity and is accompanied by a high content of small non-processing grades in the mined ore.

Zone 2 depicts high productivity factor but low energy efficiency values. The specified combination of efficiency indicators is typical when the unit executes undercutting of the seam (the operation uses a partial section of the final element), or in the case of a continuing limitation of the combine’s feeding speed to the face, when the operator is focused on the operation of a self-propelled car.

\[ \begin{align*}
  &k_{p.r.u} & 1 \\
  &k_{e.ef.u} & 0 \\
  &0 & k_{p.r.u} \\
  &1 & 0 \\
\end{align*} \]
The high technical level of the use of heading-and-winning machines with poorly organised stope mining operations is involved in the coefficients located in Zone 3. For example, lower productivity of self-propelled cars due to the mining of remote chambers would mean longer distances for delivering the mined ore and therefore higher idling time for the combines. This feature is typical for a chamber system for the development of layers of potash ores and is a common reason for a decrease in the actual values of the performance coefficient of combines. According to the authors, the value $k_{p.p.} = 0.5 \ldots 0.6$ should be considered satisfactory.

High productivity of ore delivery vehicles in stope and stability of the potash ore mining process provide for high values of coefficients of energy efficiency $k_{e.ef}$ and productivity $k_{p.r.}$ (Zone 4) [7].

Verification of the proposed methodological approaches and theoretical conclusions was carried out during experimental studies in the conditions of potash mines.

3. Experimental Studies for Evaluating the Performance of Heading-and-Winning Machines in Potash Mines

VATUR, a portable instrumentation unit, was developed and made for experimental research in potash mines. It is designed to measure and register voltages, currents, effective and apparent powers of the combine’s electric actuators, tilt angles and the distance traveled by the combine. VATUR is used as a system for mobile measurement and computation; it consists of several blocks and is installed in the explosion-proof magnetic station of the combine. The portable system (Figure 3) includes a power supply unit, a computing unit, voltage dividers and sensors for current and displacement.

![Figure 3](image)

**Figure 3.** Block diagram (a) and general view (b) of the VATUR unit.

The VATUR unit records the electrical parameters of the combine’s actuators using two voltage inputs. Each input is designed to control the loads of three electricity consumers. The effective power in a three-phase circuit is measured by the method of one wattmeter with a dummy zero.

The device records 100 measurements in a single period of the supply voltage fluctuation cycle. In the course of the experiment, the software of the computing unit runs the
initial processing of instantaneous values and the calculation of quantitative indicators of the combine’s operation. The following parameters of the controlled electric actuators of the combine are calculated:

- effective current
- effective value of phase voltage
- effective and apparent power
- power factor

The displacement sensor was used to control the combine’s feeding speed to the mining face.

The obtained parameter values are recorded in the non-volatile memory of the “VATUR” complex. Specialised PC-VATUR software installed on a personal computer helps with further processing and analysis of the data array [11].

Experimental studies for assessment of the performance of mining machines in the conditions of potash mines were carried out on the Ural-20R-11 combine at the Verkhnekamskoye potassium-magnesium salt deposit. The combine was developing the Krasnyj-II seam; the seam bedding angle during the study period was $-5^\circ + 1^\circ$.

The design features of Ural-20R-11 heading-and-winning machines and the technology of their use together with the equipment of the mining sets determine the magnitude and nature of the load change in the actuators of executive units [28–30]. Figure 4 shows the change curves of effective drive power of the executive units for the Ural-20R combine operating in the stope. Using the load curves, it is possible to single out the intervals of actuator operation in various modes: T1 when the engines off, T2 when the engines are starting, T3 for the transient mode, T4 for steady-state operation, T5 for no-load operation of the combine.

![Figure 4. Changing energy parameters of the actuators operating in the Ural-20R combine: U1—input phase voltage, V; N1—active power of the cutting disc drive, kW; N2—active power of the fender drive, kW; N3—active power of the portable motion drive, kW; T1—the duration of the “off” state of the combine’s electric motors, s; T2—duration of motors’ start, s; T3—hewing duration, s; T4—duration of steady-state operation mode, s; T5—duration of no-load operation mode, s.](image-url)
The total time of the productive work of the combine $\Sigma T_{p.t.}$, time spent on auxiliary operations $\Sigma T_{t.t.}$, and technological breaks $\Sigma T_{l.t.}$ are determined by the load curves of the combine actuators in accordance with the expressions:

$$\Sigma T_{p.t.} = \Sigma T3 + \Sigma T4; \Sigma T_{t.t.} = \Sigma T2 + \Sigma T5; \Sigma T_{l.t.} = \Sigma T1.$$ (8)

The actual data obtained by recording the operating parameters of the electric actuators of the Ural-20R-11 were used to determine the component periods of the mining machine’s operation. The duration of the analysed time interval was 26 days.

The productivity time of the heading-and-winning combine is determined by the periods of operation of the drag-bar conveyor-reloader, which provides for loading the freed ore from the working area. By correlating the obtained values with the total time of use of the combine (minus the time for scheduled maintenance $\Sigma T_{s.m}$ and unscheduled repairs $\Sigma T_{u.r}$), the values of the productivity coefficients for each day were determined (Figure 5).

![Figure 5. Values of the productivity coefficient for the Ural-20R combine.](image)

The average value of the productivity coefficient for the entire analysed time period was $k_{p.r.} = 0.29$.

The authors analysed the recorded data about the load of the electric actuators of the Ural-20R-11 combine and determined the total time for performing individual technological operations. During the considered time period, the combine was mining ore using the technology of two-layered mining of chambers. This technology includes the sequential execution of the following operations:

1. “Hewing”, defined as a preparatory operation, where the combine moves from the gateway into the stope;
2. “Full-face mining”, defined as productive work of the combine using a full section of the final element;
3. “Returning”, defined as movement of the combine to the beginning of the stope;
4. “Undercutting the seam”, defined as the productive work of the combine using a partial section of the final element.

Distinctive features have been defined for each technological operation. The durations of technological operations for the analysed time period were established according to the load graphs of the Ural-20R-11 actuators (Table 1).
Table 1. Productive time of the Ural-20R-11 combine in various technological operations.

| No. | Process Operation      | Total Operation Time, h | Combine’s Total Productive Time, h | Share of the Execution Time of Separate Technological Operations, % |
|-----|------------------------|-------------------------|-----------------------------------|---------------------------------------------------------------|
| 1   | Hewing                 | 48.08                   | 10.14                             | 9                                                             |
| 2   | Full-face mining       | 403.08                  | 118.10                            | 63                                                            |
| 3   | Returning              | 48.67                   | 0.00                              | 5                                                             |
| 4   | Undercutting           | 132.17                  | 52.45                             | 23                                                            |
|     | Total                  | 632                     | 180.69                            | 100                                                           |

The actual values of the specific energy consumption $H_{wa}$ of the potash ore mining process with the Ural-20R-11 unit were determined for individual time intervals of its operation by Formula (4) based on the data on the consumption of electrical energy and the combine’s feeding speed to the face (its technical performance). The energy efficiency coefficient of using a heading-and-winning machine $k_{e.ef.}$ is calculated using Formula (5). The results of performance evaluation of the Ural-20R-11 combine are shown in Table 2 [7].

Table 2. Values of energy efficiency coefficients, breakdown by combine operation in various mining conditions.

| No. | Combine’s Operation during Measurement | Mining Face Area, m² | Operational Productivity, t/min | Specific Energy Consumption $H_{wa}$, kWh/t | Energy Efficiency Coeff., $k_{e.ef.}$ | Productivity Coefficient, $k_{p.r.}$ |
|-----|----------------------------------------|----------------------|---------------------------------|--------------------------------------------|--------------------------------------|--------------------------------------|
| 1   | Mining the chamber with a dead-end face, passed 10.5 m per measurement | 15.5                 | 5.9                             | 1.33                                       | 0.87                                 | 0.28                                 |
| 2   | Mining the chamber with a dead-end face, passed 16.6 m per measurement | 15.5                 | 5.8                             | 1.20                                       | 0.97                                 | 0.29                                 |
| 3   | Undercutting the seam (second-pass chamber mining), passed 13.8 m per measurement | 6.2                  | 3.4                             | 1.78                                       | 0.65                                 | 0.37                                 |
| 4   | Mining the chamber with a dead-end face, passed 11.2 m per measurement | 15.5                 | 4.5                             | 1.49                                       | 0.78                                 | 0.26                                 |

The results are graphically presented in Figure 2. Analysed data shows the unsatisfactory technological performance of the studied machine Ural-20R-11, which is mainly due to the low productivity of the mine district transport.

With the existing mining technology, the productivity of self-propelled mine cars transporting the mined ore from the combine to the ore gates varies depending on the delivery distance, and is on average 2 to 2.5 times lower than the technical productivity of the combines (Table 3).

Increasing the production time of combines in the purification chambers of potash mines and, as a consequence, increasing the actual values of $k_{p.r.}$ is possible through the use of means of continuous delivery of ore from the combine to the ore gates: Mobile or telescopic conveyors. Combines with two self-propelled cars are known to operate but are not widely used at present. The need to remove the mining machine from the completed stope and to remount the equipment of the combine complex results in a
significant negative impact on the efficiency of the use of heading-and-winning machines in potash mines. At the same time, the high values of the energy efficiency coefficient show that the productivity of the machine is on par with design conditions. A decrease in the values of the energy efficiency coefficient is observed when the combine is operating at an incomplete section of the bottom (when undercutting the formation) due to a decrease in the technical productivity of the mining machine.

Table 3. Ore delivery rates using self-propelled mine cars.

| Carrying Capacity of a Self-Propelled Mine Car, t | Delivery Rate of a Self-Propelled Mine Car, t/min, with Delivery Length, m |
|-------------------------------------------------|-----------------------------------------------------------------------------|
|                                                 | 35               | 100              | 150               | 200               |
| 15                                              | 4.15             | 3.18             | 2.75              | 2.38              |
| 18                                              | 4.98             | 3.82             | 3.3               | 2.86              |
| 22                                              | 5.62             | 4.38             | 3.8               | 3.3               |
| 30                                              | 7.12             | 5.64             | 4.93              | 4.32              |

4. Conclusions

Currently, there are no approved procedures for assessing the performance of heading-and-winning machines operating in the conditions of potash mines. This leads to difficulties in determining the field of application of heading-and-winning machines, prohibits real-time monitoring of the stability of stope-based technological processes and complicates the search for implicit technical solutions for the modernisation of existing models of mining units.

The proposed methodology and software-recording equipment ensure determination of quantitative values for efficiency indicators of the heading-and-winning machines operating at potash mines.

The authors suggest that performance of heading-and-winning machines for potash mines should be assessed by determining complex indicators describing the technological and technical levels of organising the work in stopes. Such indicators are the coefficients of productivity and energy efficiency, respectively.

Using the above methodological approaches, the paper shows that the unsatisfactory technological performance of the studied machine is due to the low productivity of the mine district transport. The average productivity coefficient was 0.29. At the same time, high values of the energy efficiency coefficient show that the productivity of the machine is on par with design conditions.

Monitoring the quantitative values of performance indicators over time will make it possible to identify and, in a timely manner, eliminate the implicit reasons for destabilisation of the potash ore mining process.

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