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Management of Scraper-Self-Propelled ore delivery parameters in caving operations

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Abstract:

This paper analyzes ore delivery methods suitable for the deep-level mining environments of the Kryvbas region. The study focuses on the feasibility and economic advantages of utilizing a combined scraper-self-propelled ore delivery system within sublevel caving operations. Through comprehensive analysis, it is found that the integration of self-propelled equipment significantly enhances the efficiency and cost-effectiveness of ore transport. The proposed delivery method involves using multi-bucket scraper winches for primary ore movement and deploying a self-propelled load-haul-dump (LHD) machine for secondary transport. Economic and mathematical modeling results demonstrate that this combined approach enables optimization of operational parameters, identifying the most effective application ranges for different types of self-propelled LHDs in secondary ore transport. Specifically, the study highlights that the ST7 model of self-propelled LHD is the most cost-effective solution for secondary transport, minimizing specific delivery costs while maintaining productivity. Additionally, the findings provide practical guidance on the optimal usage limits for various self-propelled LHD types, helping to inform equipment selection for enhanced operational efficiency in caving systems. These insights contribute to improved decision-making in mining operations, promoting both economic and technical benefits in high-depth mining scenarios.

Keywords: ore drawing and delivery, actual mining, ore drawing intensity, ore delivery methods, self-propelled loading and hauling machine, capital ore pass

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1. Introduction

The effectiveness of extraction operations and the comprehensive quantitative and qualitative recovery of ore reserves are critical issues in the development of high-grade iron ore through sublevel caving systems in Kryvbas mines [1]. A primary technological process in this system is ore release through horizontal bottom drifts of the receiving levels [2]. Ore transportation is a crucial component of the extraction process, determining the efficiency of ore release and overall mining productivity [3]. The selection of transportation equipment significantly impacts the organization of work and the productivity of the entire block [4].

In modern underground ore deposit extraction systems, ore release and transportation are among the most labor-intensive and inefficient processes [5]. The release of fragmented ore from the extraction area is typically carried out from under caved surrounding rock or through a network of specialized drifts uniformly distributed beneath the extraction face [6]. The ore moves through the extraction area and release drifts under the influence of gravity [7]. However, only about 50% of pure ore is recovered due to horizontal limitations in the release figure dimensions [8]. To reduce ore dilution, sequential releases from adjacent drifts are made in equal or varied doses, as per established release plans [9]. However, current release methods cannot fulfill these plans due to frequent blockages in the release drift necks and the avalanching flow of ore when these blockages are cleared [10]. Consequently, the release process is prolonged and marked by high ore losses and dilution, reaching up to 25% and 18%, respectively [11].

The inefficiency of gravity-based ore release and the use of low-capacity transportation equipment create a "bottleneck" in the technological work complex of modern extraction systems, especially when using advanced mass caving systems for ore and surrounding rock [12]. For example, the use of scraper installations in the extraction of high-grade iron ore deposits in Kryvbas with mass caving systems allows for an ore release intensity of 1.2–1.8 tons/m² per day, which is relatively low [13]. This low release intensity also negatively impacts the formation of compensation chambers, where volume accounts for only 8–12% (instead of the required 20–25%) of the primary reserve volumes needed for stable extraction units throughout their operational life [14]. Therefore, ore extraction is conducted under highly confined conditions, which at greater depths leads to the compaction of loose material [15]. Increasing rock pressure with depth further consolidates the ore within the extraction panels due to gravity [16], adversely affecting the physical and mechanical properties of the already fragmented ore [17]. Its cohesion increases to a point where it practically loses flow properties [18], leading to higher ore losses and dilution [19]. Additionally, working conditions deteriorate in the extraction area, with early failures of release and transport drifts [20].

The intensity of rock pressure is significantly influenced by the intensity of ore release; as ore release increases, the pressure from caved rock decreases toward a stable level that depends on the extraction unit parameters and the ore’s physical and mechanical properties [21]. Due to the uneven ore release, characteristic of all Kryvbas mines, the pressure on the receiving level bottom is distributed unevenly [22].

To optimize extraction, it is essential to achieve a high-intensity, evenly dosed ore release across the entire receiving level bottom area. However, traditional scraper transport methods fall short in maintaining such uniformity and intensity due to their limitations in handling large volumes consistently. As a result, alternative transport solutions must be considered to enhance ore release efficiency and minimize ore loss and dilution during extraction operations.

2. Literature and patterns background

Currently, both Ukrainian and international mining operations utilize various ore transport methods, including scraper winches with a capacity of 150–250 tons per shift [23], self-propelled load-haul-dump machines (LHDs) with a capacity of 800–1200 tons per shift [24], conveyors with a capacity of 800–1500 tons per shift [25], and vibrating feeders with a capacity of 700–900 tons per shift [26]. Additionally, there are combinations of multi-bucket scraper winches and self-propelled LHDs, with the capacity ranging from 400 to 2200 tons per shift, depending on the type of LHD used.

Another method involves blast-assisted ore transport, where productivity depends on the cleaning space parameters, the ore body's dip angle, and the transport distance, and can vary significantly [5, 27, 28].

Scraper transport is the most widely used method in Kryvbas mines due to its simplicity and low cost, but it has low productivity [29]. Conveyors are the most productive, yet they are rarely used due to rapid wear, frequent ore blockages, and resulting downtime for maintenance [30]. Vibrating feeders have proven efficient mainly in near-surface mining, as their installation underground is labor-intensive and costly [31]. Blast-assisted transport is feasible only with chamber mining systems and ore bodies with a dip angle of 15–45°, making it unsuitable for Kryvbas underground mines. Despite the high productivity of self-propelled LHDs with end-discharging ore techniques in foreign mining practices [32], these machines are not widely used in Kryvbas mines due to significant ore losses between discharge points, leading to increased ore dilution levels of 25–35% [33]. Furthermore, using high-capacity self-propelled LHDs in Kryvbas's complex geomechanical conditions requires large cross-section openings of 12–14 m², which increases maintenance costs due to high ground pressure, impacting labor intensity and ore transport costs [34, 35].

The combined scraper-self-propelled transport method (Fig. 1) is both rational and effective due to the complementary advantages of scraper winches and self-propelled load-haul-dump machines (LHDs) [5]. By employing multi-bucket scraper winches, it becomes possible to achieve an evenly dosed release from each discharge point along the transport axis, enhancing control and efficiency. Furthermore, utilizing larger discharge niches, measuring 2×2 m instead of the conventional 1.5 m diameter holes, significantly reduces equipment downtime, as it helps to localize blockages of oversized ore pieces at the discharge throat, thus minimizing interruptions. To ensure continuous high productivity of the self-propelled LHDs, larger diameter permanent ore passes are necessary, allowing for independent transport processes without bottlenecks [36, 37]. These larger passes contribute to a steady flow of material and reduce reliance on multiple transport points, increasing overall efficiency. Consequently, the productivity of the transport process is determined primarily by the average ore transport trajectory length for the LHDs, allowing for a more predictable and stable operation. This optimized combination of transport methods offers an adaptable solution that aligns with the operational demands and geomechanical constraints typical of deep-level mining operations.

This proposed combined ore transport scheme is well-suited to the complex geomechanical conditions of Kryvbas's deep mine levels and allows for:

- minimizing the impact of human factors on ore release management;
- ensuring evenly dosed ore release from all discharge points along the primary transport line;
- performing sequential ore release from discharge points, moving from the hanging to the footwall side of the ore body via multi-bucket scraper installations;
- reducing blockages in discharge points during ore release;
- improving the structural layout of the ore release and transport levels, reducing the specific length of preparatory development by 1.5–2.5 m per 1000 tons of ore reserve;
- enhancing the sanitary and hygienic working conditions for miners and increasing safety during ore release and transport operations; – enabling selective extraction of ore of varying quality.

The research on and optimization of the combined scraper-self-propelled transport parameters in caving systems is a relevant scientific and practical task with significant potential benefits. By optimizing these parameters, mining operations can enhance labor productivity within the ore transport process, making it more efficient and cost-effective. Improved transport efficiency can lead to faster material handling, reducing the overall operational time and minimizing delays. Additionally, fine-tuning these parameters can significantly reduce the specific costs associated with ore transport, allowing for better allocation of resources. Ultimately, this optimization supports more sustainable mining practices by lowering operational expenses and improving the overall efficiency of resource extraction processes.

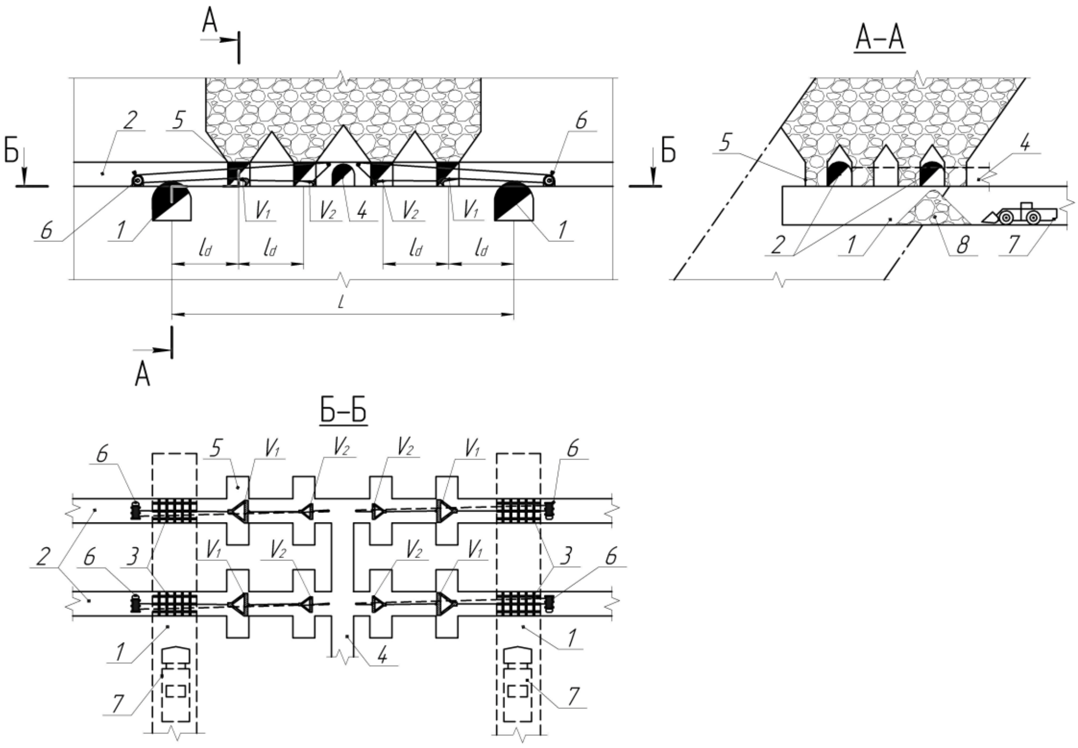

Fig. 1. Diagram of the Combined Scraper-Self-Propelled Ore Transport Method Using a Multi-Bucket Scraper Winch and Self-Propelled LHD Complex: 1 – Load-haul-dump drifts; 2 – Scraper drifts; 3 – Grizzly screen; 4 – Ventilation drift; 5 – Discharge niches; 6 – Multi-bucket scraper winches; 7 – Self-propelled LHD; 8 – Ore pile; $V_1 = 2V_2$ – Volume of the first scraper, m³; V_2 – Volume of the second scraper, m³; l_d – Distance between adjacent discharge niches and the center of the load-haul-dump drift; L – Distance between load-haul-dump drifts [own study]

3. Methods & methodology of research

To determine the optimal parameters and application boundaries for the scraper-self-propelled ore delivery method, an economic-mathematical modeling approach was employed. Based on the literature review, an economic-mathematical model was found to be the most suitable for the conditions of the Kryvbas region. This model uses the cost of transporting one ton of ore, factoring in the amortization of mine development and preparatory work, as its primary criterion and general functional.

The modeling involved assessing both technical and economic factors impacting the efficiency of ore transport, including equipment type, transport distances, and operational capacity. Various transport scenarios were simulated to analyze the effect of scraper winches and self-propelled load-haul-dump (LHD) machines in isolation, as well as in combination. This allowed for a comparative evaluation of the productivity and costs associated with each transport method under different mining conditions.

The model considered the physical limitations and wear factors of equipment, such as the maintenance frequency and expected lifespan of scraper winches and LHD machinery. The model was calibrated using data from actual ore delivery operations in Kryvbas mines, making it possible to reflect real-life constraints and optimize the system to local geological and operational conditions. To ensure accuracy, data collection involved detailed analysis of existing ore delivery systems, including factors such as loading capacity, fuel and energy consumption, and ore dilution rates. A cost analysis was conducted for each component, allowing for a detailed breakdown of expenditures associated with different aspects of the scraper-self-propelled delivery method.

The methodology also included sensitivity analysis to examine how changes in various parameters- such as transport distance and ore density – would affect the overall efficiency of the ore delivery system. By adjusting these variables within the model, the research was able to identify the most cost-effective and operationally efficient configurations under varying conditions. The proposed model and resulting recommendations were validated through pilot implementation in select mining sites within Kryvbas. The outcomes of these trials were compared to the model's projections, allowing for further refinement of the system parameters. This validation phase ensured that the model's recommendations align with practical constraints and demonstrate improved productivity and reduced costs in real-world applications.

The following input data were selected for the modeling. The combined scraper-self-propelled ore delivery method involves using 55LS-2SMA scraper winches for primary delivery and various types of self-propelled LHD machines for secondary delivery, suitable for the geomechanical conditions found at the deep levels of the Kryvbas mines (models EST2D, ST2D, ST3.5, ST7, ST1030, LH409E, TORO400D). The ore deposit thickness was chosen to reflect the average conditions in Kryvbas, at 25 meters. In all cases, the sublevel height is fixed at 37.5 meters. Ore extraction was carried out into a compensation space with a volume equivalent to 23% of the total reserves of the mining unit.

4. Results of the research

Based on the calculations performed using the economic-mathematical model, graphical dependencies were constructed to illustrate the specific costs of ore delivery relative to the productivity of various types of Load-Haul-Dump (LHD) machines used in secondary ore transport. These relationships are presented in Fig. 2. The results provide insights into the cost-effectiveness of different LHD machine types under varying productivity conditions, allowing for an optimized approach to secondary ore transportation.

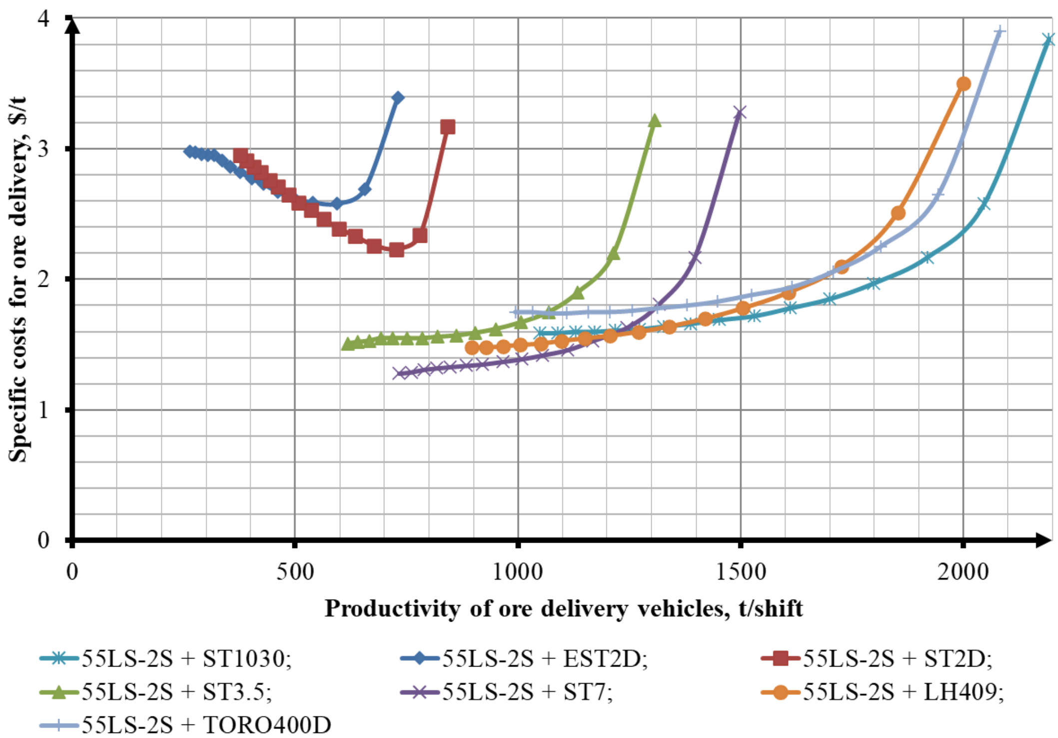

Fig. 2. The dependence of specific ore delivery costs on the productivity of various LHD machine types [own study]

Fig. 2 shows that the lowest specific ore delivery costs are achieved when using a combined scraper-self-propelled transport method, utilizing multi-bucket scraper winches of the 55LS-2SMA type for primary delivery, and the self-propelled LHD ST7 type for secondary delivery. This scheme has the lowest cost indicators when the average transport distance is within the range of 120–270 m. Under these conditions, the productivity of the system is between 720–1110 tons per shift, which is 1.4–3.3 times higher than when using only scraper winches for ore delivery.

A significant reduction in specific ore delivery costs is achieved by increasing the average transport distance from 120 m to 270 m, as seen in Fig. 3. This reduction is due to a notable decrease in specific capital expenditure for constructing the primary ore pass, dropping from $1.24 per ton to $0.21 per ton. However, there is a corresponding decline in the productivity of the self-propelled LHDs used in secondary ore delivery, with performance decreases as follows: EST2D from 460 tons per shift to 264 tons per shift, ST2D from 600 tons per shift to 375 tons per shift, ST3.5 from 950 tons per shift to 620 tons per shift, ST7 from 1110 tons per shift to 730 tons per shift, ST1030 from 1610 tons per shift to 1050 tons per shift, LH409E from 1500 tons per shift to 890 tons per shift, and TORO400D from 1520 tons per shift to 990 tons per shift.

By approximating the maximum values (Fig. 3), an empirical dependency was obtained to describe how specific capital costs for constructing the primary ore pass change with respect to the balance of ore reserves. This dependency highlights the relationship between the ore reserves allocated to a single ore pass and the associated capital investment required for its construction. As the balance of ore reserves increases, the model demonstrates how specific costs can be optimized, providing a clear framework for cost management. The empirical model also allows for adjustments based on varying reserve balances, making it adaptable to different mining conditions. Overall, understanding this dependency is crucial for making informed decisions on resource allocation and reducing construction expenses in ore pass development. The specific costs for constructing the primary ore pass, depending on the balance of ore reserves transported by one ore pass to the receiving level, can be determined by the formula:

$$P_{vytr.} = 200.27 B_{zap.}^{1.422}, \text{ \$/thousands tons with } R^2 = 0.9848,$$

where:

$B_{zap.}$ – ore reserves per primary ore pass, thousands of tons;
R^2 – approximation accuracy.

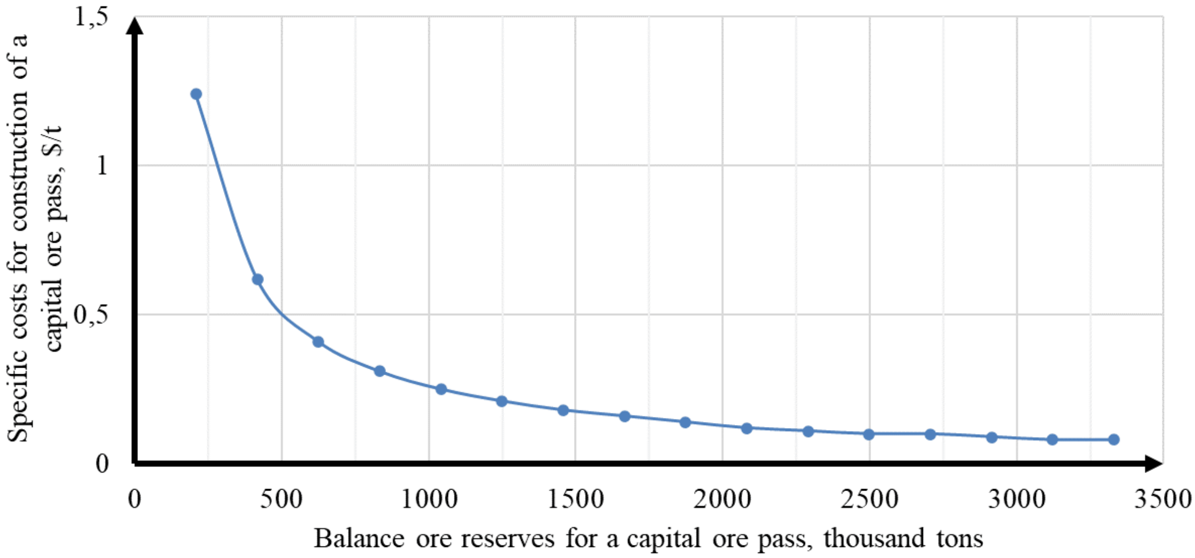

Fig. 3. The dependence of specific costs for constructing a primary ore pass on ore reserves delivered by a single pass to the receiving level [own study]

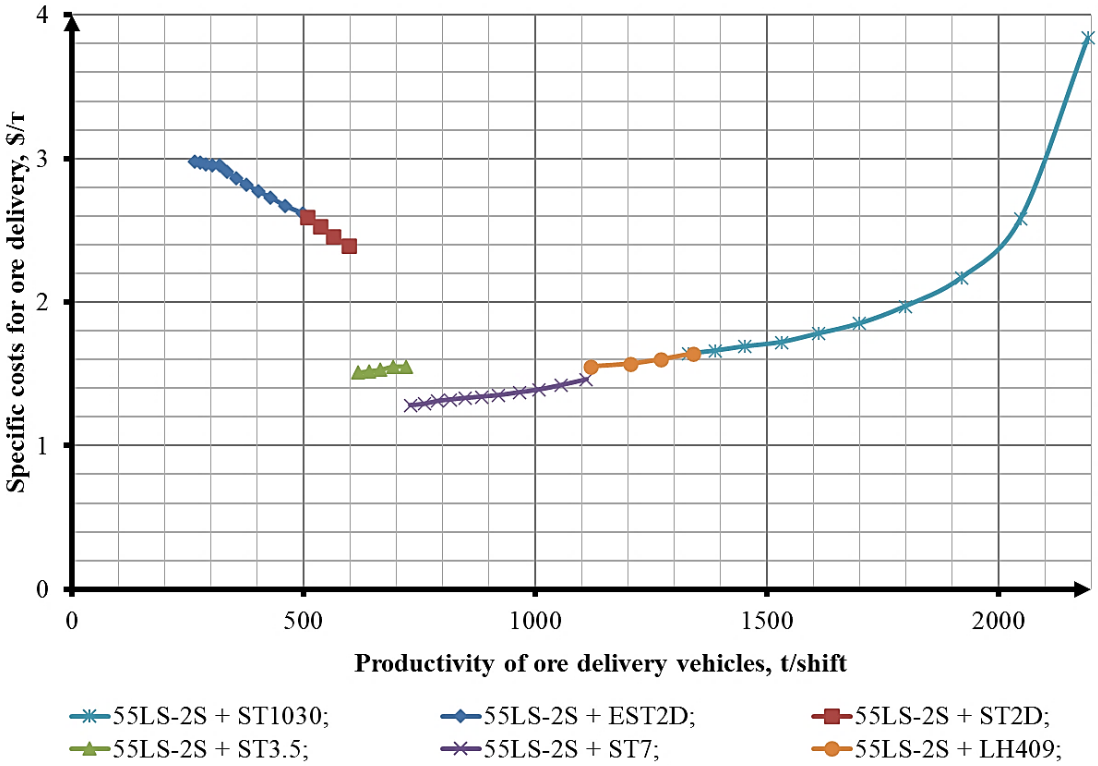

Fig. 4. The dependency of optimal application limits for various types of self-propelled LHDs in secondary ore transport [own study]

As shown in Fig. 4, when employing the combined scraper-self-propelled method for ore transport, scraper winches of the type 55LS-2S are consistently used for primary transport in all cases. To maintain a productivity range of 260–500 tons per shift in the stope, the EST2D self-propelled LHD is necessary for secondary transport, with specific transport costs decreasing from $2.98/ton to $2.62/ton as productivity increases. For productivity between 500–620 tons per shift, the ST2D self-propelled LHD should be used, resulting in a decrease in specific transport costs from $2.59/ton to $2.23/ton as productivity rises.

In the productivity range of 620–720 tons per shift, the ST3.5 self-propelled LHD becomes necessary for secondary transport, though specific transport costs slightly increase from $1.51/ton to $1.55/ton with higher productivity. When productivity ranges from 720–1110 tons per shift, the ST7 LHD is optimal, with costs gradually increasing from $1.28/ton to $1.46/ton. For higher productivity requirements of 1110–1330 tons per shift, the LH409E LHD is recommended, as specific costs rise from $1.59/ton to $1.64/ton.

In cases of extremely high productivity, such as 1330–2200 tons per shift, the ST1030 LHD is necessary, with transport costs increasing significantly from $1.64/ton to $3.84/ton as productivity rises. However, the optimal productivity range for the ST1030 LHD is between 1300–1700 tons per shift, which keeps ore transport costs within a manageable range of $1.64–$1.78 per ton, ensuring efficient and cost-effective ore transportation.

5. Discussion of the results

The research findings offer insights into the cost-effectiveness and operational efficiency of the combined scraper-self-propelled ore transport method. Using an economic-mathematical model tailored to the mining conditions of the Kryvbas region, the study identifies optimal configurations for primary and secondary ore transport. Specifically, scraper winches, such as the 55LS-2SMA model,

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are consistently effective for primary ore transport, while various types of self-propelled Load-Haul-Dump (LHD) machines, like the ST7, EST2D, and ST1030, demonstrate specific productivity and cost advantages in secondary transport. This approach reveals that a combined transport system can significantly reduce delivery costs and increase productivity, especially when transport distances range between 120 and 270 meters.

The results indicate that the combined transport method is particularly efficient within specific productivity thresholds. For instance, the ST7 LHD yields optimal results at productivity levels of 720–1110 tons per shift, while the ST1030 LHD is more effective at the higher end of the productivity spectrum, between 1300–1700 tons per shift. Additionally, the study identifies a notable cost reduction when transport distances extend to 270 meters, where capital expenses for ore pass construction decline from $1.24 per ton to $0.21 per ton. However, as transport distances increase, there is a corresponding decline in the productivity of certain LHD models. This interplay between transport distance, equipment type, and operational cost forms a critical component of the optimization process.

The empirical dependency identified through approximation provides a framework for understanding how ore reserves correlate with the cost of constructing primary ore passes. By analyzing this relationship, the study offers a practical approach to managing costs associated with ore pass development. This model also facilitates sensitivity analyses, allowing for adjustments based on reserve balances and varying operational conditions. Through pilot trials and validation, the model proved to be adaptable to the real-world challenges faced by mining operations in the Kryvbas region, underscoring its utility in guiding decisions on resource allocation, equipment choice, and cost management.

6. Conclusions

The study concludes that the use of self-propelled equipment for ore delivery in sublevel caving systems, as applied in the Kryvbas mines, is both feasible and economically justified when employing a combined scraper-self-propelled transport approach. For secondary ore delivery, specific self-propelled Load-Haul-Dump (LHD) machines, such as the EST2D, ST2D, ST3.5, ST7, ST1030, LH409E, and TORO400D, were found to be particularly suitable and cost-effective.

The combined approach, utilizing multi-bucket scraper winches (55LS-2SMA type) for primary delivery and self-propelled ST7 machines for secondary delivery, achieves the lowest specific delivery costs, ranging from $1.28 to $1.46 per ton. This cost advantage is realized when the average transport distance is between 120 and 270 meters, enabling productivity levels between 720 and 1110 tons per shift. Such productivity represents an improvement of 1.4 to 3.3 times compared to a transport scheme that uses dual 55LS-2SMA scraper winches alone.

The research establishes optimal productivity ranges for each type of LHD used in secondary ore delivery under the combined transport system. The identified productivity thresholds include EST2D for 260–500 tons per shift, ST2D for 500–620 tons per shift, ST3.5 for 620–720 tons per shift, ST7 for 720–1110 tons per shift, LH409E for 1110–1330 tons per shift, and ST1030 for 1330–1700 tons per shift. These findings provide a valuable framework for optimizing ore transport operations within similar mining environments, ensuring cost efficiency and increased productivity.

In our further research cwe'll the integration of automated control systems and advanced monitoring technologies within the combined scraper-self-propelled ore delivery system to improve efficiency and safety. These studies would focus on real-time data collection and predictive maintenance for Load-Haul-Dump (LHD) machinery to reduce downtime and extend equipment lifespan. The analysis would evaluate the environmental impacts of ore transport methods, identifying ways to minimize energy consumption and emissions. Research into optimizing LHD types for varying geological conditions and assessing alternative energy sources, such as electric or hybrid-powered LHDs, could also contribute to more sustainable mining practices.

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