

Article

Simulation-Driven Mining Logistics Towards Sustainable and Reliable Production

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Abstract

It is essential that the extracted raw material, after mining, is transported to its processing facility. In mining companies, this transfer is managed by a logistics system. However, it is crucial to first adopt the Mining 4.0 concept and subsequently begin implementing new technological trends. This study thoroughly analyzes and evaluates the transportation system of a specific mining operation. The application of modeling and simulation introduces several benefits to this process. Developing a comprehensive model from pre-verified components is the most effective way to represent the system reliably. The objective is to achieve and verify the potential for a monthly output of 10,000 tons of raw material. Experimentation with the model produced a significant amount of data, indicating that the transportation system may achieve the production target. With proper maintenance and precise alternation of processes, as determined by the modeled experiments, the system could be even more effective. The simulation outputs also identified the productivity of other processes within the logistics system. The experiments focused on both improving the system and ensuring its sustainability for the future. The company must ensure and strengthen its system, particularly in terms of its components and management, as this will have the greatest impact on system safety, longevity, and reliability.

Keywords: Mining 4.0; sustainable production; modeling; simulation

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1. Introduction

Logistics plays an indispensable role in the primary sector of industry as well. The logistics systems of mining operations and quarries are analogous to those of manufacturing companies. In their case, the core of the system is the extraction process [1]. A logistics system is a hierarchical structure integrated from coordinated logistics flows. A logistics flow often utilizes advanced technologies for tracking and management. The logistics system manages, secures, and executes material, information, and financial flows [2,3].

The logistics of mining companies is fundamentally based on supply chain management. It involves more than just supporting the extraction process and demand and supply management. It also includes managing reverse material flows during mine backfilling, which significantly increases demands on efficient and purposeful transportation [4]. In underground mining processes, raw minerals are rarely processed at the extraction site due to spatial constraints and operational conditions. Mining logistics systems are increasingly influenced by advancements in digitalization and Industry 4.0 technologies [5].

Mining transportation systems are internal industrial transportation networks. Their primary function is to transport raw materials, supplies, by-products, equipment, personnel,

and various technical or handling devices [6]. Internal mining transportation significantly impacts operational efficiency, cost structures, and safety performance. It is involved not only in tunneling, extraction, processing, and shipment activities, but it also serves as the most essential support process in both underground and surface mines [5,7]. The principal objective of internal transportation is to ensure the efficient, timely, and cost-effective movement of the required quantities and types of materials throughout the entire company [8].

Efficient mining transportation systems are critical to ensuring not only the delivery of the required quantity of raw materials to the surface but also the timely supply of diverse materials and equipment. These systems employ technologies and methodologies aimed at increasing productivity, reducing operational costs, enhancing safety, and improving planning efficiency [6,9]. The most significant constraints of these systems include spatial restrictions, capacity limitations, high initial investments in technology and infrastructure, the need for robust maintenance, potential equipment failures, and the establishment of reliable communication channels [10]. Communication channels are essential for effective dispatch control of transportation operations. Modern dispatch systems facilitate efficient resource allocation and ensure the rapid and accurate movement of materials [11].

Material flow comprises both active and passive elements, which must be synchronized. Active elements represent the technical component of the logistics system. Active elements include mechanical and technological equipment. They facilitate the movement of passive elements and physically execute logistical functions. Passive elements do not perform actions themselves but are moved by the active elements [12,13].

Material flow, or the transportation of raw materials from the extraction site to the location of further processing, can be carried out using various methods. These methods include rail transport, truck haulage, conveyor systems, or vertical transportation [14,15]. Rail transport holds the position of the oldest and most widely used form of mining transportation. Locomotives and mine cars are specifically engineered for efficient operation and maneuverability within the confined spaces of mining environments [8,16]. Rail transport in mining operations is often used in combination with truck haulage. Truck haulage encompasses loaders and haul trucks [17].

The integration of Industry 4.0 technologies significantly enhances the efficiency and safety of mining operations. Technologies transform traditional procedures into smarter and more automated systems. Industry 4.0 technologies play a pivotal role in improving operational performance and sustainability. The adoption of these technologies allows for real-time monitoring and control of mining processes, improving production quality and operational efficiency, and reducing the environmental footprint [18,19]. The application of Industry 4.0 technologies in mining is often referred to as Mining 4.0. Traditional mining relied heavily on manual labor, reactive maintenance, and static geological models. Mining 4.0 shifts this paradigm to predictive, integrated, and automated systems that enable continuous operation with reduced human intervention [20]. The combination of IoT and digital twin solutions facilitates better decision-making, predictive maintenance, and sustainable resource utilization. Additionally, Mining 4.0 supports the sustainable development of the mineral resource sector by minimizing environmental and social impacts while maintaining safety standards. The concept prioritizes worker safety through remote sensing, planning, and computational modeling [19–21].

The implementation of modeling and simulation within the framework of Mining 4.0 offers enhanced system performance, improved design and planning capabilities, and increased operational efficiency. Simulation modeling can uncover actual operational workflows and forecast potential future issues and system productivity [22]. However, several challenges exist, including the complexity of the systems being modeled, the need

for accurate representation of process control mechanisms, and the validation of simulation models. Modelers are driven to develop more detailed simulation scenarios and create reference meta-models [23,24]. In summary, sustainable production in underground mining companies is the outcome of both sustainable extraction and sustainable transportation. Can discrete event simulation be one of the pillars towards sustainable production in underground mining logistics systems?

The objective of this study is to highlight the emerging trend among mining companies in Slovakia: the integration of new technologies into their operational processes. The results of modeling and simulation indicate necessary system changes aimed at achieving sustainable transportation within mining processes. The presented case study applies a simulation tool to the mining transportation system with the goal of increasing production output, enhancing safety, and enabling more efficient planning of mining activities. To accomplish this objective, the mining transportation system is subjected to a systematic analysis.

2. Materials and Methods

The modeling and simulation of the mining transportation system in this study follows the main sequence of the following processes:

1. System analysis;
2. Selection of the simulation tool;
3. Preparation of input parameters;
4. Modeling and validation of model segments;
5. Synthesis of the comprehensive model;
6. Validation of the comprehensive model;
7. Model experimentation;
8. Presentation and implementation of suitable solutions.

The rigorous method of systems analysis applies a systems approach, viewing the company as an integrated whole. It decomposes the individual components of the system into elementary parts for further examination. Systems analysis first verifies the objectives and then defines the system along with its external and internal interrelationships [25].

Modeling and simulation operate on a system in which a problem has been identified. The term system can be defined as a set of entities that interact with one another, producing a form of reaction or behavior that is observable over time. The reactions within a system can be described as flows—chains of activities that require management. However, interventions in systems do not manifest their effects immediately. They emerge after some delay, which stems from the sequential arrangement of processes. Through modeling and simulation, insights and understanding of systems are gained. Subsequently, it is applied to their control, management, or transformation [26].

Once the simulation model is created, the simulation can be executed. A simulation is the observation of a system's behavior on the constructed model with a defined objective. Simulation is followed by the adjustment of parameters, with subsequent control through further observations. The first simulation run is always a validation simulation. The purpose is to verify the accuracy of the model in relation to the outputs of the real-world system. Only thereafter can analyses be conducted that lead to the desired trajectories and outcomes [27]. In general, the modeling and simulation procedure can be described according to Figure 1.

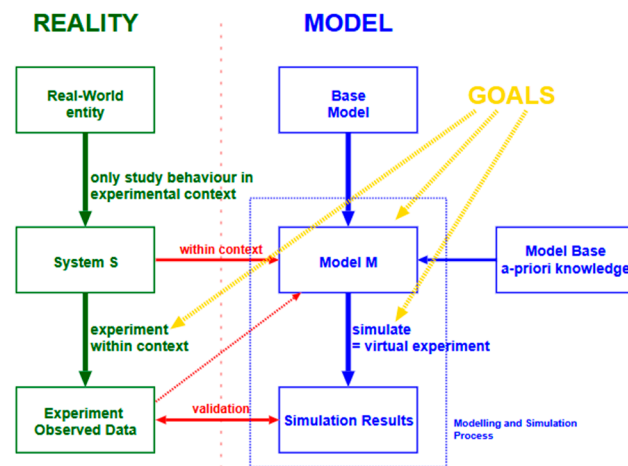


Figure 1. Process of modeling and simulation [28].

The benefits of modeling and simulation tools are leveraged by companies across various industrial sectors, including mining companies. Researchers apply simulation to address a wide range of problems, such as predicting surface subsidence above the excavation area of an underground mine [29], preparing rapid on-site decision-making scenarios [30], and modeling gas dispersion in underground mines along with its control [31]. The available literature predominantly features models and simulations related to transportation and haulage systems in mining operations. The transportation of raw materials in the mining industry is an inseparable component of the extraction process. While the primary activity is extraction, transportation likewise plays a critical role. Transportation operations are indispensable in mining production, as extraction sites are often located far from distribution points [32].

Each mining transportation system has unique requirements and parameters. The parameters are determined by the type of mine, the mode of transportation employed, the constraints defined by operational transportation regulations, and the configuration of the transportation network itself. Consequently, the approaches adopted by authors developing models of mining transportation systems vary [32]. Table 1 presents an overview of simulation models of mining transportation systems, with simulation software used as the primary classification criterion.

Table 1. Application of modeling and simulation in mining transportation systems.

Simulation Software	Scale of the Simulation Models	Findings/Limitations
AnyLogic	Model for regulating the duration of transport and technological operations ¹ [33].	Uneven utilization of system elements adversely affects car downtime rate and transport services.
	Model for the optimization of the logistics system for production and development ¹ [34].	Model optimization improves production efficiency. The complexity of coordinating mining logistics processes remains a challenge.
ARENA	Model for assigning trucks to loaders and the dispatch simulation model ¹ [35].	Proposed dispatching systems increase production rate. The simulation also identifies key bottlenecks and enables flexible testing.
	Comparing four variants of tunnel layout and transportation strategies ¹ [36].	The model yields detailed visualization and helps optimize transport costs.

Table 1. Cont.

Simulation Software	Scale of the Simulation Models	Findings/Limitations
ExtendSim	Model of loading raw material into two vehicles, ExtendSim8 [37].	Discrete-event simulation methods reflect realistic operational conditions and variability. Modeling provides a basis for improving transport system key indicators.
	Model for planning a quarry transportation system, ExtendSim8 [38].	Simulation improves transport system performance and decision-making. The model simplifies certain stochastic aspects of the transport system.
FlexSim	Model for comparing two mining transportation systems ¹ [39].	Simulation represents ore movement as discrete units. Assumptions in the discretization process may oversimplify complex interactions.
	Model for configuring trucks in the transportation system, FlexSim 19.0.0. [40].	Simulation results demonstrate improved mining efficiency, reduced operating costs, and minimized truck idle times.
SimMine	Interlevel ore haulage model, SimMine 1.19. [41].	Highlights that simulation combined with validation is a suitable method for analyzing mine operations.
	Variable fleet mine transportation system model, SimMine 1.19. [42].	Demonstrates potential improvements in haulage efficiency, cycle time reduction, and operational savings.
Tecnomatix Plant Simulation	Mine car uncoupling model ¹ [43].	Highlights the practical application of simulation combined with programming tools for enhanced accuracy.
	Transportation system control and scheduling, Tecnomatix Plant Simulation v2302.0004 [44].	Digitalization facilitates adaptive management capable of responding to evolving mine conditions and operational requirements.
Custom simulation program	Model for the optimization of loaders and trucks [45].	Simulation optimizes loaders and trucks number under various constraints including dynamic factors.
	Model for truck dispatching [46].	Two novel dispatching policies are proposed. The optimization approach can control ore quality and manage truck queue sizes.

¹ Unspecified version of the software.

Each study focuses on a specific aspect of either an existing or a conceptual system. Recent research has examined such systems at various levels of resolution. Some studies analyzed the transport process solely through the intensity of mine car flows [33] or simplified haulage operations into a single or a limited number of blocks [38]. In contrast, Wang et al. proposed a more comprehensive approach but encountered limitations arising from the complexity of coordinating haulage and backfilling processes [34]. Zhang et al. developed a robust and advanced model aimed primarily at optimizing the allocation of loaders and trucks [40]. But it lacks utilization for the implementation of modern technologies and sustainable development. Other researchers incorporated sustainability-oriented metrics—such as the number of truck collision avoidance events—and accounted for the dynamic behavior of input parameters [45]. Nevertheless, that model examines a

novel trackless system and is implemented as a code-based simulation, which restricts its user accessibility.

Therefore, in this study, we aim to develop a robust and comprehensive simulation model that captures all essential aspects of a mining transportation system at a high level of detail, including its stochastic nature. The proposed model will enable reliable coordination between haulage and backfilling processes, serve as an effective tool for system performance evaluation and sustainability assessment, and remain accessible for use by company personnel.

According to Table 1, numerous simulation software packages are used in practice. These tools differ, but all are suitable for modeling logistics processes. The selection of the appropriate simulation software can have a decisive impact on the accuracy of the model, its functionality, and the overall cost. In this study, the model is developed using ExtendSim 10 Pro 2024.

ExtendSim has been developed and marketed since 1987. The original Extend software was created in collaboration with NASA and was the first high-performance, low-cost simulation package designed for use on personal computers. ExtendSim is characterized by its customizable modeling logic, flexibility, processing power, and capability to reduce risk during the decision-making process [47].

As a block-oriented simulation software, it organizes its blocks into libraries: Value for continuous simulation, Item for discrete-event simulation, and Chart for graph-generating blocks. In addition to these, the system has five more libraries. The libraries can be expanded with user-defined custom blocks. Interaction between blocks is facilitated through connectors. The use of color-coding in the software assists in distinguishing between operations involving entities and those involving values. The description and functionality of each block used in the model developed for this study can be found in the user manual available online [48].

3. Results and Discussion

This section presents the complete process of evaluating and improving the transportation system in an underground mine located in Slovakia. The principal research question is whether the system can haul 10,000 tons of raw material per month. In addition, the volume of other entities was also assessed. As part of the model experimentation, we conducted supplementary experiments to further enhance the system's performance.

3.1. System Analysis

The surface area of the mining excavation zone covers 4.965 km². The designated area comprises underground mine workings (see Figure 2) and surface facilities, including a control room, processing plant, and concrete plant. The concrete plant produces both concrete and backfilling mixtures. The Elisabeth adit, the main underground working, extends in a straight alignment for approximately 4200 m. It serves both as the primary entry point and as the exit from the underground section. The adit constitutes a critical point in the mine's transportation system. It is equipped with a single rail track. Haulage within the adit is carried out using locomotives and mine cars.

The essence of the mining method is backfilling all excavated stopes with a mixture composed of lean concrete or another inert material possessing suitable mechanical and physical properties. Blasting operations are carried out using emulsion explosives. The underground mining operation is equipped with internet connectivity. Communication and ventilation are controlled by advanced systems from the control center located within the underground section. Through the implementation of these methods and tools, the mining operation aims to achieve a higher level of sustainability in extraction.

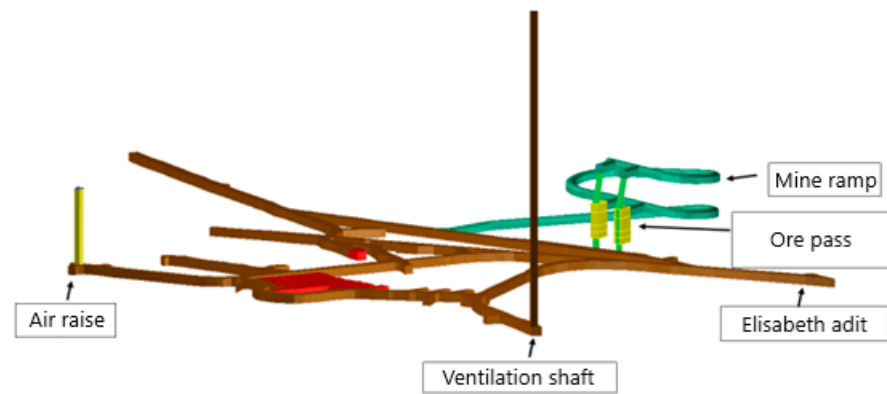


Figure 2. Underground mine workings and excavation area.

The subject of the detailed analysis is the process of transporting raw material, concrete, backfilling mixtures, and other entities between storage facilities and application sites, both underground and on the surface. The development of a comprehensive understanding of the system begins with the collection of available documentation. This process continues with familiarization with the operational rules of the mine's transportation code, visualization of the transportation network, on-site visits and interviews, and close collaboration with qualified personnel. The personnel involved should possess in-depth knowledge of both the mining processes and the haulage network. Given the large volume of data obtained from the analysis, the following sections focus on the adit as the main artery of the transportation system.

The total length of the rail track within the adit is 4350 m, of which 4200 m lies inside the adit itself. The remaining 150 m extends beyond the adit. The track gauge is 750 mm. The currently used S24 rails with wooden sleepers are undersized and in poor condition. However, their state does not yet prevent the track from being operated. Figure 3 shows a map of the adit from the portal to the underground stationing point. For clarity, the straight track is divided into three sections.

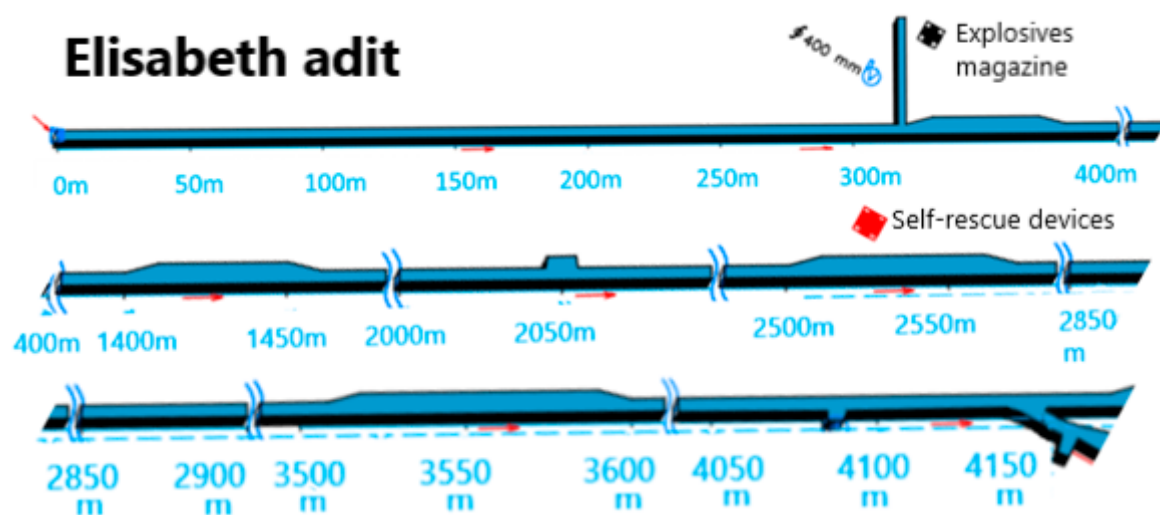


Figure 3. Haulage rail track of the Elisabeth adit.

Along the length of the track, avoidance spots are installed. Each spot is 100 m long, with the siding track dimensioned to accommodate eight mine cars coupled with a locomotive, corresponding to a length of approximately 80 m. Mine cars must not be pushed by a locomotive except when specifically required by a given operational procedure. The maximum haulage speed is 10 km/h. In practice, a speed of 5 km/h is most used.

The single-track alignment in the adit thus serves as both the inbound and outbound transportation route. For geological and structural stability reasons, it is not possible to construct an additional track within the adit. Similarly, aerial ropeway transport over the rail track is not a viable option due to safety considerations and insufficient adit height.

Haulage operations are not centrally managed by a dispatch control center. Communication between drivers, foremen, and other stakeholders takes place directly via radios. Current production volumes range from 150 to 600 tons per day. The volume depends on the transportation requirements for backfilling materials, other auxiliary supplies, and personnel. The mine operates continuously in 12 h shifts. The underground transportation network leads to the following:

- Ore passes (+40 m)—haulage of raw material using four mine cars, each with a capacity of 10 m³.
- Loader (+160 m)—haulage of raw material using four mine cars, each with a capacity of 8 m³.
- Backfill mixture pump (+195 m/+275 m)—haulage of the mixture by dedicated backfill mine car (8.5 m³ capacity). For concrete haulage, the procedure is identical except that a different mine car type is used (11 m³ capacity).

At the surface, access to the adit is possible either from the concrete plant (+80 m) or from the stationing point (+72 m). Also located on the surface is the dumping trestle (+42.5 m), where raw material is dumped into two ore bins. When dumping into the second bin, the set of four mine cars must be split into two halves and unloaded separately.

The fleet of the transportation system is extensive but outdated. Two Schoema CHL 60G locomotives are high-powered and capable of handling all types of haulage. The DHD 20 locomotive is less powerful and in poorer condition, but it remains suitable for all haulage operations. The DHD 15 locomotive can perform only personnel transport. The fleet is equipped with eight side-dump mine cars with capacities of 8 m³ or 10 m³, four concrete mine cars, three backfill mixture mine cars, and two personnel mine cars. All mine cars are in full operational use. In addition, other mine cars—some parked in underground areas, including at avoidance spots—are used only infrequently, with four units completely out of service. During each shift, two locomotive drivers carry out haulage tasks. Occasionally, an additional driver is available. Table 2 presents the model parameters related to the fleet and its operation.

Table 2. Transformation of fleet restrictions into model parameters.

Fleet Element	Model Allocation	Restriction
Locomotives	Resource Item block initial number	Drivers
Locomotive downtime caused by degraded track	Transport blocks speed	Maximum 5 km/h
DHD 20 utilization	Transport sideloop for supplementary materials	Mining activities are performed by Schoema locomotives
DHD 15 utilization	Transport sideloop for personnel	A 100% mining task rejection due to failure
Mine cars	Automatically assigned after task selection in the Equation block	Four for raw material and only one for mixtures (due to pump performance)
Mine car degraded mechanisms	Activity blocks at avoidance spots 1 and 4 and the second bin splitting activity	A high maximum value in a triangular distribution
Drivers	Resource Pool allocation	User defined value (currently 2)

Table 2 does not include the failure rate of the Schoema CHL 60G locomotive. There is no evidence of any failure during mining operations, except for downtime caused by degraded track conditions. The model operates exclusively with Schoema locomotives, while DHD locomotives are used only in the transport sideloop for supplementary transportation. Table 3 presents the achievability matrix for the performed haulage tasks, considering personnel and fleet availability.

Table 3. Achievability matrix for the performed haulage tasks.

Tasks	Drivers	Locomotives	Loaders	Mine Cars
One-point raw material haulage	1	1	1	4 (10 or 8 m ³)
One-point double raw material haulage	2	2	1	8 (10 and 8 m ³)
Mixture haulage	1	2	0	3 (concrete or backfill)
Double mixture haulage	2	2	0	3 (concrete or backfill)
Mixed raw material and mixture haulage	2	3	1	4 (10 or 8 m ³) and 3 (concrete or backfill)

Personnel transport is always carried out separately, without any concurrent haulage in the adit. The trip takes approximately 27 min and is limited to crew changeovers between shifts. Special transport of personnel into the mine must be approved by the mine manager. The additional findings from the analysis that are important for modeling include the following:

- Ore haulage has priority over all other processes in the transportation system.
- Locomotives must push mine cars into loading and unloading positions—their position is changed at avoidance spots 1 or 4.
- All other underground and surface transportation is performed using automotive (road) vehicles.
- Raw material is delivered to the ore passes by a loader with a bucket capacity of 4 m³.
- Only one loader is available—simultaneous loading of material at both locations is therefore not possible.
- Ore blasts from different parts of the deposit must not be mixed in the ore pass.
- The number of locomotive drivers is low, preventing the simultaneous operation of all locomotives.
- The mechanical equipment of locomotives and mine cars shows a high failure rate.

3.2. Modeling of the Transportation System

The modeling of the transportation system was carried out using ExtendSim 10 Pro 2024 simulation software. To develop the simulation model, it is necessary to define the parameters required by the model. Rarely are all these parameters fully obtained during prior analyses. Regarding transportation processes, it is essential to determine the time intervals for individual activities within the simulated system. The key time data sought included the duration of loading and unloading for all entities, driver shift length, time required for locomotive repositioning, and the time needed to couple or uncouple a train set. The input time parameters were measured empirically on-site. Measurements were repeated at different times of the day and on different days. Based on these measurements, time intervals were established and subsequently entered into the model's blocks in the form of distribution functions. The time distributions can be found in Appendix A.

During model development, we utilized ExtendSim software's capability for combined simulation. The model incorporates both discrete and continuous simulation elements and

integrates them in an appropriate manner. The discrete elements include the locomotives and mine cars, while the continuous part represents material flows and hauled resources. The model contains numerous input variables and a significant number of branching points. In line with logistics modeling principles, the main problem was therefore decomposed into sub-problems. We created segments of the primary activities within the transportation system. The function of these segments is to create a representation of the selected activity in the simulation software and then, through constant simulation, verify the logical correctness of the model for that specific activity.

The first segment is the rail track in the adit (Figure 4). Haulage in the adit is bidirectional but operated on a single track. In ExtendSim software, it is not possible for a single block to represent traffic in both directions. Therefore, in the simulation model, we modeled the inbound and outbound tracks as parallel representations. In front of each track, we added blocks (Information) to detect the presence of an entity in the paired representation. Together with Information blocks, Gate blocks restrict the flow of entities. When the paired blocks detect an entity moving in one direction, the corresponding flow in the opposite direction is either delayed or diverted to the siding track at an avoidance spot. The model segment ensures that all train sets performing any haulage process execute locomotive repositioning at avoidance spot 4 when entering the adit and at avoidance spot 1 when exiting the adit.

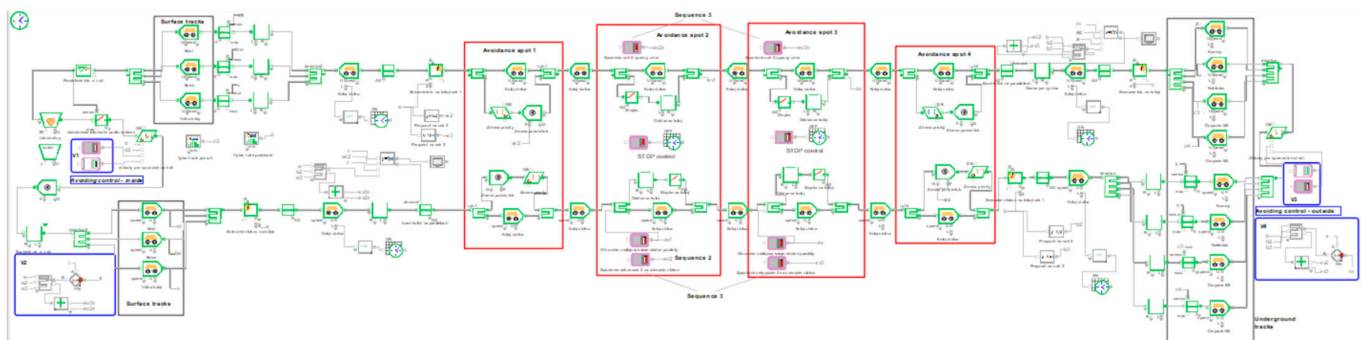


Figure 4. Model of a single-track bidirectional transportation system.

In Figure 4, avoidance spots are highlighted in red boxes, track sections outside the adit are marked in black boxes, and control blocks are shown in blue boxes. In this case, it is necessary to control the continuous flow of information within the model. Avoidance spots 2 and 3 serve primarily as parking/holding areas, but their status can be changed by pressing the grey-purple button blocks. When a button is activated, the counting sequence is also modified, and the control equations identify multiple train sets operating in the same direction. Constant simulation confirmed the correctness of the control logic, with no track collisions detected.

In the model, it is also necessary to simulate raw material handling operations (Figure 5). In the transportation system, the raw material is loaded underground and unloaded on the surface at the dumping trestle. Unloading at the dumping trestle is carried out in two different ways at the same location. But underground loading is performed in two different ways at separate locations. Prior to loading, the raw material is stored in Holding Tank blocks. Using a Get block, the model reads from the entity's capacity. This capacity is then requested from the Holding Tank block. In the Equation block, the retrieved quantity is determined and recorded as a new attribute. Subsequently, the Equation block defines the material quality and sets the loading time for the corresponding Activity block.

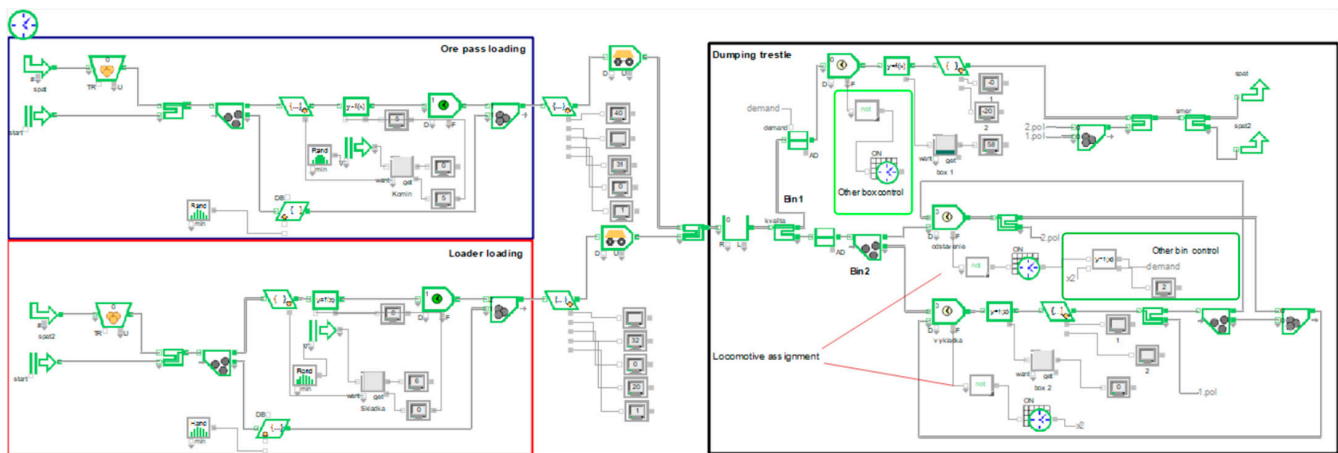


Figure 5. Loading and unloading raw material.

The quality handling is ensured by task termination. The raw material flow into the Holding Tank will stop temporarily. This allows haulage of all remaining material from one stope (which corresponds to the same quality). This procedure must be implemented using a table inside the Create block, which fills the Holding Tank. After the last transportation cycle from one stope, the model moves the train set to the start and clears all attributes. If the table generates raw material from another stope, a new task with attributes corresponding to the relevant quality and ore bin will be selected.

For unloading, the model first simulates the unloading time based on the entity's attribute; then, via an equation, it sends the quantity recorded in the attribute to the Holding Tank block representing one of the ore bins. For the second bin, unloading of the four mine cars must be performed in two stages: first simulating the tipping time for two mine cars, then the time required to split the emptied mine cars aside, followed by the tipping of the remaining two.

In the case of loading, the Unbatch block evenly distributes the value of the incoming attribute among all outgoing entities. The capacity value is assigned to the four mine cars and the locomotive. Therefore, only the locomotive proceeds to a Set block, which removes its capacity property. We extended the unloading operation with a safeguard preventing simultaneous unloading into both bins. Embedded Shift blocks monitor bin usage and send a value of 0 (closed) or 1 (open) to the Gate blocks located before the dumping trestle. Before unloading into the second bin, the train set in the model is split into two halves. The first half is unloaded while the second half is set aside. However, only one locomotive is available. In this case, the Shift block completely disables the splitting activity until the unloading of the first half of the train is completed. Once this is finished, the splitting activity is triggered, followed by unloading the remaining half of the train set.

Another major component of the transportation system is the loading and unloading of backfill mixtures and concrete (Figure 6). Pumping or unloading of the backfill mixture is simulated by modeling the unloading time first. Subsequently, based on an attribute specifying the type of material, the corresponding output connector is assigned to a value. The value is then written to the Holding Tank block associated with that material type. Loading of backfill mixture or concrete is performed from a single discharge of the concrete plant. Upon entering the concrete plant, the entity selects one of two Get blocks. Each Get block is linked to a different Holding Tank, ensuring that the requested material type is loaded. The model then simulates the loading time and records the type of loaded material. This approach uses information on either the quantity of material in the mine car or the quantity of the required material, multiplying it by the time value per cubic meter. For

simplification of the loading-time equation, the model sums the output values from both get connectors from the Holding Tanks, since one of them will always be zero.

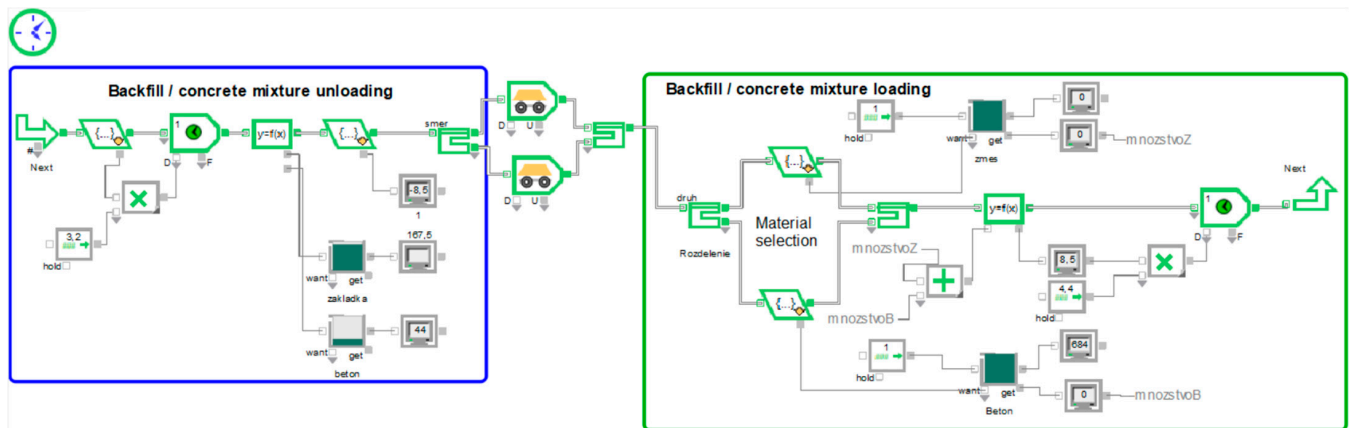


Figure 6. Backfill and concrete loading and unloading operations.

The final segment represents the modeling of shift initialization (Figure 7). The simulation generates locomotives and drivers. Each locomotive is assigned the property of a transportation cycle, which monitors when the driver's work assignment should be changed. Drivers are then allocated to available locomotives. If no driver is assigned, the locomotive remains held within the block. This is followed by the simulation of the personnel transport, moving crews inbound at the start of the shift and outbound at the end. This function is managed by a Shift block, which contains a timetable specifying when to redirect a locomotive with its driver into the Transport sideloop. The timetable can be extended with time data for special personnel transport or the haulage of other materials.

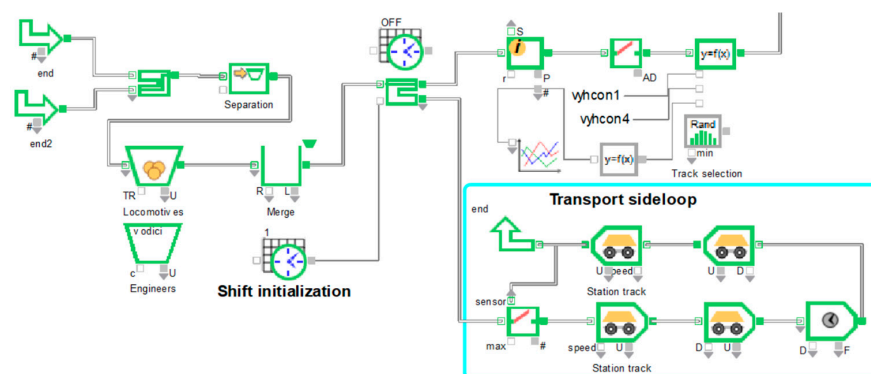


Figure 7. Task assignment and special transportation in the system.

Route selection constitutes the assignment of a work task. This can be defined using a random-number generator (for stochastic experimental runs) or via an Equation block (to set predefined tasks in configured experiments). A second, higher-placed Shift block tracks the remaining time in the driver's shift. If there is insufficient time to complete a full haulage cycle, it closes the gate and prevents further entry underground.

During the assembly of the comprehensive model in ExtendSim 10, we implemented creative and logical modifications. We had to insert additional Gate and Information blocks to enhance model control. Naturally, as the model's complexity increased, so did the intricacy of the conditional logic. We created more safeguards to prevent potential collisions on tracks outside the adit. All loading and unloading operations were constrained by Gate blocks using an area-gating system. For surface operations, both loading and unloading sequences, we supplemented with blocks monitoring the driver's operational cycles. The

final value in the cycle count terminates the current work assignment and routes the driver with the locomotive back to the initial segment for a new task assignment. In underground loading and unloading sequences, we made cosmetic adjustments, including the addition of a Set block and modifications to the Activity block corresponding to the loader.

The full transportation system simulation model is of considerable scale, making single-frame visualization impractical. To enhance readability, we implemented hierarchical blocks (sub-models). Each sub-model encapsulates a complete process segment comprising multiple functional blocks. Within the top-level frame, the hierarchical model (Figure 8) preserves all essential parameter-setting blocks required before commencing experimental runs.

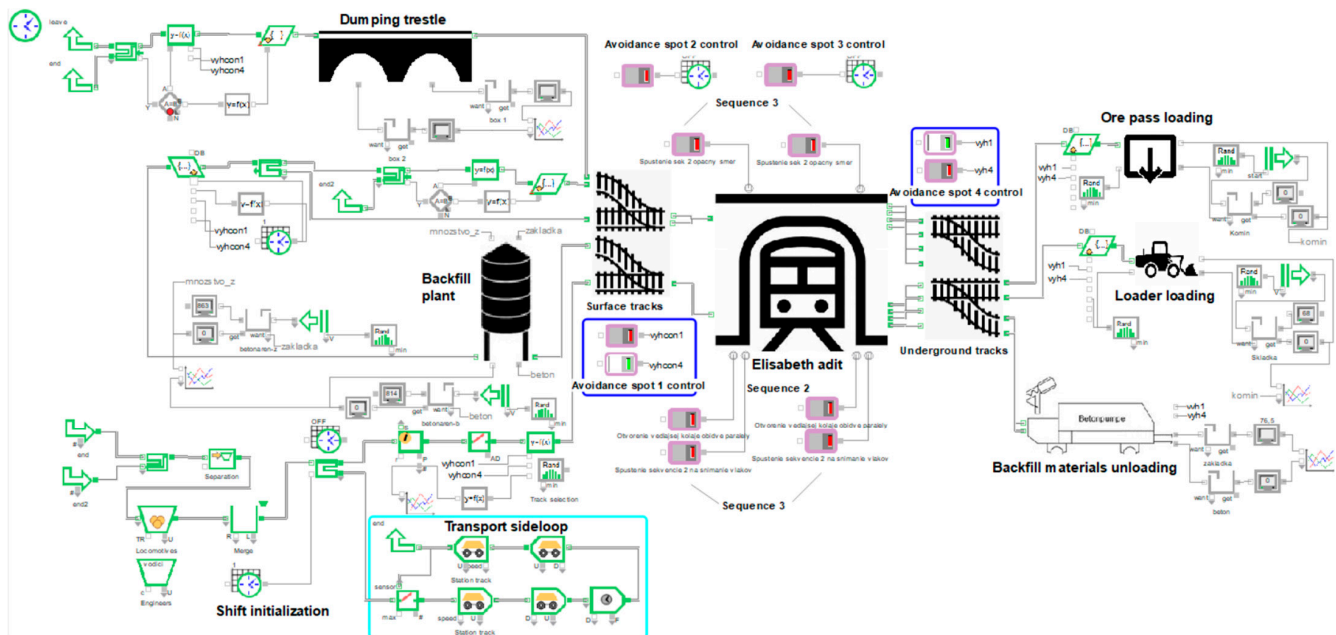


Figure 8. Hierarchical model of the mine transportation system.

Model validation is an essential prerequisite step before deploying the simulation model in practical applications. The primary objective is to evaluate whether the developed simulation accurately represents the real mining transportation system under study. The mine transportation system at the examined site is not centrally controlled via a dispatch center, which results in limited documentation of ore haulage and backfilling activities. Consequently, quantifying the extent of stochastic variability affecting measured cycle times is challenging. There are no records of exact speed values. All speeds in the Transport blocks are set to 5 km/h based on the system analysis outcomes. This speed applies to all experiments presented in this paper. The validation experiments, summarized in Table 4, reveal deviations ranging from 3% to 32%.

Some discrepancy values exceed the ideal acceptable error bounds of 10% to 20% commonly regarded in simulation studies. Therefore, we performed a sensitivity analysis. In this analysis, we altered the triangular distribution of locomotive repositioning and the speed in the Transport blocks by $\pm 30\%$. When the triangular distribution was modified, we observed only a minor impact on the outputs. As a result, Table 5 examines this input solely in cases where the validation discrepancy exceeded the upper boundary. In contrast, speed was found to be a critical parameter. We evaluated speed effects across all experiments.

Table 4. Simulation model validation results.

Operation	Location and Volume	Train Sets/Engineers	Measured Process Duration (hh:mm)	Simulated Process Duration (hh:mm)	Discrepancy
Haulage	B488—161.8 t	2/2	05:14	04:44	9.55%
		1/1	05:48	07:01	20.98%
Haulage	C492—114.1 t	2/2	04:39	04:29	3.58%
		1/1	06:55	06:05	12.05%
Backfilling	C—M3—834 m ³	1/1	216:00	235:29	9.02%
Backfilling	C—M3—583 m ³	1/1	168:00	149:39	10.92%
Backfilling	C—M3—615 m ³	1/1	192:00	144:42	24.63%
Backfilling	C—M3—611 m ³	1/1	144:00	172:31	19.80%
Backfilling	B—M4—366 m ³	1/1	96:00	103:20	7.65%
Backfilling	B—M4—828 m ³	1/1	264:00	233:47	11.44%
Backfilling	B—M4—613 m ³	1/1	120:00	157:21	31.12%

B488, C492, C—M3, and B—M4 are designations used within the mining company for specific stopes.

Table 5. Sensitivity analysis.

Operation	Discrepancy	Locomotive Repositioning		Train Set Speed Input Change	
		Input Change −30%	Input Change +30%	Input Change −30%	Input Change +30%
		Output Discrepancy			
Haulage/B488—161.8 t/2/2	9.55%			9.25% (343.07 min)	16.97% (260.71 min)
Haulage/B488—161.8 t/1/1	20.98%	18.7%	22.4%	4.31% (363 min)	43.7% (500 min)
Haulage/C492—114.1 t/2/2	3.58%			12.12% (312.84 min)	14.38% (238.87 min)
Haulage/C492—114.1 t/1/1	12.05%			6.07% (440.22 min)	23.87% (315.9 min)
Backfilling/C—M3—834 m ³	9.02%			42.9% (308.71 h)	6.57% (201.80 h)
Backfilling/C—M3—583 m ³	10.92%			7.69% (180.92 h)	29.18% (118.97 h)
Backfilling/C—M3—615 m ³	24.63%	25.73%	22.9%	3.5% (185.23 h)	35.12% (124.56 h)
Backfilling/C—M3—611 m ³	19.80%			57.17% (226.33 h)	2.78% (148.01 h)
Backfilling/B—M4—366 m ³	7.95%			41.2% (135.56 h)	7.65% (88.65 h)
Backfilling/B—M4—828 m ³	11.44%			16.44% (307.42 h)	23.65% (201.51 h)
Backfilling/B—M4—613 m ³	31.12%	28.9%	33.6%	13.55% (206.5 h)	72% (136.26 h)

B488, C492, C—M3, and B—M4 are designations used within the mining company for specific stopes.

According to the sensitivity analysis, speed is a significant input parameter. Its variation at the level of $\pm 30\%$ considerably affects the outputs of the validation experiments. As mentioned earlier, due to limited documentation of transportation operations, input parameters such as the exact speed or the number of train stops are unknown. Therefore, the validation experiments were conducted using an average speed of 5 km/h determined during the analysis. The actual speed in the observed real operations may have differed.

Nevertheless, in two experiments focused on haulage, the results remain within the desired range. In all other experiments, at least one measured value does not exceed the upper limit of the desired interval. Based on the results of the sensitivity analysis, the identification of speed as a critical parameter, and the absence of precisely measured input values, we considered the model as adequately valid.

3.3. Simulation Model Experimentation

Core simulation experiments targeted a sustained ore haulage throughput of 333 t/day ($\approx 208 \text{ m}^3/\text{day}$ at bulk density), equivalent to 10,000 t/month. Table 6 lists operational cycle times for alternative haulage configurations by loading location. Trials employing two train sets consisted of the ore pass loading station utilizing the entire fleet of side-dump mine cars. At the loader-fed location, larger mine cars cannot be deployed. Concurrent haulage from both loading points is precluded by the availability of only a single loader.

Table 6. Core simulation experiments results.

Train Sets	Loading Type	Ore Bin	Raw Material Source *	Shortest Duration [h]	Longest Duration [h]
1	Ore pass	1	OP	10.55	10.67
		2	OP	12.21	12.41
	Loader	1	ROM	12.78	13.01
			S	18.21	18.41
		2	ROM	14.47	15.15
			S	19.95	20.72
2	Ore pass	1	OP	5.49	5.59
		2	OP	6.30	6.89

* OP—ore pass, ROM—run-of-mine stockpile, S—stope.

The experimental results demonstrate that a sustained raw material haulage throughput of 333 t/day is achievable across all operational configurations tested. All these scenarios focus on haulage. Other operations, such as backfilling or supplementary transportation, are completely suppressed, especially when two train sets are used for haulage. The durations of the last two experiments in Table 5 do not cover the whole day, not even a full shift. This leaves time for other operations later during the shift. Experiments with one train set leave the second train set available for other tasks.

We performed additional experiments utilizing the second train set for backfilling. The volume of transported mixtures varies depending on the raw material loading location. The location changes intervals when the first train set (performing haulage) passes through the adit. The second train set must wait for a clear passage. Figure 9 shows the minimum and maximum volumes of mixtures per day. The minimum volume is achieved when loading is performed directly from the stope, while the maximum occurs during haulage from the ore pass.

Analysis of simulation runtime against the total material moved indicates a potential raw material delivery frequency to the loading locations of approximately 12 min. The system has two loading locations: the ore pass and ROM. Loading from the stope is direct, without any preceding material deliveries to a specific location. First, after loading from the ore pass, there is an average transit time of 54 min through the adit. Then, it takes 2 min to unload into the first bin or 2 plus 9.5 min into the second bin. Subsequently, there is another 54 min transit time, plus a loading time for three mine cars totaling 6.75 min. In total, this results in a cycle time of 116.75 or 126.25 min. To maintain continuity, during this

cycle, the loader must fill the ore pass with 40 m^3 of raw material. The shovel capacity is 4 m^3 , meaning a total of 10 material deliveries. Dividing the cycle time by the number of deliveries gives 11.7 or 12.6 min per delivery.

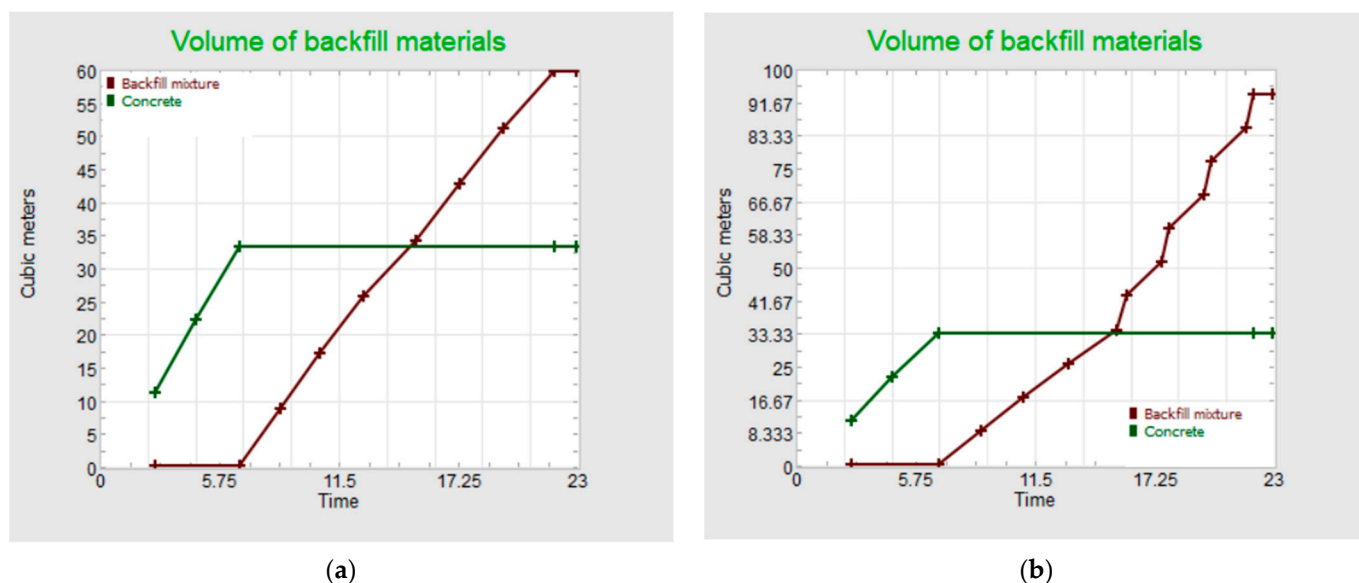


Figure 9. Additional results for one train set haulage experiments: (a) minimum volume of transported mixtures; (b) maximum volume of transported mixtures.

In the case of ROM, the transit time through the adit is 55.4 min. The loading time is excluded from the calculation. Since the same loader performs both loading and material delivery, it cannot load mine cars and deliver material to ROM simultaneously. The ROM delivery only needs to reach 32 m^3 due to the lower capacity of the mine cars. As a result, the time per delivery is 14.1 or 15.3 min. Figure 10 shows the residual in both the ore pass and ROM loading locations. Material delivery is set to a constant value of potentially 12 min.

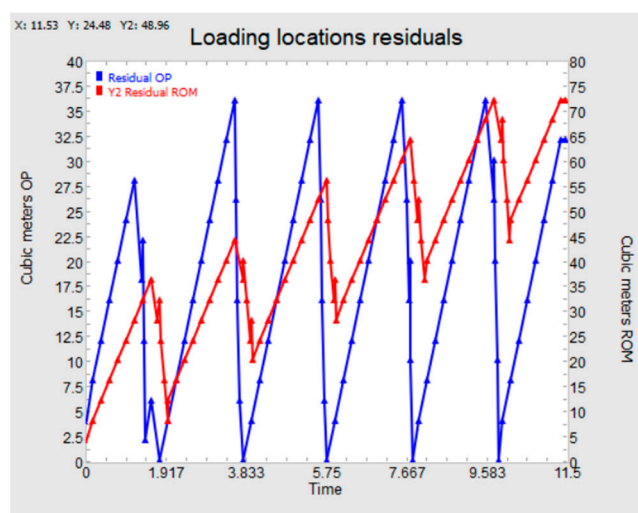


Figure 10. Loading location residuals at a 12 min material delivery frequency.

The subsequent experiment aimed to identify the optimal supply interval duration for delivering material to loading locations. Drawing on the potential material delivery frequency from the primary experiment, we defined four candidate intervals. The simulation trials also included a dual-loading location haulage scenario. However, implementation of

this configuration in actual operations would necessitate the acquisition of an additional loader. The experimental outcomes are summarized in Table 7.

Table 7. Raw material supply interval experiments outcomes.

Interval [min]		4.5 to 5.5	15 ± 2	10 ± 1.5	5 to 15, Most Likely 10
Loading Type		Volume per Shift (11.5 h) [m ³]			
One Train Set (OP)	Bin	312	152	213	235
	Residual	263	38	35	38
Two Train Sets (OP)	Bin	480	120	200	208
	Residual	77	34	33	35
One Train Set (ROM)	Bin	211	136	181	192
	Residual	331	26	52	58
One Train Set (OP) and One Train Set (ROM)	Bin	432	248	379	392
	Residual OP	275	31	39	42
	Residual ROM	337	28	88	86

Based on the simulation results, even the longest raw material supply interval tested is sufficient to achieve the targeted haulage rate. The shortest interval identified the maximum throughput attainable with the selected haulage configuration. The elevated residual volumes in the loading locations indicate that material was available but could not be hauled within the available cycle time. From an operational efficiency perspective, the final two tested intervals represent the most favorable balance, combining high transported volumes with low residual material levels.

The simulation scenario incorporated an additional loader, with its parameters kept identical to the primary unit—implying that actual implementation would require procurement of the same loader model. Market data indicate that the price of an underground mining loader varies according to year of manufacture, condition, and cumulative operating hours. Recent listings show that a 2018 unit with approximately 5900 h of operation typically sells for about EUR 322,700 [49]. The cost of a new unit would be expected to exceed this figure, depending on the selected specifications and the region of purchase.

Backfilling of mined-out stopes is performed in two operational modes:

- Two locomotives with a single driver when ore haulage is carried out concurrently;
- Two locomotives with two drivers when no ore haulage takes place.

This constraint is driven by the number of locomotive drivers available per shift. The mine currently operates two high-performance locomotives and one haulage-suitable locomotive. Upon hiring an additional driver, it would be possible to allocate two locomotives and two drivers to backfilling, while the third driver continues ore-haulage duties. Across all experimental runs, a maximum of 120 m³ of raw material was hauled. The volumes of backfill material are illustrated in the charts provided in Figure 11.

Given the increased availability of locomotive drivers, the acquisition of an additional locomotive becomes a viable strategic option. Deploying a new unit would both enhance the overall condition of the fleet and enable the full retirement of the aging DHD locomotive that is currently in poor operating condition. Operationally, such procurement would support haulage operations with two locomotives and corresponding drivers while enabling the third driver—paired with two locomotives—to focus exclusively on backfill material haulage (Figure 12).

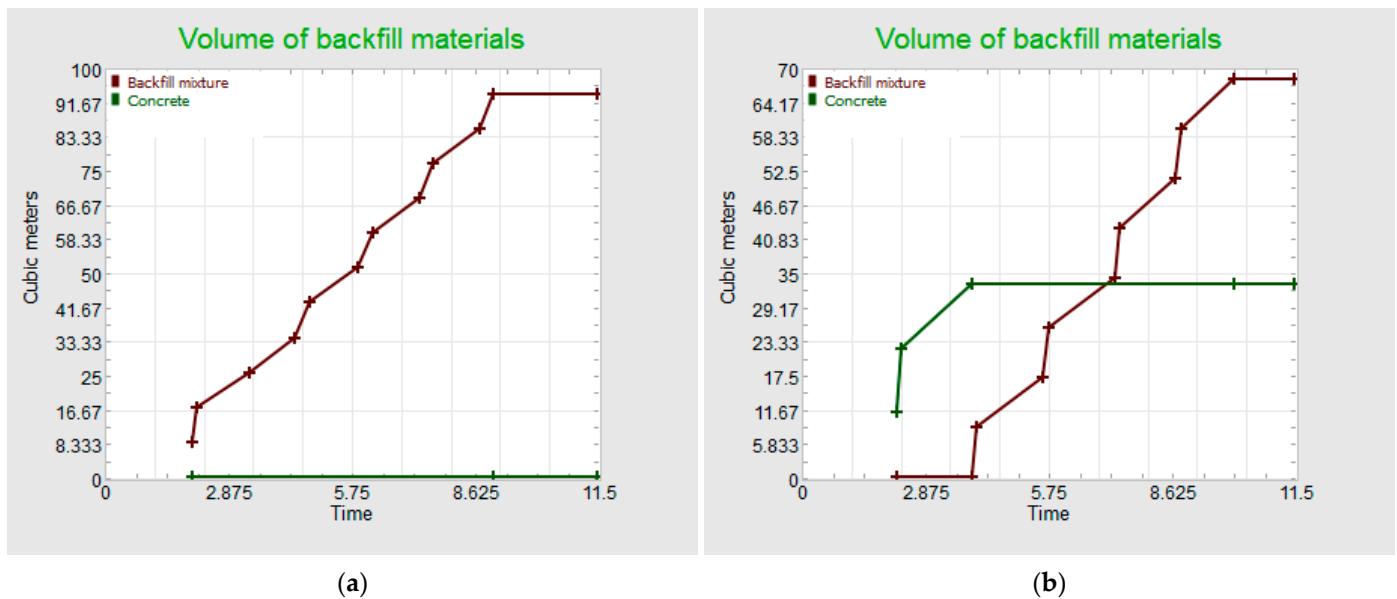


Figure 11. Hauled and discharged volumes of backfill materials: (a) in the case of the backfill mixture only; (b) in the case including concrete.

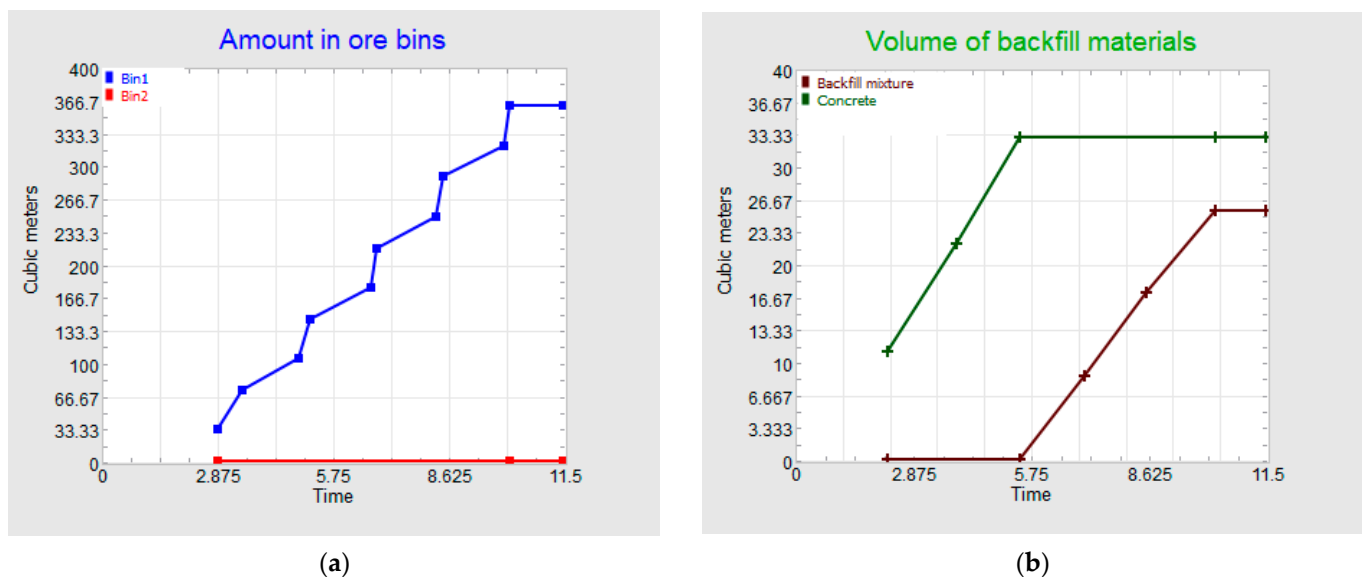


Figure 12. Experiment with three locomotive drivers and four locomotives: (a) volume of raw material hauled; (b) volume of backfill materials hauled.

At full operational capacity—utilizing four locomotives and three operators—the transportation system can achieve an ore haulage output of 360 m^3 and a backfilling rate of 58 m^3 . Despite these figures, the configuration retains certain constraints. Given the current number of available side-dump mine cars, this setup is viable only for haulage from ore passes or for mixed haulage combining ore pass and ROM loading. Realization of maximum performance further depends on the availability of suitable underground track alignments and the satisfactory mechanical condition of all operating equipment.

We did not obtain formal quotations for procuring a new locomotive or additional side-dump mine cars, nor did we identify any suitable online offers. Nevertheless, experimental trials combining both haulage and backfilling were conducted using three locomotives and two drivers, with train-set lengths adjusted for the tests (Figure 13).

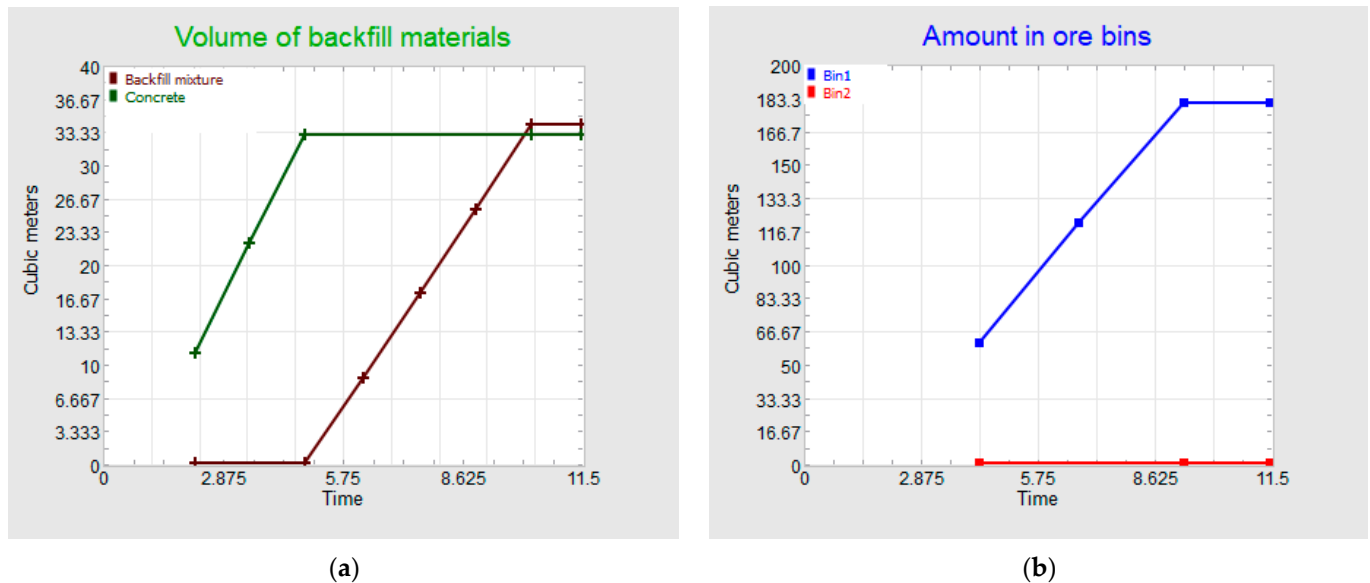


Figure 13. Variation in material volumes with changes in train set size: (a) a modest increase in the hauled backfill mixture observed from consist lengths of five mine cars and above; (b) a reduction in hauled raw material volumes occurring from consist lengths of six mine cars onwards.

The result variations were minimal. From a consist length of five mine cars, a modest increase in discharged backfill mixture was noted. However, further increases in consist size produced no additional gains. This is attributed to greater clearance in the adit since raw material is hauled in fewer trips. At five mine cars, the haulage volumes remained effectively unchanged, except in isolated cases where set-outs of individual mine cars led to slightly lower totals. With six mine cars per consist, the haulage volumes began to decline due to extended loading location dwell times and the need to uncouple mine cars during unloading. Under such circumstances, a shorter supply interval would be required, which may not be operationally feasible given mining constraints.

Additional simulations examined scenarios in which either waste rock had to be hauled to the surface or necessary materials had to be hauled underground to support mining operations. As anticipated, the performance changes were negligible. When both conditions occurred within the same shift, the total output was reduced by approximately one carload of raw material and one carload of backfill. When they occurred in separate shifts, we observed only one of these effects—corresponding to whether raw material loading or backfill unloading was interrupted.

Beyond the scope of the simulation experiments, the following enhancements were recommended to the mining enterprise:

- Replacement of S24 rails with S30 profile rails mounted on steel sleepers.
- Comprehensive overhaul of all mechanical systems within the fleet and equipment.
- Adoption of an integrated condition-based and planned maintenance program engaging all employees.
- Implementation of centralized dispatch control for the transportation system, supported by digital technologies.

Implementation efforts began with the phased replacement of rails, scheduled on predetermined days. Replacements are executed in short track segments to minimize operational performance losses. A full mechanical overhaul of the fleet has not yet been undertaken. Instead, regular corrective maintenance cycles have been established to sustain equipment availability until definitive repairs are completed. Concurrently, a detailed

condition-based maintenance framework is under development, placing accountability for equipment condition on the operators directly responsible for its use.

The simulation experiments provided compelling evidence for the necessity of procuring an additional underground loader—a process currently being actively pursued by mine management. The demonstrated capability and performance of the transportation system, under conditions of suitable track infrastructure and proper equipment maintenance, have strengthened the company's motivation to pursue higher production targets. While the observed raw material supply frequencies approximate those predicted in simulations, they remain highly sensitive to the variability in the extraction process—a dependency confirmed during operational validation. Considering deviations recorded during field verification, management elected not to expand the locomotive driver workforce nor to invest in additional locomotives at this stage.

Despite its potential, one of the most significant advantages of the developed simulation model remains underutilized. The absence of a centralized dispatch center for the transportation system prevents integration of the model into operational planning. Resistance stems partly from the paradigm shift in management philosophy that such a change would require, which is not universally embraced by the workforce. Furthermore, model deployment requires both a trained operator and at least one licensed software installation. Rather than recruiting new staff, the company is negotiating with its partner university to provide specialized training for the personnel currently responsible for the transportation system.

The concept of a sustainable underground logistics system is still nascent. However, mining operations have begun to focus more deliberately on their development. The company's main focus is on production volume stability and continuity. Initiatives such as phased track replacement, the preparation of a robust maintenance framework, and the procurement of an additional loader enhance underground productivity and transportation system utilization. Backfilling cycles serve as tangible indicators of sustainable waste management and high recycling rates of mining waste and by-products incorporated into used mixtures. Simulation model planning contributes to reducing collision near-misses in the adit and, subsequently, improves worker safety. Further steps primarily involve quantifying carbon emissions and energy consumption per ton-kilometer. When coupled with the company's adoption of sustainable mining methodologies and tools, these measures form the foundation for genuinely sustainable production within the mining sector.

4. Conclusions

Logistics plays a critical and irreplaceable role in the primary industrial sector, including mining. Within the studied system, sustainable mining is exemplified by the application of emulsion explosives, comprehensive underground internet connectivity, seamless communication with the surface control center, and systematically managed ventilation.

This case study presents a detailed analysis and subsequent optimization of the transportation system in an underground mining operation in Slovakia. The primary objective was to evaluate the feasibility of achieving a consistent monthly production target of 10,000 tons of extracted raw material. To ensure a sustainable systems perspective, a structured modeling and simulation methodology was applied using the ExtendSim 10 platform. The resulting integrated model incorporates multiple interconnected segments, each representing a critical component of the transportation system.

Model validation demonstrated several deviations beyond ideal tolerance limits. Sensitivity analysis identified speed as a critical parameter affecting results. As exact input values

for speed and train stops remain unknown for validation experiments, and most measured outputs respect the upper discrepancy boundary, the model is considered sufficiently valid for its intended purpose.

The simulation experiments in Table 5 validated that the daily production target of 333 tons can be met across multiple operational configurations. The experiments were dedicated to the haulage. Processes like backfilling were suppressed and limited by the availability of locomotives, the presence of drivers, and the reliable operation of the fleet. Figure 9 shows supplementary results for some Table 3 experiments. In these experiments, the backfilling process was partially suppressed, meaning one locomotive was left to backfill excavated stopes.

The following experimentation aimed to achieve sustainable system performance. Material delivery was examined to ensure continuity of mining operations. To strengthen stability, safety, and waste management, we examined alternation of haulage and backfilling processes. These experiments evaluated multiple outputs during one shift, with a minimum of 104 m³ of raw material required to be hauled to meet the production goal. The proposed measures include the procurement of a second loader, optimization of raw material supply intervals, replacement of existing track sections, restructuring of maintenance systems and scheduling, and operational deployment of the simulation model for production planning.

Practical implementation has, to date, been constrained by organizational, personnel, and financial factors. Furthermore, during model development, significant limitations were imposed by the single track in the adit and by inherent constraints of the ExtendSim platform. Future simulation initiatives should evaluate alternative modeling platforms, with a view towards evolving the approach into a modern digital twin framework.

We have confirmed some of the conclusions through simulation or implementation, but others remain open for further research. Therefore, in Table 8, we provide a structured distinction between our robust and tentative conclusions.

Table 8. Summarization of robust and tentative conclusions.

Robust Conclusions	Tentative Conclusions
The model appropriately represents the real system	Backfilling can be performed after the raw material haulage process using two train sets
Speed is a crucial input parameter	Safety and waste management improve through process alternation—KPIs needed
The target of 10,000 tons per month is achievable	Improvements in mechanism reliability can be achieved through restructuring of maintenance systems
Backfilling can be performed on a reduced scale when using one train set for raw material	The model is suitable for operational process planning
Continuity secures proposed frequencies	Developing a digital twin requires further research and software modification
A second loader allows more haulage options with higher production	Sustainable underground logistics system is still nascent—quantification is needed
Replacement of rails increases the actual speed of locomotives	The problem-solving methodology can be transferred and adapted across different mining contexts

This study delivered a comprehensive and operationally verifiable perspective on optimizing an underground mining transportation system within the framework of Mining 4.0 and sustainable production principles. The developed simulation model demonstrated high utility as a decision-support tool—enabling systematic identification, alternative evaluation, and planning. Future research should formalize and document the applied

problem-solving methodology for enhancing mining logistics systems, ensuring it can be transferred and adapted across different mining contexts. The methodology should also address the quantification of crucial sustainability metrics. This quantification will more robustly support sustainability claims in future applications. The approach should be validated through additional adaptations, including surface mining operations.

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Appendix A

Table A1 contains samples from on-site measurements of time intervals and their representation in distribution functions. We selected the triangular distribution in both cases presented in the table based on expert assessments conducted with company representatives and our own judgment. The main rationale for this choice was the triangular distribution’s common application. In situations where the available data are limited, but the minimum, maximum, and most likely values can be estimated. For the loading and unloading of mixtures, we applied a constant distribution according to the recommendations of the company representatives. The uniform and normal distributions were determined using a goodness-of-fit test. We tested the uniform distribution with the Kolmogorov–Smirnov test. At the chosen significance level of 0.1, the null hypothesis that the observed values fit the selected distribution function was not rejected in any case. In the case of the mine car tipping operation, the sample data rejected the hypothesis, but the entire dataset marginally did not. We also tested the normal distribution using the Kolmogorov–Smirnov test under the same hypothesis and significance level. Again, the hypothesis was not rejected in any case.

Table A1. Operation time parameters.

Operation	Amount [m ³]	Time Measurements Samples [mm:ss]	Distribution [mm:ss]
Ore pass loading	10	02:12, 02:16, 02:22, 2:50, 02:25, 02:31, 02:24, 02:37	02:12–02:50
ROM loader loading	8	04:49, 04:35, 04:40, 04:27, 04:56, 05:01, 04:44, 05:00	04:27–05:01
Stope loader loading	8	15:52, 15:42, 15:45, 15:44, 15:55, 15:53, 15:59, 16:01	15:49 ± 00:07
Mine car tipping	8/10	00:14, 00:14, 00:15, 00:14, 00:15, 00:16, 00:14, 00:16	00:14–00:16
Second bin train set splitting	NA	03:30, 04:44, 04:15, 03:45, 12:12, 16:44, 03:38, 04:02	03:30; 16:44; 04:08
Locomotive repositioning	NA	02:52, 03:01, 05:21, 03:04, 02:58, 04:26, 03:14, 03:12	02:52; 05:21; 03:04
Mixtures loading	1	04:20, 04:24, 04:24, 04:24, 04:23, 04:24	04:24
Mixtures unloading	1	03:19, 03:18, 03:19, 03:19, 03:17, 03:19	03:19
Supplementary and personnel transportation	NA	27:18, 27:55, 27:25, 27:17, 26:55, 26:42	27:10 ± 00:27
Mine car entry and exit activities	NA	04:12, 04:10, 04:25, 04:54, 04:50, 04:28	04:10–04:54

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