A SIMULATION OF THE MATERIALS FLOW IN A QUARRYING OPERATION

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ABSTRACT. Determining the exact number of different types of mining equipment on an annual base or for the life of a mine is one of the most crucial elements in a mining project. In most cases, such estimates are based on analytical models which utilise certain empirical coefficients as correction factors, as they account for the individual conditions under which the deposit is exploited. However, their exact values to some extent is unknown and their values used for calculations can be based on subjectivity, leading to a biased estimate of the productivity of different mining equipment. The reason for such bias can originate from the use of data from similar mining operations. Therefore, for this study, a simulation approach was used to more accurately estimate the productivity of different mining equipment for a quarrying operation. Following this approach, certain design decisions can be validated or invalidated in a more robust way. In addition, results from the simulation model are compared to one another, which leads to the adoption of a hybrid solution between two of the considered scenarios.

Key words: hauling, quarrying, simulation of technological processes, overall and annual design projects, open-pit design

СИМУЛАЦИЯ НА ТОВАРОПОТОЦИТЕ МИННА МАСА В КАРИЕРА ЗА СТРОИТЕЛНИ МАТЕРИАЛИ

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РЕЗЮМЕ. Определянето на необходимата комплексна механизация за изпълнението на годишния производствен план е един от най-важните елементи при изготвянето на цялостни и годишни работни проекти. В повечето случаи това се базира на формулен апарат, включващ поправъчни коефициенти, отчитащи спецификата на работата в производствените условия. До известна степен съществува елемент на субективност при определите стойности за производителността на използваните видове механизация, която се дължи на непълното съответствие на проектирания минен обект с други аналогични на него. Именно затова е възприет симулационен подход за по-точно изчисляване на производителността на основната механизация, участваща в технологичните процеси по добив и транспорт на минната маса. По този начин много точно може да се валидира проектното решение и при необходимост да се коригира своевременно. Настоящата статия разглежда приложението на симулационен модел при работата на комплексна механизация в кариера за строителни материали. Направено е сравнение между получените резултати от симулационния модел. Същевременно е предложено комбинирано решение между разглежданите варианти.

Ключови думи: рудничен транспорт, добив на строителни материали, симулация на технологични процеси, цялостни и годишни работни проекти, проектиране на открити рудници

Introduction

The mining industry has long relied on deterministic analytical models to plan and optimise open pit and quarry operations (Koprev and Aleksandrova, 2022). However, these models often overlook dynamic changes and unforeseen events in real-world environments. To address these limitations and enhance operational efficiency, the mining sector has embraced simulation-based approaches. These approaches provide a more accurate depiction of mining conditions, enabling the exploration of various scenarios to improve equipment utilisation, reduce costs, and minimise environmental impact. Simulation models have emerged as indispensable tools, reshaping the planning, execution, and optimisation of mining processes by facilitating well-informed decision-making. This paper delves into the transformative power of simulation models, highlighting their advantages, applied methods, and illustrates their practical implementation with a case study.

Simulation methods in mining and quarrying operations

Traditionally, open pits and quarries rely on analytical models that are deterministic in nature and often fail to account for dynamic changes in the real environment, as well as the occurrence of unforeseen events. The emergence and application of simulation-based approaches are proving to be a powerful way to more realistically represent the conditions and features of a mining site. This provides the opportunity to consider different scenarios in order to increase the efficiency of production activities by ensuring higher equipment usability, realising lower production costs, as well as reducing the environmental footprint of mining activities. For this reason, globally, simulation models have emerged as a critical tool in the mining industry, transforming the way core, ancillary and service work processes are planned, executed, and optimised based on reasoned decisions.

Modelling of mining workflows

In the context of the mining process and its constituent work operations, such a class of software products simulating work in open-pit mines and quarries covers a wide range of techniques for modelling the work of different types of mining equipment. Each modelling method included in the simulation software product is designed to solve a specific task or the interaction between individual participants in a given situation. Some of the more important tools used to model the complex relations for work operations and the general flow of work include:

1. ***The Monte Carlo method****.* This method is a statistical approach for modelling the probabilistic nature of a set of variables in a given system. By generating an arbitrarily large number of random numbers under a known cumulative distribution function, the computer can realise a set of trials that "mimic" the actual realisation of a given process or a set of possible values for a variable whose actual value is not known. In this way, a more comprehensive understanding of the functioning of the system is ensured precisely by considering it probabilistic (Kroese et al., 2011).

2. ***Discrete element system (DES).*** DES is one of the most widely used techniques in the simulation of complex systems. The method focuses on modelling individual events that occur sequentially over time, e.g. movement of dump trucks, stages of work processes (loading, unloading, turning the bucket, etc.). Sequential realisation of these events in a finite number of time intervals for the entire system allows one to obtain a more complete picture of the material flows and the mining equipment. In this way, potential "bottlenecks" in the system can be identified and irrational processes can be avoided in a timely manner (https://rpmglobal.com/product/haulsim/).

3. ***Agent-based modelling (ABM).*** ABM is a computer technique aimed at modelling the behaviour of individual agents (participants) in a given system (e. g. excavators, front loaders, dump trucks, etc.) as autonomous units. This approach is particularly suitable for analysing the interactions and dynamics between individual agents, allowing to clarify the emergent behaviour of the system under different conditions (Grimm and Railsback, 2005).

Other notable methods can also include Markov chains, queueing theory models (Czaplicki, 2008), different optimisation algorithms, most notably linear programming (Koprev, 2018), non-linear methods and heuristic methods. Additional sampling strategies are also known to work well in simulation and uncertainty models, e.g. Latin hypercube sampling (LHS), which can decrease the number of required simulations.

Advantages of simulation models

Integrating simulation methodologies into the planning workflow in mining operations offers several advantages over traditional analytical models. The most important ones are listed below:

1. ***Realism and accuracy.*** Simulation software such as *HAULSIM* creates a virtual replica of the mining site, capturing various factors that affect hauling operations, including geological formations, road conditions, loading and unloading times, truck characteristics, and material properties. The model accurately reflects the real environment by simulating these elements, providing planning and design teams with accurate and reliable information.

2. ***Flexibility and ability to analyse multiple scenarios***. In contrast to traditional planning models, simulation allows the study of different scenarios under different detailed conditions. One can test and evaluate multiple scenarios to understand the implications of specific decisions and identify the most effective strategies. This flexibility enables one to proactively optimise mining operations by taking into account various factors that can affect productivity and costs.

3. ***Risk Reduction*****.** Safety is a primary concern in quarrying operations, given the presence of heavy machinery and potentially hazardous environments. Simulation methodologies allow operators to assess potential risks and identify safety hazards before they actually occur. By proactively addressing these concerns, operators can implement appropriate safety protocols, minimising the likelihood of accidents and providing a safer work environment for personnel.

Main features of *HAULSIM*

HAULSIM is specialised software that revolutionises the design and optimisation of production processes in the mining of raw materials. The product was developed to simulate the work of different types of mining equipment (i. e. trucks, shovels, conveyors, etc.) and includes a powerful set of functions designed to model the complex relationships between the participants in the production system of a mining site. At the heart of *HAULSIM*, apart from the aforementioned modelling capabilities, lies its ability to create detailed 3D models of the investigated mining site. These 3D models include the spatial location of given geological formations, road networks, material sources, and destination points for storing (ore stockpiles, waste dumps, etc.). The program also includes three-dimensional models of mining equipment and individual animations of different operations from the workflow. In this way, an overview of operational dynamics can be gained and potential opportunities for optimisation can be identified at the same time *(*https://rpmglobal.com/product/haulsim/*)*.

Another characteristic feature of *HAULSIM* is the use of data received in real time from various sources, such as GPS systems for tracking mining equipment, etc. The software allows simulation inputs to be updated throughout the various stages of a field's development to reflect the latest conditions and operational features. This flexibility allows *HAULSIM* to ensure that operators make decisions based on up-to-date information, resulting in more accurate and reliable results.

One of the key functionalities of *HAULSIM* lies in its algorithms that run during the simulation process. These algorithms take into account a large number of factors, including the technical characteristics of the equipment used, the set of possible transport routes, the traffic rules adopted, the condition of the road surface, the time of the work operations, the capacity of the processing facilities, etc. *HAULSIM* can identify the most efficient and cost-effective transportation strategies by optimising these variables, increasing the efficiency of using different equipment, reducing fuel consumption, CO_2 emissions, and operational costs.

Last but not least, *HAULSIM* provides an easy-to-use interface for performing different analyses of individual scenarios, allowing the understanding of the mechanisms of interaction between technological processes and the efficiency of the whole system. Typical scenarios considered are the study of the consequences when a different number of dump trucks is used, the distribution of mining equipment at different sources, the exact estimation of the production volumes of different types of equipment, as well as the more accurate estimations regarding the maintenance schedule of mining equipment (https://rpmglobal.com/product/haulsim/).

The successful use of *HAULSIM* to solve a specific production problem for a given mining site is a systematic process starting with data collection and ending with simulation model calibration and validation. As with any computer modelling-based approach, the availability of a sufficient set of accurate and precise data is paramount to the successful integration of *HAULSIM* into the operational environment. The availability of field data on rock properties, road conditions, equipment specifications, transport routes, and historical data on the individual performance of equipment and the overall production system is essential. The data collection process may include the use of surveying instruments, GPS devices, fleet management systems, and other sensor technologies. Once the data is collected, one can begin constructing the simulation model in *HAULSIM*. The three-dimensional model of the mining site and the input of the key information for the software creates the so-called "digital twin" of the mining site. The next stage is the calibration and validation of the model to ensure that the simulation accurately represents the actual operational conditions. This involves comparing simulation results with historical data and field observations. If necessary, adjustment of the model's input parameters is made to minimise discrepancies between simulated and actual results. When a calibrated and validated model is at hand, it is now possible to make predictions and analyses on alternative scenarios. By running multiple simulations under different conditions, it is possible to assess the impact of different factors on the performance of the production system. The information provided on the cycle times of excavators and front loaders in different conditions, as well as the course time of dump trucks, fuel costs, and other critical indicators, allow for an improved decision-making process. The possible situations illustrating the simulation capability of the *HAULSIM* software product are indeed many. For this reason, a typical problem in open-pit mining and quarrying is considered: determining the required equipment for achieving the annual target rate of mining production for a quarry.

Case study: Using *HAULSIM* for annual planning of quarrying operations

Fig. 1 represents the studied mining site and its 3D model used for the purpose of simulation. Five panels are planned for drilling, blasting, and mining to meet the quarry's desired output for 1 year. The quarry deals with basalt mining, and the planned annual pit's output is 320 000 t/a for a total of 235 scheduled shifts. The assumed work schedule is 5 workdays per week and one 8-hour shift per day. The quarry is currently dealing with the extraction of the commodity only, as the overburden is already removed. The remaining pushbacks for the quarry are situated only in the to-be-extracted commodity. Hence, the direction of mining is oriented downwards and fully coincides with the vertical advance rate of the mine.

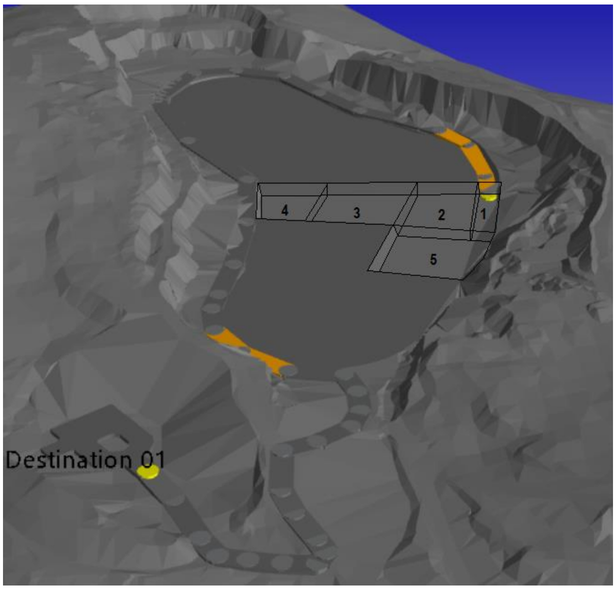

Fig. 1. Scheduled panels for blasting and mining

More information on the volume and mass of each panel can be found in Table 1.

Table 1. *Scheduled panels for blasting and mining for 1 year*

Blast panel №	Bank volume, m³	Mass, t
1	8,582.90	23,173.82
2	24,843.83	67,078.33
3	26,647.85	71,949.18
4	25,783.19	69,614.60
5	32,682.93	88,243.91
TOTAL	118,540.70	320,059.84

The specific properties of the material mined, related to the simulation model and the mining operation, can be seen in Table 2.

Table 2. *Parameters of the handled material*

Parameter	Value
Bank density, t/m³	2.64
Bulk density, t/m³	1.80
Swell factor	1.47
Fill factor (struck)	0.80

The specifications of the mining equipment used for this case study, as well as their relative costs, are presented in Table 3.

Table 3. *Equipment specifications and assumed cost factors*

Parameter	Excavator	Trucks
Engine power, kW	147	194
Bucket capacity, m³	2.00	-
Payload, t	-	22.68
Max energy consumption, l/h	11.96	15.79
Idle fuel consumption, l/h	23.92	7.89

Results

For this particular case study, three scenarios have been considered – using 2, 3 or 4 trucks for the joint work with a single excavator. Their respective results are shown in Tables 4, 5 and 6. The main parameters of interest are Fuel costs, Fuel consumption, Working operational efficiency, Operational efficiency, and Overall efficiency regarding the use of the shift's time, similar to a previous case study (Aleksandrova, 2007). The assumed diesel price is 1.30 EUR/l.

Table 4. *Simulation results for Scenario 1 (utilisation of 2 trucks)*

	Truck 01	Truck 02	Truck 03	Truck 04	Loader 01
Fuel Cost, (K EUR)	12.88	12.88	-	-	49.43
	75.18				
Fuel Consumed, (10^3 l)	9. 90	9.90	-	-	38.02
	57.83				
Working operational efficiency	0.98	0.99	-	-	0.79
Operational shift efficiency	0.87	0.87	-	-	0.87
Overall shift efficiency	0.86	0.86	-	-	0.69
Work shifts	251				

As can be observed, this scenario ensures that the annual target can be completed within 251 shifts (days), which exceeds the scheduled days for the year. This would mean that certain holidays or days from the weekend should also be mobilised for operational work. Furthermore, the presence of days with unfavourable weather conditions may also hinder meeting the target rate of the pit if this scenario is picked. Additionally, although the overall efficiency of the trucks is superb, the excavator remains idle at some points, which leads to the consideration of the scenario with 3 trucks (Table 5).

Table 5. *Simulation results for Scenario 2 (utilisation of 3 trucks)*

	Truck 01	Truck 02	Truck 03	Truck 04	Loader 01
Fuel Cost, (K EUR)	12.15	12.13	12.15	-	45.68
	82.11				
Fuel Consumed, (10^3 l)	9. 34	9.33	9.34	-	35.14
	63.16				
Working operational efficiency	0.77	0.77	0.76	-	0.92
Operational shift efficiency	0.87	0.87	0.88	-	0.87
Overall shift efficiency	0.67	0. 67	0.66	-	0.80
Work shifts	217				

In this scenario, the annual target can be reached in 216 shifts (days), which is more favourable in terms of unscheduled loss of shifts. However, the overall shift efficiency for the trucks is lower, which can be considered an average level of efficiency. In contrast, the overall efficiency of the excavator has improved from 0.69 to 0.80, i. e. from average to good (Koprev and Aleksandrova, 2022).

For the purpose of seeing how a fourth truck would affect the system, the third scenario was simulated. Its results are shown in Table 6. It shows that the overall efficiency of the loader does not improve, while at the same time, the overall efficiency of the trucks has decreased, leading to the accumulation of more fuel consumption and fuel costs. Additionally, the required number of shifts for meeting the annual output rate of the pit is 216 shifts once more. Hence, it has not improved, as utilising 4 trucks converges to the highest possible output rate for the current equipment and shift schedule.

Table 6. *Simulation results for Scenario 3 (utilisation of 4 trucks)*

	Truck 01	Truck 02	Truck 03	Truck 04	Loader 01
Fuel Cost, (K EUR)	12.96	12.95	12.96	13.11	45.67
	97.65				
Fuel Consumed, (10^3 l)	9.97	9.96	9.97	10.09	35.13
	75.12				
Working operational efficiency	0.58	0.58	0.58	0.58	0.92
Operational shift efficiency	0.87	0.87	0.87	0.87	0.87
Overall shift efficiency	0.50	0.50	0.51	0.51	0.80
Work shifts	217				

A graphic representation of the results obtained from the simulation can be seen in Fig. 2 for the efficiency of the loader in the three scenarios and in Fig. 3 for the efficiency of the trucks.

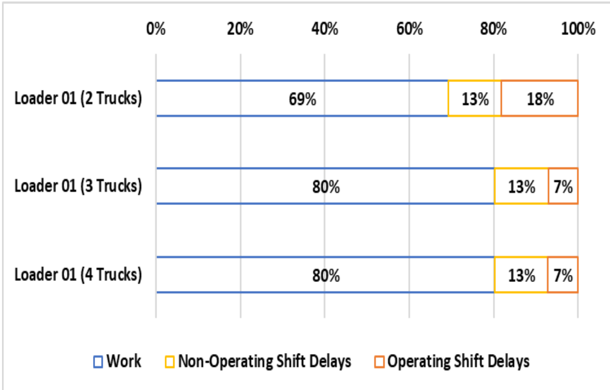

Fig. 3. Loader overall efficiency in the considered scenarios

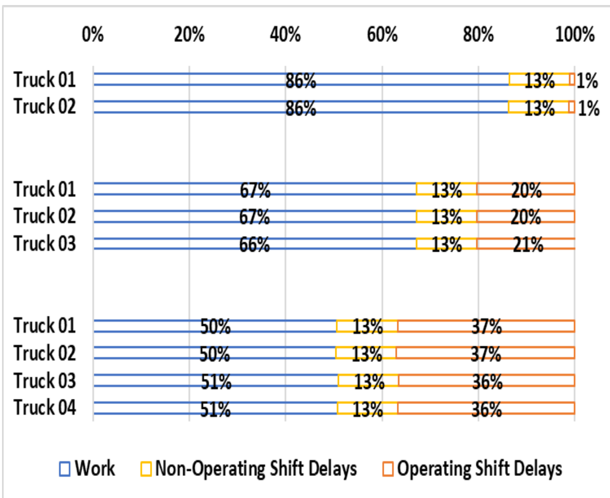

Fig. 4. Truck overall efficiency in the considered scenarios

A visual representation of the results, related to fuel consumption and the number of shifts required for completing the task is shown in Fig. 5.

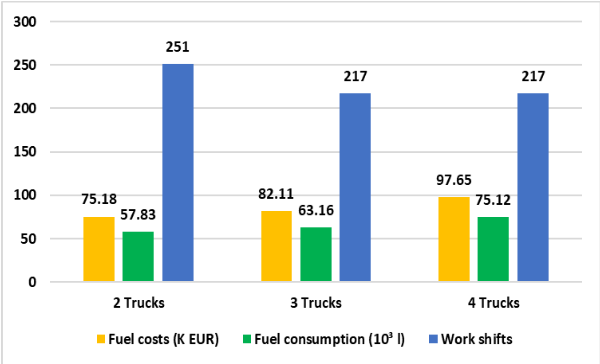

Fig. 5. Simulation results for the three considered scenarios

All fuel-related parameters increase with the adoption of more trucks for the task. The choice of which scenario to implement remains between the use of 2 trucks or 3 trucks, as Scenario 1 is more cost-effective and environmentally friendly, while at the same time, it is inefficient. In contrast, Scenario 2 is more efficient but less cost-effective and less environmentally friendly.

An interesting approach to solving this dilemma is by the adoption of a linear programming problem, based on both scenarios. The relative costs for the extracted material in the scenario with two trucks is 0.2349 EUR/t, while in the case with three trucks it is 0.2565 EUR/t. The average shift output in the first case is Q_1 = 1275.14 t/shift. In the second scenario, it is Q_2 = 1474.93 t/shift. Hence, the optimisation problem can be formulated as:

$$N_1 Q_1 c_1 + N_2 Q_2 c_2 \rightarrow min \qquad (1)$$

subject to:

$N_1 + N_2 \leq 235$, (the total number of shifts should not exceed the scheduled number of shifts),
$N_1 Q_1 + N_2 Q_2 = 320\,059.84$ (the scheduled annual pit output should be reached by the hybrid schedule),
where:
N_1 – optimal number of shifts for utilising 2 trucks;
N_2 – optimal number of shifts for utilising 3 trucks;
Q_1 – average shift output when working with 2 trucks, t/shift;
Q_2 – average shift output when working with 3 trucks, t/shift;
c_1 – average costs per 1 t of material when working with 2 trucks, EUR/t;
c_2 – average costs per 1 t of material when working with 3 trucks, EUR/t.

The number of shifts is assumed to be a real number to see where the optimal solution lies by considering the fraction of the shift's time. The obtained solution to this problem is N_1 = 132.9 and N_2 = 102.1, leading to an estimate of 78.43 K EUR for fuel costs and 60,323 l of diesel fuel consumption. Hence, a better choice for using the mining equipment is the use of two trucks for 133 shifts and three trucks for 102 shifts. This way, a minimal amount of costs and a minimal environmental impact in terms of CO_2 emissions are guaranteed, compared to other alternatives. At the same time, this solution is technologically feasible as it respects all considered operational constraints and considers unscheduled losses of shifts. As the quarry has additional trucks in reserves, this solution can also be regarded as practical.

For future improvement of the estimate in the current case study, random unscheduled shifts due to unfavourable weather conditions and random breakdowns can also be implemented in this analysis for a more realistic view of the problem. It should also be pointed out that the best domain of use for *HAULSIM* is for short-term planning; longer-term plans need to be constantly validated as the project progresses in time. Nonetheless, *HAULSIM* provides a superb way of validating a planning concept.

Conclusions

In the realm of mining operations, simulation models have emerged as a pivotal force in revolutionising the traditional approaches of open pit and quarry planning. By transcending the limitations of deterministic models, simulations offer a more realistic representation of mining environments, enabling comprehensive scenario analysis and optimisation. The use of simulation methodologies, such as Monte Carlo, Discrete Element System (DES), etc. empowers mine planners with a holistic understanding of work processes, equipment dynamics, and potential bottlenecks. The application of specialised software like *HAULSIM* exemplifies the shift towards data-driven decision-making, leveraging real-time inputs and 3D modelling to accurately depict mining sites. *HAULSIM*'s algorithms enable the optimisation of critical variables, fostering efficient transportation strategies, reduced CO_2 emissions, and operational costs. The presented case study demonstrates the practical utility of simulation models, showcasing the intricate interplay of trucks and excavators in a mining context. Through rigorous analysis, the study highlights optimal scenarios for equipment utilisation, minimising costs and environmental impact, while ensuring operational feasibility. Additionally, the considered scenarios were combined in a hybrid scenario, which adopts the positive sides of both alternatives. The result is a schedule configuration which is difficult to acquire when relying solely on conventional analytical models, used for pit design and planning. As the mining industry continues to evolve, simulation models will have a pivotal role, reshaping industry practices, and offering a pathway to more sustainable, efficient, and informed decisions.

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