“Modeling and simulation of coal flow in a mine using discrete events"

“Modelado y simulación del flujo de carbón en una mina usando eventos discretos"

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ABSTRACT

Today's industry requires increasingly accurate and faster results in analysis that lead to continuous improvement of its processes. Simulation is one of the tools that meets this need as it allows us to design models of a real system and carry out experiments with these models in order to understand their operation and evaluate different operating strategies. This work uses discrete event simulation as a method to analyze and simulate the flow of coal in an open pit coal mine from the moment it is extracted from the subsoil until its rail shipment, with a view to providing a system in which can evaluate different possible operating scenarios. The methodology used in this work is related to discrete-event simulation methods and combined with statistical techniques of data analysis. As a result, was obtained a model that explains the behavior of coal production from the extraction to the transport, and this will have impact in further developments.

Keywords: Modeling, Discrete-event simulation, Mining, Coal flows.

RESUMEN

La industria actual exige resultados cada vez más precisos y rápidos en los análisis que conduzcan a la mejora continua de sus procesos. La simulación es una de las herramientas que satisface esta necesidad, ya que permite diseñar modelos de un sistema real y realizar experimentos con estos modelos para comprender su funcionamiento y evaluar diferentes estrategias operativas. Este trabajo utiliza la simulación de eventos discretos como método para analizar y simular el flujo de carbón en una mina a cielo abierto, desde el momento de su extracción del subsuelo hasta su envío ferroviario, con el objetivo de proporcionar un sistema en el que se puedan evaluar distintos escenarios operativos. La metodología empleada en este trabajo está relacionada con métodos de simulación de eventos discretos, combinados con técnicas estadísticas de análisis de datos. Como resultado, se obtuvo un modelo que explica el comportamiento de la producción de carbón desde la extracción hasta el transporte, lo que tendrá un impacto en futuros desarrollos.

Palabras clave: Modelado, Simulación de eventos discretos, Minería, Flujos de carbón.

1.INTRODUCTION

The coal mining industry has generated great contributions to the national economy not only because of the royalties it has generated but also because it has become a development reference applicable to other mining industries [1]. However, the high competitiveness of the international market requires that today's industries achieve increasingly precise and rapid results in continuous improvement of their processes. This knowledge allows industries to adapt to changes in the environment and meet the changing requirements of their clients. The mineral coal extraction process requires studies that allow the proposed goals to be achieved with high efficiency since any decision made incorrectly can affect the company's operation.

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Suppose that a process of interest for a mining company is the management of the production chain between the mining front and the loading of trains, as is the case of the Cerrejón mine (Colombia). The studies carried out in [2] show that the coal feed received by the crushing plants is a restriction of the system. In turn, the feed flow is a function of many interrelated variables such as pit and pile productivity, hauling times, plant capacity and availability, train configuration and schedule, among others; that have behaviors that depend on the time of the shift, and therefore it is very useful to design a logical model in which these variables can be manipulated in order to have a clear vision of the functioning of the system to find opportunities for improvement in the feeding and second, simulate and evaluate different viable operation scenarios. Therefore, discrete event simulation is proposed as a technique to design and build a system that simulates the aforementioned process and is capable of replicating the coal flow.

Shannon defines simulation as the process of designing a model of a real system and conducting experiments with said model for the purpose of understanding the operation of a system or of evaluating different strategies within the limits imposed by a set of criteria for system operation [3]. This work shows a designed model of the system and experiment with decision effects using simulator software, and thus interpret the results in terms of the behavior of the system under study [4].

2. METHODOLOGY

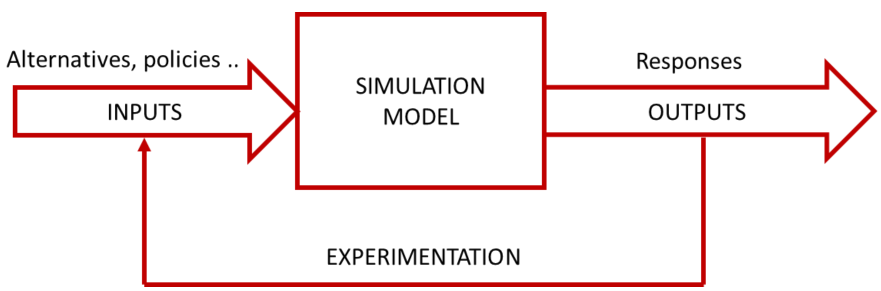
The main purpose of this work is to design a simulation model that explains the operation of the coal loading flow, in order to examine the effects of decisions that affect production and transportation rates. Figure 1 shows the phases of the simulation study, in which is based this work, which will be detailed below.

Figure 1- Phases of simulation study

Phase 1: Fundamentals and system description.

Figure 2 shows the outline of the simulation process proposed in [4]. Most simulation studies aim to answer questions such as *What would happen if...*? Questions whose main objective is to evaluate possible alternatives that support a decision-making process.

Figure 2- Scheme of the experimental simulation process

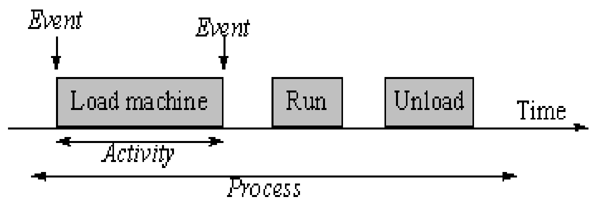


The quality of a simulation model can be evaluated by validating part of its results with the observed system, which serves as a guide on the magnitude of the errors derived from the model and can allow the introduction of corrections [5]. Error reduction can be achieved through greater precision in the model components or by adding additional elements that allow better representation of system relationships [6].

For Bertalanffy, a system is defined as a collection of objects or entities that interact with each other to achieve an objective [7]. For its part, Discrete Event Simulation (DES, from now on) interprets systems as a set of entities related through a structure, and that exhibits behaviors that can be observed in the values of their attributes. These entities can carry out activities, delimited by events.

DES consists of determining an initial state and from there generating a set of events and observing the change of state variables. The distribution of events over time must have a statistical behavior similar to the real historical events of the system. In [8] the logical structure of a discrete event-oriented model shown in Figure 3 is explained. It is observed that the processes are composed of one or more activities that are delimited by events.

Figure 3- Logic structure of a discrete-event model



Summarizing several authors ([4], [9], [10], [11] and [8]), the elements of interest in discrete event models are:

-Entities: They are the objects that circulate through the system. Entities can be resources that are used by the system (permanent) or objects that are processed in the system (temporary).
-Attributes: These are the properties of the resources and temporary objects of the system.
-Resources: They represent the elements of the system for which entities compete, such as equipment, operators or spaces. An entity can request a resource, use it, and then release it.
-Queues: represent places where entities must wait for a resource to be released or for an order to continue with its cycle.
-Activities: These are the tasks that are carried out in the system, delimited by two events: one that starts it and one that ends it. Activities generally involve an entity with one or several resources.

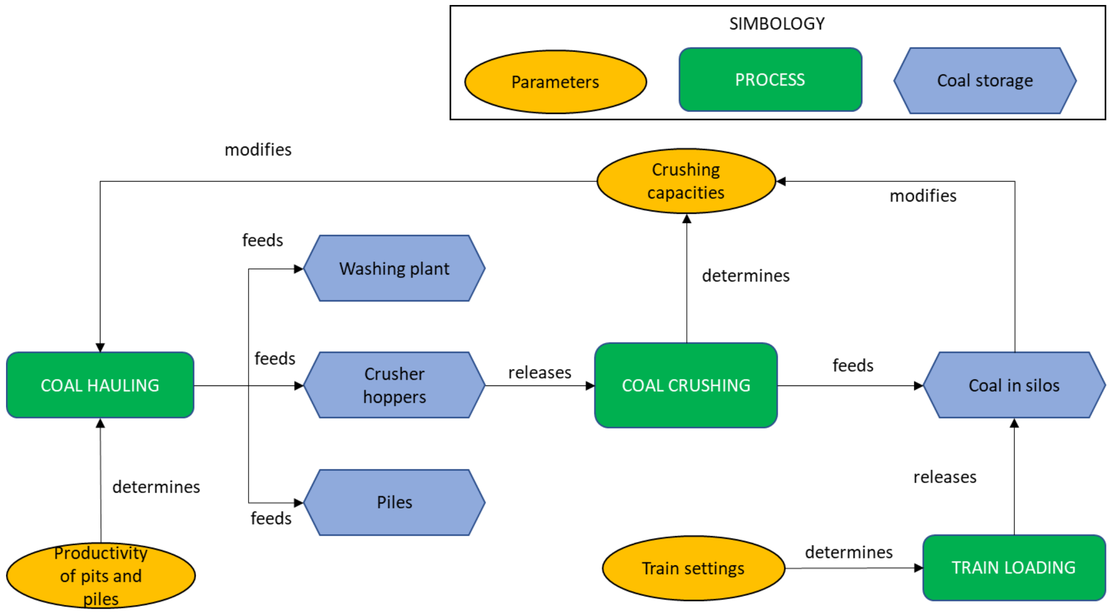
The coal flow system in the mine is regulated by 3 fundamental processes: The transportation of coal, from the pits to the plant and pile areas, the processing and storage of coal, and the train loading operation. Each of these processes is related to the levels of carbon that they temporarily store, and stimulate the flow of carbon to one destination or another. In system model, the element of interest in discrete-event model are identified and implemented in a simulator.

Phase 2: System model.

The system model is based on Sarmiento's description [12] which states the flow of coal in the mine starting at the moment when a truck is loaded at the pit faces or in the piles and transported to the different destinations. Coal rehandling and washing operations are not detailed. In addition, it is assumed that the trains regularly comply with the loading schedule (delays in train arrivals at the silos are not analyzed) and delays in serving the trains are determined due to insufficient availability of coal in the silo to carry out he loads.

In Figure 4, the first variable is the production in the pits or claim in piles, which obeys a probability distribution for each front in each hour of the shift. Of this coal supply, a part corresponds to the coal to be washed. On the other hand, crushing capacity depends on the availability of the plants, which is affected by multiple events and is variable throughout the shift. Therefore, the destination of coals to plants or piles depends on said capacity at the time of the arrival of each truck to the area.

Figure 4- System model, general approach



The crushing operation frees the hoppers and feeds the silos. The level of the silo is a determining variable because if the silo is filled before the arrival of the train, the crushing must be suspended, and as a consequence the hauling fleet will necessarily have to unload in piles. Finally, the loading operation of the train clears the silo but it also depends on the level of the silo, because if it does not have the necessary amount to fill the train, it must wait for the silo to have a sufficient level of coal.

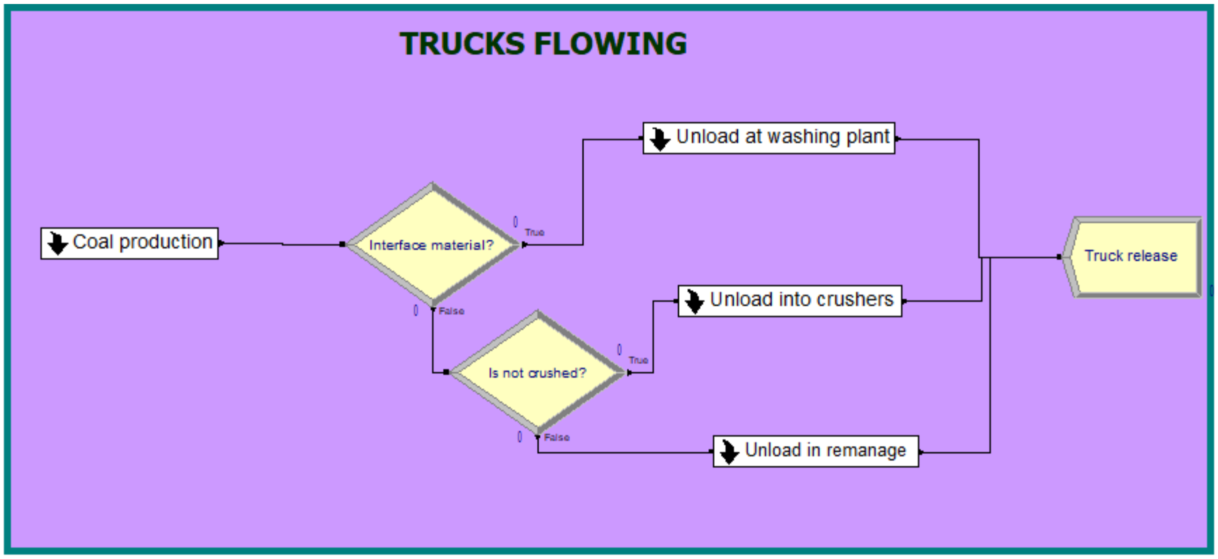
To implement the proposed model in a simulator, 3 discrete event models were built: the first to simulate the transportation of coal from the pits and piles to the plants or piles. The second simulates the crushing and storage operation in a silo. The third simulates the train loading operation. Each of the models are interrelated by global system variables: Hopper Level, Silo and Plant Availability.

Coal Haulage Model

The coal hauling model represents the different processes by which trucks and tractor trailers transport coal from the pits and piles where they are shipped to the plants or piles where they unload the coal.

Figure 5 shows the general diagram of the coal hauling process carried out by trucks and tractor trailers. The process is divided into submodels, the first of which corresponds to coal production process. Once the trucks leave the submodel, they can be directed to 3 different destinations, depending on the state of the plants and the transported material.

Figure 5- Coal haulage model



Crushing Model.

Crushing can be analyzed as a hybrid system composed of two subsystems: a continuous one that models the flows that empty the hoppers and fill the silo, and another discrete one that modifies the state of the flow. However, the flows can be modeled by a difference equation of the form:

$$x(t_{k+1}) = f(x(t_k), t_k)$$

Where the difference t_{k+1}-t_k can be constant (Δt) or variable and the function f can be implicit or explicit [13].

The following set of equations is established as a continuous model:

$$V_P(t) = V_P(t-\Delta t) - MIN\left[f_P \Delta t, V_P(t-\Delta t)\right]$$

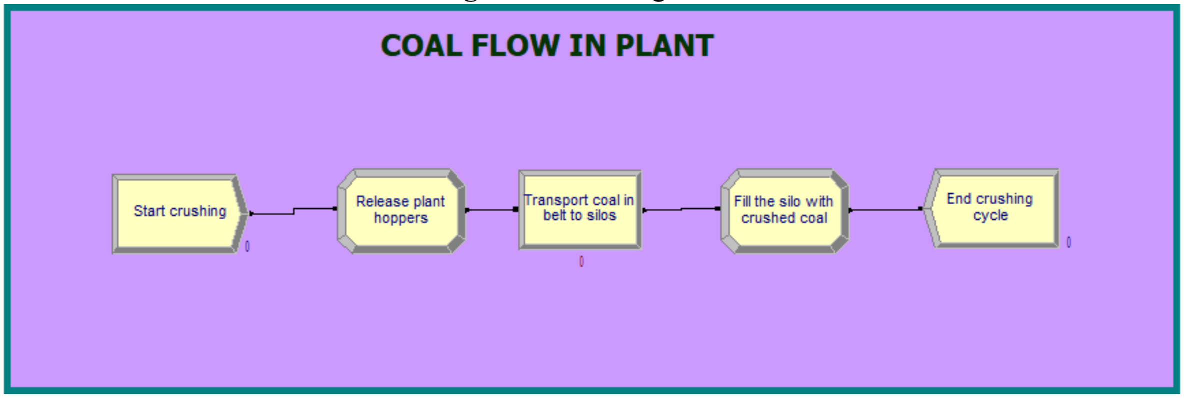
$$V_{Sec}(t) = V_{Sec}(t-\Delta t) - MIN\left[f_{Sec} \Delta t, V_{Sec}(t-\Delta t)\right]$$

$$\begin{aligned} V_S(t) = V_S(t-\Delta t) &+ MIN\left[f_P \Delta t, V_P(t-\Delta t)\right] \\ &+ MIN\left[f_{Sec} \Delta t, V_{Sec}(t-\Delta t)\right] \end{aligned}$$

where $V_p(t)$, $V_{sec}(t)$ and $V_s(t)$ are the levels of the hoppers of the main, secondary and silo plants in time t, f_p and f_{sec} are the flows coming from the hoppers of the main and secondary plants, and *MIN(a,b)* is the function that returns the minimum value between *a* and *b*.

The general diagram of the coal crushing and storage process is relatively simple. According to a time interval between generations of crushing events (Δt), batches of coal will be released from the plants, which are subsequently subjected to a transportation process and finally update the silo level, as shown in figure 6.

Figure 6- Crushing model

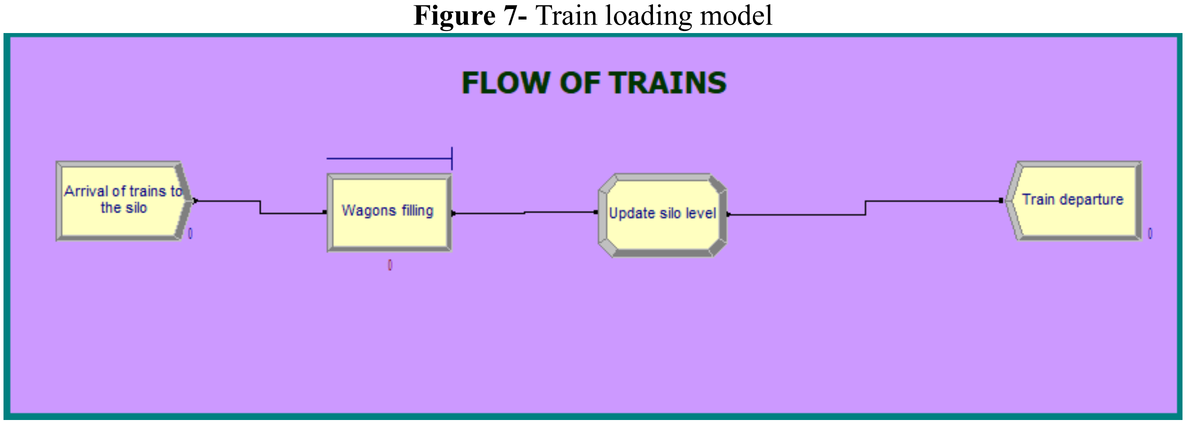


Train Loading Model.

If the hauling and crushing operations are carried out without any other operation that frees the silo then there will come a time when the latter will not be able to receive any more crushed coal and therefore the crushing operation must be stopped. Therefore, it is necessary to incorporate into the model a silo emptying system, corresponding to the train loading operation.

Figure 7 shows the train loading process diagram. Periodically, train arrival events are generated that require loading, however, these may or may not be attended to depending on the cancellation decision made at the time of the arrival event. A train's loading process is canceled if there is only one other train in the loading process or if the previous train is still waiting to be served because the silo did not have enough coal to serve it.

Figure 7- Train loading model



In order to summarize the former descriptions, table 1 shows the components of the above descripted models.

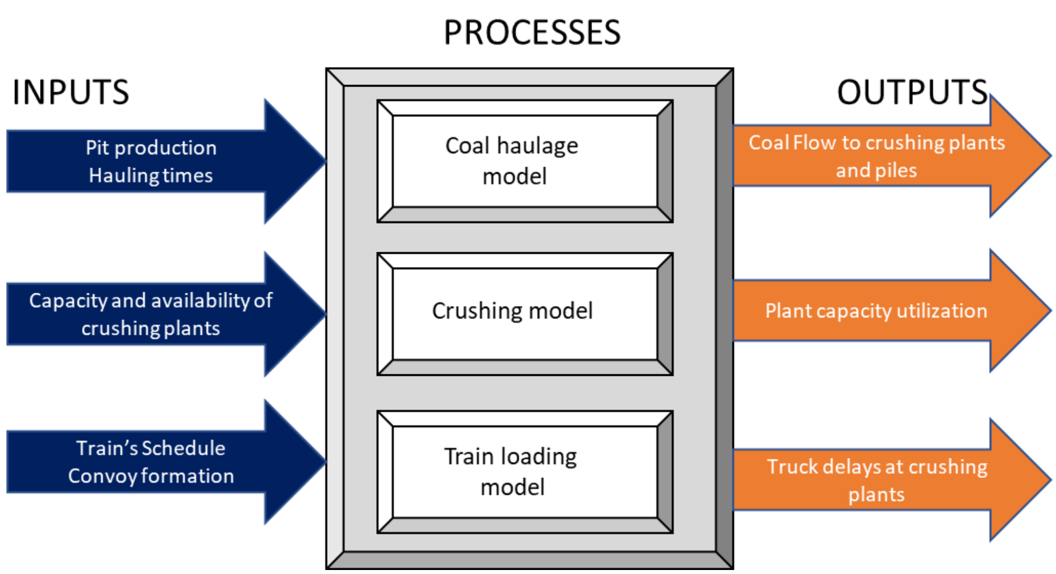
Component	Coal haulage model	Crushing model	Train loading model
Entities	Trucks and tractor trailers	Lot of coal	Trains
Attibutes	quantity and origin of the coal transported	amount of coal coming from the main plant and amount coming from the secondary plant	number of wagons
Resources	Plant Unloading Docks and Coal Stacking Tractors	Crushers, Conveyor belts	dispatcher
Activities	Transportation, dock packing and coal unloading	Release of Hoppers, Transport in Bands to Silo and Filling of the Silo	Filling of train cars
Queues	by free docks and by unloading order in plants		wait for prepared silo

Table 1- Components of the models

Phase 3: Simulation model.

To implement the previously descripted model, the Arena software version 15 was used. Figure 8 shows a global view of the architecture of the built simulator. It is showed that the proposed models constitute the main processes of the system's operation.

Figure 8- Simulator architecture



The main input data required by the system to simulate the hauling, crushing and train loading processes are the following:

-Hourly production profile of the pits and piles: This profile is mainly composed of a probability distribution of achievable loads in each pit per hour of the shift according to historical records, in turn associated with a distribution of load factors and with another distribution of cycle times between the loading front and the silo/pile area.
-Crushing capacity: It is the amount of coal that the plants can crush at a given time, after discounting the times affected by "DOWN" and "LOST" events such as PMs, unforeseen damage, metals, rocks and others. The respective profile obeys a probability distribution built based on historical data.
-Train information: Consists of fixed train loading schedules and convoy formation, loading rate and loading factors per wagon.

By manipulating each of these inputs, operating scenarios can be built and tested. The main results (among others) that the simulation shows are:
-Average flow hour by hour that the crushing plants and batteries will receive in the simulated period.
-Availability and utilization of the plants, detailing capacity losses due to events in the plants and waits to fill the hoppers.
-Number of trains loaded in the simulated period, as well as the number of trains lost due to insufficiencies in the supply to the plants and delays of trains due to waiting for silos with enough coal to carry out the loading.
-Truck delays at crushing plants (number of trucks and number of hours lost).

Phase 4: Implementation settings.

The table 2 shows the initial conditions and operating parameters of the model. Some scenarios were made in order to simulate some decisions and changes. It is showed that the proposed models constitute the main processes of the system's operation.

Variable	**Description**	**Value**
Main hopper	Coal tons in hopper	0
Silo	Coal tons in silo	0
Máx main hopper	Capacity of hopper	1500
Máx silo	Capacity of silo	24000
Tons per truck	Capacity of truck	170
Secondary hopper	Coal tons in hopper	0
Max sec hopper	Capacity of sec hopper	500
Main crushing rate	Rate of coal crushing	3000
Wagons	Number of wagons per train	100
Tons per wagon	Capacity of each wagon	100
Probability_int	Probability of finding interface material	0.36
Sec crushing rate	Rate of coal crushing at secondary hopper	1500

Table 2- Initial conditions

3. RESULTS

After carrying six replications and store the most relevant indicators with their statistics, some results obtained are showed in table 3. Indicators as waiting time and occupation rates shows low variances, while other indicators have a higher variance value. Some waiting lines appeared in the process of loading/unloading due to the truck's arrival is independent of the service time of loader. With this table layout, comparisons can be made with other simulation scenarios [14,15]. The last column is the confidence interval width, around the average value.

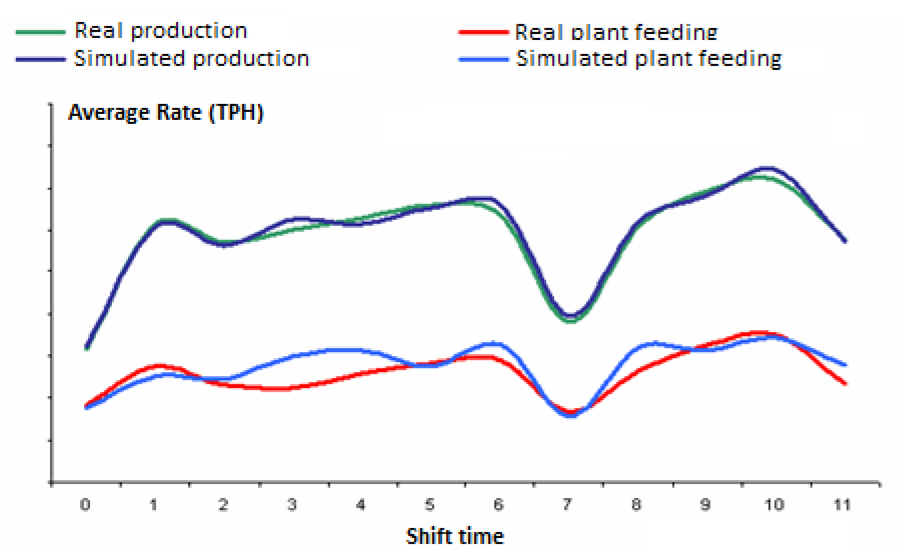
Indicator	Average	Half width
Queue at hopper	0.02147	0.01663
Wait in unloading (hours)	0.14112	0.04651
Truck load time	0.09769	0.00197
Truck wait time	0.00529	0.00224
Train load time	1.3333	0.021
Trucks in process	63.194	2.147

Table 3- Summary of statistics result

To validate the proposed model, different simulations of 720 shifts were carried out, corresponding to one year of operation, and the results were compared with previously observed production data documented in [12].

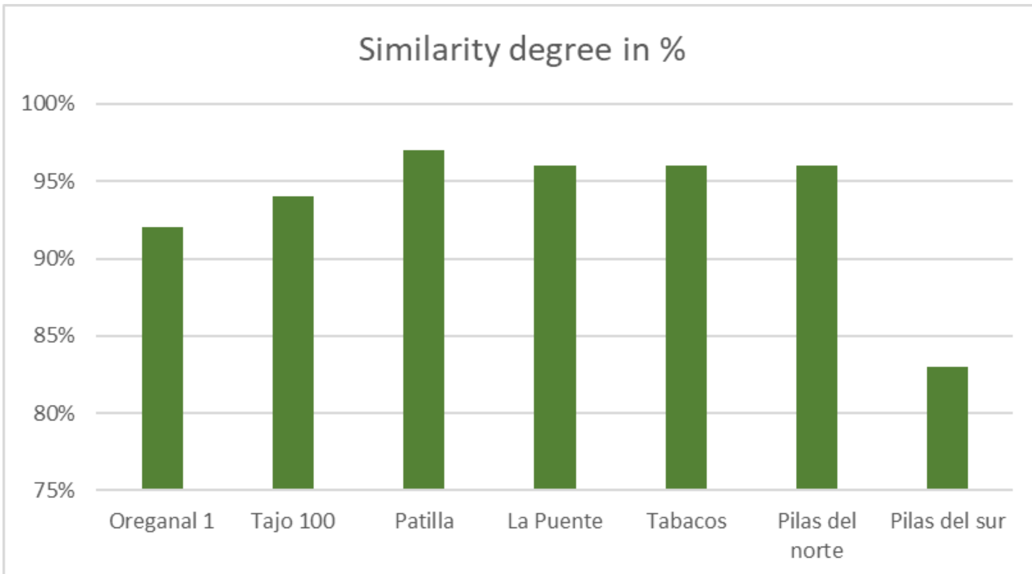
In the first instance, the production rates of the pits and piles are compared within a 11- hour period of shifting, obtaining a 95% similarity on average, as shown in Figure 9, but it should be highlighted that the pits that present a higher production obtained the best approximations (97% of accuracy, proximately).

Figure 9- Hour-by-hour production and crushing patterns, real vs. simulated



Subsequently, the hourly production and crushing patterns were analyzed and compared with document production data, and the result is showed in Figure 10, with the simulator managing to replicate 98% of the production (upper lines) and 95% of the feeding to the plants (lower lines). The worst result shows an 83% of accuracy, while the best result had a 98% of accuracy with respect to system's observations. Thus, the behavior of the production rates can be explained by the proposed model, and therefore the effect of certain management decisions can be simulated with this work.

Figure 10- similarity in production rates



4. CONCLUSION

Simulation is a tool that allows us efficiently study systems with a certain degree of complexity. It is shown that it is possible to establish an artificial system (simulated model) that describes behaviors very close to the real production-processing-loading system in the mine and with which it is possible to evaluate different operating scenarios within the restrictions established in the model.

By means of discrete-event system simulation the complete behavior of this kind of systems can be explained. However, the model can be improved to allow the incorporation of significant variables in the model such as the coal quality factor, delays in train arrivals and rain times which affect the transport. Besides, modern techniques based on multi-agent systems can be used to simulate the effect of real-time decisions that affect the whole performance of the coal production system. Future developments in this area will be arising from this work.

The implementation of the project in the business sector constitutes a useful guide for the works of other researchers into solving problems in the mining sector.

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