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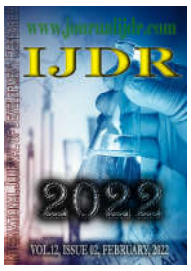

RESEARCH ARTICLE OPEN ACCESS

OPTIMIZATION TECHNIQUES APPLIED TO MINERAL FLOW PROBLEM IN DIFFERENT TRANSPORTATION MODES

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ABSTRACT

This article discusses the flow of minerals in open-pit mines, emphasizing the type of modal used to perform. Also, it discusses simulation techniques of productive systems based on applied science that aims at solving real problems, that is, operational research. It was believed that the modal through which the flow is made is a determining factor in the productivity of an open-pit mine and an attempt was made to find a modal (or a combination of modes) whose use would represent an optimal solution to the problem of ore flow. For that, the bibliographic review method was used to study the works already contextualized in the area of interest. It also had the aid of a simulation tool, the Arena software, to create and analyze models related to mineral flow. The results showed that the choice of an optimal flow modal is an isolated decision for each problem situation since it implies the analysis of several factors. In summary, it was concluded that the development of simulation tools can be relevant in the mining scenario since they allow the choice of the optimal modal in each situation.

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INTRODUCTION

It is notable that, nowadays, there is an increase in competitiveness in several areas, especially in the mining sector, which results in greater investments in this field. A large part of investments in technique are designed for operational research (OR), which manifests itself as a set of actions that help decision making. It is important to note that the practice of or makes use of a crucial tool called simulation, which among other definitions is presented as the representation of a real system through computer tools (Teixeira *et al*., 2020). In this way, the relevance of the use of or techniques are notorious, which include the practice of simulation for the decision making of large systems such as, for example, the operation in an iron ore mine (da Cruz Faria *et al*., 2021). Systems with a high degree of complexity, such as operation in an open-pit mine, involve a series of variables and processes that together make the heterogeneity of the operation (Silva *et al*., 2021). One of the processes that integrate the activities in a mine is the flow of extracted minerals, which can be done by different modes with an infinite number of options. Thus, the present work is specifically concerned with the flow of ore in an open-pit mine. Therefore, it is attentive to the importance of simulating the production system to obtain the transport modal through which it is more productive to drain this ore. In other words, the main objective of this paper is to study how the practice of or can generate optimization for production processes. The relevance of this work as well as that of other papers that also discuss the topic is understood when we verify the economic scenario in 2011. During this period, a large part of Brazilian exports was related to iron ore, which implies that there is in fact, a great economic movement around mining. Once this was completed, we sought to link information regarding programming techniques and the mining scenario to identify in several cases which modal makes the production chain more efficient. From the bibliographic review, information was sought about the transport modes used for each situation in the scenario of iron ore extraction. Along with the analysis of relevant papers on the subject, the Arena simulation software was studied. Subsequently, a simplistic sketch was elaborated in such an environment that suggests the

finding of a satisfactory modal for the mineral flow allowing the analysis of some data such as queuing time and the generation of conclusions.

In summary, the findings obtained as well as the information collected from works contextualized to the theme of the present paper suggests that the choice of an optimal transport mode can vary in each problem situation. Such finding makes the combination of simulations and optimization techniques crucial for the best decision making of managers - with technical and scientific bases.

LITERATURE REVIEW

In the industrial sphere, it is common to use an important tool called operational research (OR). Such a tool is understood as a set of decision-making models, that is, this important mechanism manifests itself as a technique that can help to solve problems of different kinds (Taha, 2011). The notoriety of the practice of OR is justified even in its appearance, since the first formal activities in this field were initiated in England during the second world war to choose correct war strategies. With the development of research related to decision making, the use of such techniques has become common in a multitude of areas. Another important aspect about the mechanism studied in this paper is the need to consider human interference to create a model that is reliable to the real problem. In summary, an OR model seeks to maximize or minimize an objective function subject to restrictions. Such an optimization model is designed to optimize a specific objective criterion subject to a set of limitations.

It is important to note that the set of techniques for solving real problems also includes simulation, which is the imitation of real-world process operations involving the generation of a virtual history of the system (Banks, 2000). That is, the practice of simulating is understood as the reproduction of real situations in computational environments so that it is possible to carry out quality tests in the production processes. Thus, the decision-making process - which involves high financial turnover - is preceded by a technical evaluation, reducing considerably both errors in the process and decreasing profit (Teixeira *et al*., 2019). Thus, the contribution offered by the correct use of simulation to productive systems of great complexity is undeniable since it is possible to obtain favorable economic results for organizations.

Simultaneously with this production systems modeling technique, the optimization strategy is widely used, since it is understood as the search for the efficient functioning of the system. According to Yassine, Khalid and Said (2019), what is understood when working with optimized systems is that such an arrangement will include economically favorable characteristics such as adequate cost and satisfied customers. Thus, simulation and optimization are routinely combined to obtain the optimal solution. In the field of mathematical modeling, several software is developed so that decision-making is efficient, and the tests performed on production systems are completed in an increasingly smaller computational time since there will be benefits to the system. Among the computer programs widely used to make simulation practice possible, Arena stands out for its interactivity and satisfaction in the response provided (Yassine, Khalid and Said, 2019). Thus, it is noted that through this tool it is possible to develop program logics that assist production systems with wide relevance. An important characteristic common to most mathematical models created to solve problems is their stochastic nature (Alexandre *et al*., 2015). That is, the models developed are non-deterministic in nature and thus it is only possible to announce probabilities. An important feature of OR techniques and systems modeling is its great usability in systems with a high degree of complexity, so its use in the mining field is inevitable. It is known that transportation problems aim to determine the shipping schedule that minimizes the total cost of the operation and, at the same time, satisfies the supply and demand limits (Taha, 2011). This means that when understanding mineral flow as a type of transport problem, it is necessary to use mathematical and computational techniques to determine when a transport mode is optimal and for which situation it is valid. According to Navarro Torres *et al*. (2020), the operation of a mine requires the interaction between different agents and process variables, since a good understanding of this type of problem requires that we make use of simulation and optimization tools. Thus, the use of modeling techniques is extremely important to turn the activity into a more productive mine. It is important to note that due to the high degree of complexity of operations in an open pit mine, the present paper focuses only on a relevant part of the operation: the mineral flow along different modes.

According to a report released by the National Mineral Production Department (DNPM), Brazil exported approximately 44 billion dollars in iron ore in 2011. Through this data it is possible to observe the importance, for the Brazilian economy, of the development of effective tools that act in the management of mineral flow. This statement supports the fact that simulating and optimizing are highly necessary in the ore extraction process. The existence of several modes of transport located in the context of mining is valid, since the products derived from such practice are adapted to differentiated forms of flow, that is, in the case of iron ore, the flow can be made among other possibilities along the railways, roadways and even through pipelines. For Tang, Yung and Ip (2004), small changes in the cycle and even in the type of modal chosen can generate gains of great magnitude for the organization. In other words, both the maximization of profits related to mining activity and the minimization of costs arising from the same activity are linked to the definition of an optimal modal for the flow of mineral products. Therefore, there is a need to increase the activity of mineral flow with practices and techniques that enable logical reasoning in situations of this nature.

The transport system is characterized by being crucial for logistics, given that it is responsible for transporting materials from different areas, moving the country's economy. From the perspective of logistics, the basic transport modes are roadways, railways, airways, waterways, and pipelines. The choice of each modal is related to the cargo you want to transport and to the logistical cost of the operation in general and should therefore be conducted based on the potential of each one. Among the main modes of transport, roadways, railways, and pipelines stand out due to the high potential for transportation on national soil. It is noted that the road modal is characterized by being the one that has the greatest national use, its great use occurs because, from the '50s, with the advance of the automobile industries and the paving of the highways, this modal is expanded and now covers a large part

of the Brazilian territory. An important characteristic of this modal is that although it presents a high freight price, the road modal has low fixed costs (highways established with public money) and a medium variable cost (fuel, maintenance, etc.). The railway transport modal stands out for having the capacity to transport large volumes and although it is characterized by a high cost concerning equipment and tracks, the modal presents low variable cost, which means that the sum of the variable production factors presents low cost. Another peculiarity about the modal is that the supply of railway modal in Brazilian territory is low when compared to countries in Europe, for example. Pipeline transport is the mode of transport that uses a pipeline system where products move from one point to another. Such modal presents itself as a plausible option to the mineral flow since it carries countless benefits like the possibility of transporting a high volume of material. Through the information demonstrated about the main means of mineral flow, the need for the elaboration of techniques that transit through the universe of operational research is notorious to find the optimal transport mode, that is, the one that best meets the necessary conditions providing productivity to the process. It is important to emphasize that although optimization together with simulation techniques can represent a concrete and powerful solution with computational effort appropriate to the problem, the result will not be unique. For each mine configuration, we will have a solution that will represent the optimal transport mode.

EXPERIMENTAL

A method is a mechanism by which the author relies on the elaboration of a study and, consequently, on the construction of knowledge. To achieve the results acquired here, the literature review and the simulation technique were used – which is important for decision making through the faithful reproduction of a real problem at a computational level. To contextualize the use of operational research and simulation techniques for the flow of minerals along with diversified modes, the references described in the present paper establish both the focus of the research and the dependence relationships between the optimal mode for flow and the problem situation. This means that the appropriate modal for the mineral flow can vary according to a series of variables such as transportation cost and distance to be covered along a given modal. With the information obtained during the preparation of the Literature Review, it was necessary to study the Arena simulation software. Arena software is an integrated graphic simulation environment developed by the company Rockwell Automation that contains numerous resources for process modeling. Subsequently, a preliminary programming block was developed to illustrate how the mineral flow of a mine can be enhanced using computational tools, which in turn is represented by a mathematical model.

It is important to emphasize that the gathering of information was characterized as a crucial step in the construction of the work since it was concerned with collecting data so that from this, a particular result could be generated. This result comes from the connection of information with the programming logic. With this aim in mind and based on the work of Cruz *et al*. (2019), a possible mineral flow that began in the region of the Iron Quadrangle (Minas Gerais state, Brazil) and extends to the coast of Rio de Janeiro state (Brazil) was studied. Based on the information collected regarding distances and average speeds, the total flow time spent in each modal was calculated. It is interesting to emphasize that the Arena software, when confronted with consistent information, generates variations by statistical models, and thus the conversion of data into flow measures has become fundamental to the success of the work. Within this context, the concept of comparison unit was adopted, that is, something that differentiated how appropriate the modal will be for the transportation of ore in the problem situation. In this case, the basic unit of comparison used - flow - was the amount of iron ore (in tons) per unit of time that was obtained through the ratio of the maximum flow capacity of each modal to the total hours contained in a year. Tab. 1 is responsible for gathering all the information described in this procedure. It is important to emphasize that the test model developed did not consider the costs that are clearly aggregated in each transport mode, since it represented a study of only the problem of mineral flow. After analyzing the literature review and the experience obtained in the Arena software, considerations were made, to verify not only the importance of using or techniques in mineral flow, but also the verification of which path to follow to identify in different situations the optimum transport modal for material flow.

RESULTS AND DISCUSSION

The mineral flow process in an open-pit mine, in general, cannot be modeled satisfactorily using simulation techniques based on deterministic models (Zhang, Zhang and Bian, 2013). That is, simulation models that are not concerned with random variables will possibly not add reasonable results to the process. To obtain the modal that represents the optimal solution to the studied mineral flow problem, a simple simulation block was created in the Arena software. Based on visual programming, a logical-mathematical model was built that represents the dynamics of the system under study. Such construction was based on the Arena platform through its set of blocks widely used in describing real situations. In the scope of simulation, workstations were created for the loading and the flow process of the material. The construction of the simulation model at the Arena is characterized by the coexistence of three processes that refer to the modalities of mineral flow: road, rail, and pipeline. Additionally, it is important to note that the transcription of the flow processes in the simulation environment was done with a mathematical basis, thus considering for each situation of transport of the mineral resource an adequate standard deviation. It is important to highlight that, in addition to the creation of the flow processes, systems were developed that pay attention to the possible delay factors in the process of ore flow for each of the situations analyzed. It is important to note that, in addition to the creation of the flow processes, systems were developed that pay attention to the possible delay factors in the process of ore flow for each of the situations analyzed. Furthermore, since Arena works with resource flow throughout the system, the ton ore factor has been established as an entity. Thus, the considerations about the simulation elaborated were based on the analysis of the time necessary for a ton of ore to go through the established process. Fig. 1 shows the workstation developed in the study. The weights established by the simulation were based on the percentage of ore drained in each modal. For this purpose, three hypothetical situations were created in which the total ore flow forecast in the process is fragmented differently for each mode of mineral flow. The quantity of ore considered in each modal, as well as the

Table 1. Average speed, average capacity, distance, time and flow for road, rail, and pipeline modes.

MINERAL FLOW			
Origin: **Minas Gerais region (Iron Quadrangle) -** Destination: **Rio de Janeiro region (Hub Port)**			
	Road Transport	**Railway Transport**	**Pipeline Transport**
Average Speed	50 km/h	60 km/h	7 km/h
Average Capacity	15 working tons per truck	80 tons per wagon	26.5 million m³ per year 68.9 million ton/year
Estimated Distance	642 km	690 km	525 km
Time	12.84 h	11.5 h	75 h
Modal Avg. Quantity	100 trucks/day	80 wagons/day	1 pipeline
Flow (Tons/hour)	62.5 tons/hour	266.67 tons/hour	7,865.29 tons/hour
Flow (Tons/minutes)	1.0417 tons/min	4.4400 tons/min	131.08 tons/min

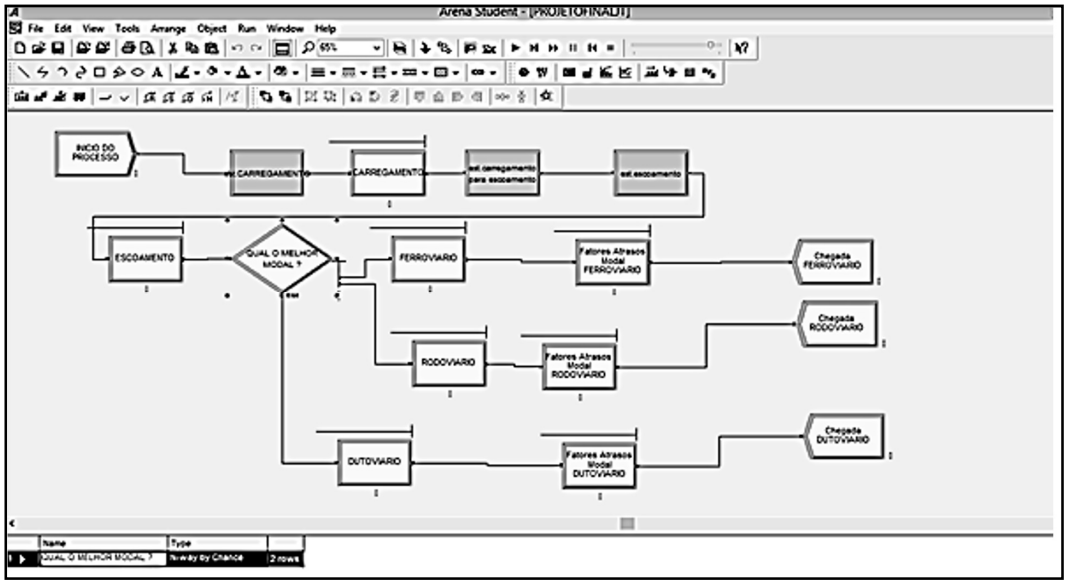

Fig. 1. Simulation in the Arena environment

Table 2. Simulation result

Situation	**Simulation – Open Pit Mine**			
	Minas Gerais region (Iron Quadrangle) - Rio de Janeiro region (Hub Port)			
		Road Transport	**Railway Transport**	**Pipeline Transport**
1	Percentage of use	5%	2%	93%
	Ore flow transported: number of entities	12	27	1741
2	Percentage of use	5%	5%	90%
	Ore flow transported: number of entities	11	56	1524
3	Percentage of use	10%	1%	89%
	Ore flow transported: number of entities	9	11	1215

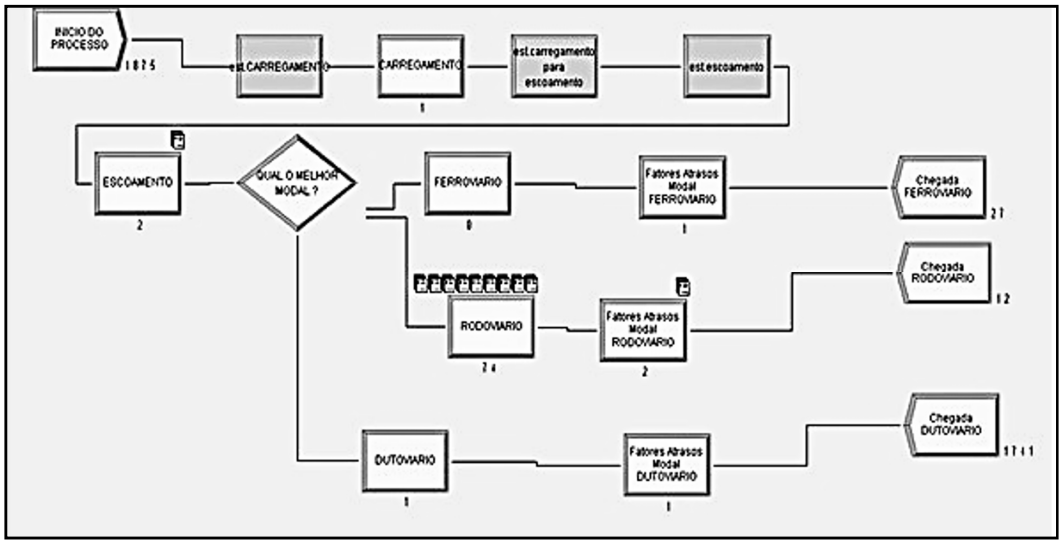

Fig. 2. Simulation result for situation 1

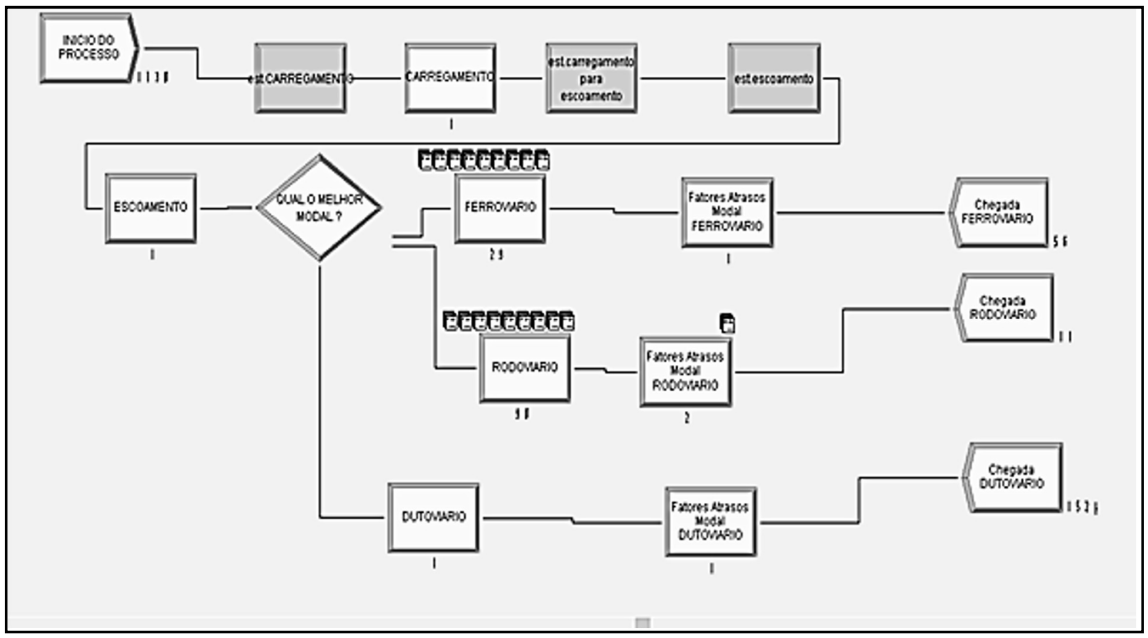

Fig. 3. Simulation result for situation 2

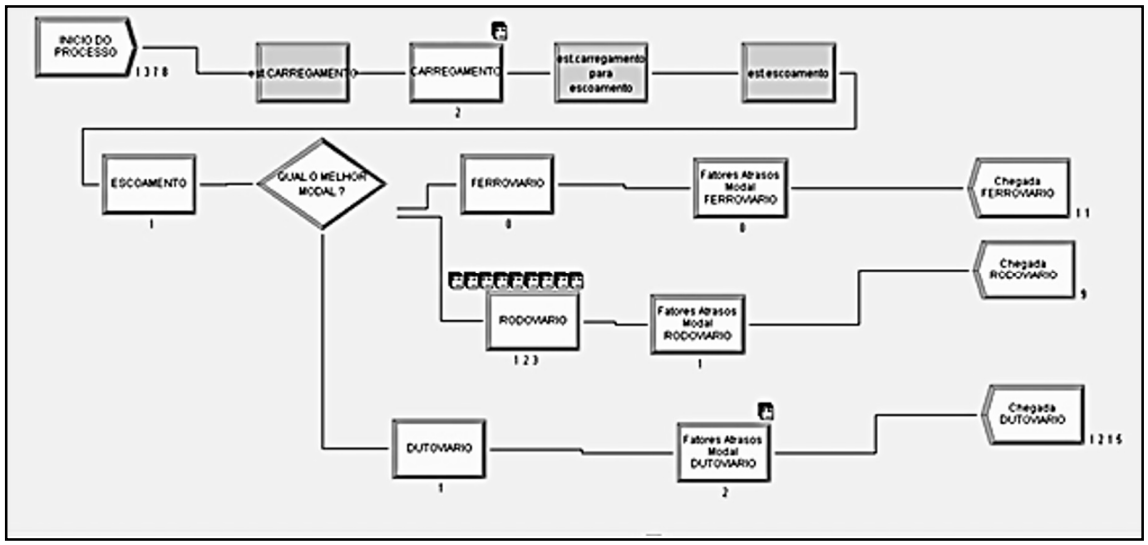

Fig. 4. Simulation result for situation 3

number of tons of ore drained by them in each situation, are listed in Tab. 2. Equally relevant is the perception that the analyzes made here were based on a process that simulates the activities carried out in an open-pit mine in a period of one hour. For studies based on another fraction of time, only a few adjustments to the model are necessary. Situation number one, shown in Tab. 2, considers a flow of about 5% of the total amount of ore destined for road transport, while 2% and 93% are allocated to rail and pipeline transport, respectively. This arrangement is exemplified in Fig. 2. After analyzing the results obtained by the simulation model described in situation Fig. 2, it is possible to observe the existence of a considerable bottleneck in the flow station through the road modal. There are some obstacles to the constant performance of the process. This is justified by the amount of delay factors present in the road flow at the time of the analysis.The problem situation number two, shown in Tab. 2, considers flows of 5%, 5%, and 90% for the road, rail, and pipeline modes, respectively. Similarly, to situation one, simulation two portrays the inefficiency of road and rail modes concerning transportation by pipeline. The second analysis, mentioned earlier, is illustrated in Fig. 3. From the results achieved, there is a bottleneck, both in the road modal, like the first simulation situation, and in rail transport, which is explained by the increase in the flow of ore that describes the rail route when compared to the situation one. The third simulation situation, shown in Tab. 2, allocates 10% of mineral resources to the road modal, and the rest of the amount is subdivided in the proportion of 1% and 89% for the rail and pipeline modes, respectively. It is extremely important to note that a large amount of mineral resource was added to the road modal (about 10%) when compared to the previous situations, which allowed the verification that it is inefficient for the flow of the mineral resource. Such statement finds support when analyzing the execution of the simulation. For simulations one and two, the process was interrupted at a fraction of 0.22 hours to analyze the bottlenecks, whereas in situation three, the analysis was performed at a fraction of 0.17 hours, since it was not possible to maintain the simulation until the time of 0.22 hours was completed. It is worth noting that the choices of the time

in which the analysis of the flow capacity of each modal was made took place at random. Fig. 4 represents the third simulation mode. The results found point to the fact that, among the modes, all related to mineral flow, pipeline transport is commonly more efficient in the analysis situation (flow of mineral resources from the region of the Iron Quadrangle to the Hub Port of Rio de Janeiro state, Brazil). On the other hand, due to the high degree of complexity of operating a mine, it is not possible to generalize situations that corroborate with this result, therefore, an analysis based on the simulation created for each problem situation is necessary. The discussions that guide the study suggest the fact that the combination of modes can offer a satisfactory result in terms of mineral flow since it will be necessary to take advantage of the potential of each one. In summary, after the analyzes carried out, it can be concluded that the pipeline modal has high potential when used for the transport of mineral resources, which does not extinguish the possibility of obtaining excellent results through the combined action of the modes represented in the simulation.

CONCLUSION

In the context of ore flow, the development of simulation algorithms allows for an increase in system productivity. In this way, the constant economic movement resulting from the mineral market will make the simulation of production processes crucial for the survival of large ore exporters. It is important to emphasize that one way to make the choice of the optimal transport mode efficient is to rely on mathematics that faithfully reproduces the real scenario of the problem. As there is an infinite number of problem scenarios in the mining sector, the logic developed must be composed of a series of generic variables that, when applied to a given situation, can generate the optimal solution for the specific case under study. Thus, the optimal mode of ore transport will depend on the conditions of each mining station, as well as the variables related to it. The results achieved brought conclusions regarding the choice of the optimal transport mode. It was observed, with the analysis of the results, that the railroad modal, as well as the road and pipeline modal have advantages. The choice for one of the three will depend exclusively on the analysis of the productive system in question. It is extremely important to emphasize that what was proposed in this work does not exhaust the questions on the topic but broadens the field of research on mineral flow and that future and more detailed studies are indicated as future research.

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