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Sequential glory hole approach as a new mining method for sustainable operations

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ABSTRACT

Some mines use shafts to outflow the material mined by surface methods aiming to reduce the average distance of haulage. However, this application is restricted due to the unavailability of a methodology devoted to integrating the underground structures with surface mining plans. This mismatch implies an intensive use of trucks for haulage operations. How can open pit mining operations with mobile equipment be developed without using trucks? The present study aims to develop a mining method that integrates underground structures, for material outflow, with the surface mining development reducing the truck fleet. Considering this innovative mining geometry, haulage can employ alternative equipment or even adopt the truckless concept. After the geometric simulations using mine planning software tools, the proposed method has reached a strip ratio reduction of 8.3%. In addition, the method allowed the stacking of waste rocks and dewatered tailings in mined areas during the mining of subsequent pushbacks. These results make mining more sustainable, since it reduces area affected by waste piles and tailings dams.

1. Introduction

Many ore bodies are strongly inclined, and the mining operations start by surface methods. If the final product has a high price, further studies to evaluate the underground mining can be worthwhile. However, there are examples of mines that adopt typical underground mining structures aiming to reduce the haulage distance. In the mineral industry, this kind of solution is rare because the enterprises that adopt it have specific conditions. The main reason that makes the use of this solution feasible is attributed to the topographic conditions, where the slopes are strongly inclined. In enterprises that already use this solution, the shafts are located in strategic points

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where trucks dump the material hauled from mining faces. Among the mining faces and shafts, the operations follow the traditional mining geometry by benches. These shafts are predominantly vertical and have crushing facilities. Then, the crushed material is transported along the galleries up to the mineral processing facilities.

Regarding the mine development, scheduling and operations, the shafts applied to surface mining are structures that just eliminate some stretches of roads. The eliminated stretches are the roads located between the pit limits and the mineral processing facilities or waste piles. Shafts avoid the need of truck traffic beyond the pit limits, where the steep topography demands switchbacks with low radius of curvature along the road. The long-term mining plans and the scheduling strategy consider traditional haulage solutions. Hence, shafts just assist in the pit development but do not represent a new haulage solution because the long-term mining geometry preparation and its scheduling are not integrated with the shaft operation.

The described procedures represent the state-of-the-art of mining projects that apply underground structures during open pit operations. However, the current practices do not meet some fundamental aspects of sustainable mining such as reducing greenhouse gas emissions (GHG) without decreasing productivity and combining mine scheduling with waste management. Communities close to mining projects, civil society, even some governments reject traditional mining practices and have adopted some concepts of sustainable mining. Nevertheless, there are few examples of sustainable mining operations worldwide. In addition, large or small mining operations still present a strong dependence on trucks. This option implies increased GHG emissions, fossil fuel consumption and other aspects that affect the surrounding communities such as mineral dust, noise and vibrations from blasting operations. Besides, the destinations of waste and tailings are structures that require large area implying other high environmental impact. This raises the question of h ow to develop projects that reduce the need for trucks, the waste volume and environmental impact of waste piles or tailings dams.

In some instances, there are surface and underground operations at the same time but independently. The general rule is a transition between methods, where underground operations begin when surface mining is stopped. Due to the strong slope of mineralized bodies and the high market value of the mineral asset, an open pit mining methodology can be replaced by an underground operation. The present work aims to develop an innovative mining method combining underground mining structures with surface mining operations reducing the truck fleet, strip ratio and environmental impact. The withdrawal of trucks from the mining faces allows the use of alternative equipment able to reduce the waste removal. Besides, the present work also proposes a mine scheduling that allows the landfill of waste and dewatered tailings during the mining operations.

The truck fleet reduction in mining operations is widely known for improving the enterprise's environmental performance. Truck replacement by more efficient equipment can substantially reduce CO2 emissions and operating costs. Truck replacement by more efficient equipment is a reality, but it is only possible with the development of new optimization techniques and mine design [1,2]. Alternative equipment, such as carry dozers, employed for short-distance haulage can generate significant gains in fuel consumption and productivity [2]. In addition, this research has a great potential to reduce the waste removal because the accesses used by trucks require a further development from the mine. Truck replacement is an important premise for mine design routines developed in the present work and can also promote a mining scheduling able to release mined areas for waste and tailings deposition. This study allows mining projects to reduce the need for new areas for tailings dams and waste piles. The reduction of impacted areas has strong synergy with sustainability in mining. Currently, sustainable development takes up a core position in new mining project development [3]. The recent tailings dam disasters further increase the importance of the present investigation, since it represents an alternative that allows the environmental recovery of the mined area and avoids the need for new dams.

2. Literature review

Due the strong decrease of mineral commodity prices between 2014 and 2016, the mineral industry faces many challenges related to large surface mining operations. The discussions remain focused on the environmental performance, economy and productivity standards. However, the current economic scenario justifies deeper revaluations on mine design and new haulage solutions. The mine operations should be economic to ensure its sustainability [4]. So, the economy sustains and promotes dimensions such as security, environment, efficiency and social articulation. The author also points out that analysis and routines linked to the long-term mining planning, with the use of computer simulation, contribute to the development of new solutions able to strengthen these dimensions. The mining scheduling optimization is the main long-term planning component [5]. The authors claim that the scheduling validates the mining optimization, and it is essential for ensuring economic results for the enterprise.

In recent years, some innovative solutions involving open pit mining design and haulage operations were published [6,7]. These authors evaluate surface mining operation geometries combined with underground operations. This topic, such as case studies related to the transition from surface to underground mining, is not considered frequently in publications. The transition from open pit mining to underground operations is recurrent in the literature and has the premise of surface operations shutdown by operations exclusively performed underground [8–10].

In the work published by [6], the geometry, specifications, features and challenges of a surface mining operation that uses ore pass shafts were presented. The authors present a case study where two ore passes were installed in a strategic point of the pit in order to reduce the average distance of haulage performed by trucks. However, even with the insertion of this new haulage structure, there was no conceptual change in the mine design. The surface operations continued to be executed in the traditional manner using loaders/shovels and trucks. In this scenario, the gains are limited and specific because they are limited to a section between the mining faces and the mineral processing unit.

The scenario of a conventional mine, which uses trucks and excavators, has several characteristics that hinder automation and the use of alternative equipment [11]. As an example, electric trucks are not intensely applicable to mining due to geometric constraints and the need for the infrastructure that this equipment requires [12]. Consistent and systemic gains require deep revisions in the mine design [13]. In this work, the authors compared the economic and operational performance of traditional haulage systems versus in-pit crusher conveyor (IPCC) systems. According to these authors, the IPCC system represents a major capital investment (CAPEX), but the lower operational costs (OPEX) can generate more attractive long-term cash flows, when compared to the traditional truck/shovel haulage systems. The IPCC provides a reduced need for labor, lower energy consumption and lower operating costs when compared to traditional haulage systems [14]. However, the IPCC requires detailed knowledge of the mine and does not allow frequent displacements [15].

Considering its characteristics and applicability, the IPCC has achieved a wide application in the industry. The latest example of this solution would be the new iron ore operations in northern Brazil, started in 2016. However, not all mining projects in ferriferous formations are compatible with the IPCC. For instance, some rock types of banded iron formations present discontinuities, strong slope and restricted geometry. In this case, it is necessary to evaluate other haulage solutions. Considering the total integration between underground haulage structures, ore pass shafts and the mine design, it is possible to employ alternative equipment for short-distance haulage. Carry dozers, commonly applied to overburden removal of strip mine operations, can be a worthwhile option regarding the mining cost and productivity [16].

Beyond operating cost reduction, the substitution of a truck-shovel system by alternative equipment can generate improvements in the environmental performance of mining companies. Regarding the short-term, this advance is due to the reduction of greenhouse gas emissions. But in the long term, alternative haulage solutions give way to new mining scheduling solutions that allow releasing some mined areas for waste or tailings disposal. The traditional tailings dams should be replaced by paste stacking [17]. This type of stacking includes the paste storage after thickening and dewatering, which reduces the volume occupied by the tailings. A description of the paste deposition process in an iron ore processing unit was developed by controlled field tests [18]. In this study, the authors have presented results where it is possible to achieve deposition slopes of 8%, considering a yield stress of 280 Pa. These specifications allow a better use of mined areas for the densified paste deposition.

3. Methodology

The comparative analysis between different scenarios and operational conditions was carried out through the simulation tools of mine design. Considering that the present work seeks to compare the results of a customized mining geometry versus a traditional one, it is necessary to use optimization, design and mine scheduling software. Each analysis round generates an economic mine geometry with the volume of ore and waste. Therefore, it is possible to calculate the strip ratio (SR) of each geometry. This will be the main variable to evaluate the mining methods.

The present work seeks to define a long-term mining geometry and a mining sequencing that combines surface operations with underground structures. This combination should eliminate the use of trucks, reduce SR, and generate tailings deposition or sterile conditions in mined areas. All these assumptions have a strongly innovative aspect compared to traditional operations. However, new geometries need to overcome traditional methods in terms of economic and environmental performance. This condition represents the main contribution and innovation of this study.

Fig. 1 shows a mineralization of hard itabirites and a topography surface that follows the mineralized layer slope. The topography indicates a steep slope over the mineralized body. This configuration can be related to a several mineral goods worldwide. The geometry shown in Fig. 1 represents an iron ore formation from southeastern deposits of Brazil as an example. This ore body will be considered in the next evaluations of the present study and has the following characteristics:

- Slope angle = 45°
- Length = 1400 m
- Average thickness = 81 m
- Average width = 200 m
- Slope height = 123 m
- Average layer depth = 10 m

The development of the present study follows four steps, which are described below:

1) Description of underground structures employed for the material haulage between the mining faces up to the mineral processing facilities.
2) Pit design and mine scheduling of the mineralization considering economical parameters, operational variables and application of underground structures.
3) Pit optimization and mine design considering the traditional methodology using trucks and shovels.
4) Ultimate pit report of traditional and proposed scenarios.

4. Underground structures

As previously proposed, this study provides the ore extraction outflow and waste removal by underground routes. The opening of underground routes, associated with crushing and conveying systems, aims to replace trucks and haul road stretches. This replacement includes the path between the mining faces and mineral processing facilities. Fig. 2 shows the cross-section AA' based on the topographic surface shown in Fig. 1 combined with the pit limits. Considering the shaft, shown in Fig. 2, the pit limits follow the main assumption of the proposed mining method regarding the haulage. The ultimate pit geometry, proposed in the present study, drives the haulage of all ore cuts and waste rocks by the shaft.

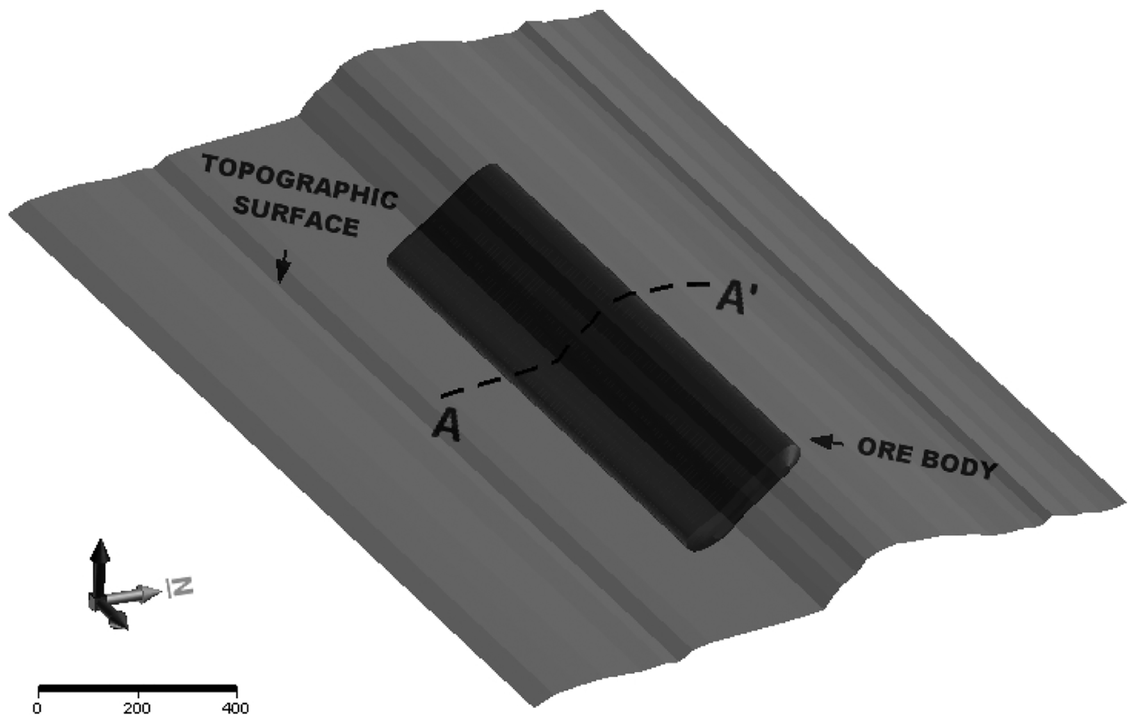

Fig. 1 – Topographic surface and hard itabirite mineralization.

Considering the slope of the ore body adopted as example, the shaft inclination is justified by the need to meet all the project benches. Therefore, it is not necessary to provide accesses to the material haulage operations by trucks because the haulage to the shaft will be carried out by dozers. In Fig. 2, the maximum distance between the ultimate pit limit and the shaft is 196.5 m with gradual reduction up to the pit bottom. Bulldozers are a productive and economic option for downhill cuts and pushing material for average distances up to 150 m [16]. The author's assertion is valid for this study, since the average distance of haulage for the project is less than 150 m.

In addition to the shafts a connection with the galleries is required. These galleries should house the primary crushing facilities and the conveying and haulage system to the mineral processing unit. Before the material cut by the dozers passes through the shaft, there must be a grid that prevents the passage of excessively large blocks. This practice avoids clogging events during the shaft's operation. Fig. 3 shows the details of the galleries provided in the project. These galleries are placed below the ultimate pit surface, so that all the mined material in the project is hauled through underground openings. Therefore, the connection galleries link the shafts. All the underground structures mentioned feature a semi-circular section. Table 1 shows the dimensions of all the underground openings provided by the project. These structures are indicated in Fig. 3 and extend along the ore body length. The production gallery, which is also in Fig. 3, links the connection galleries with the surface. The con-

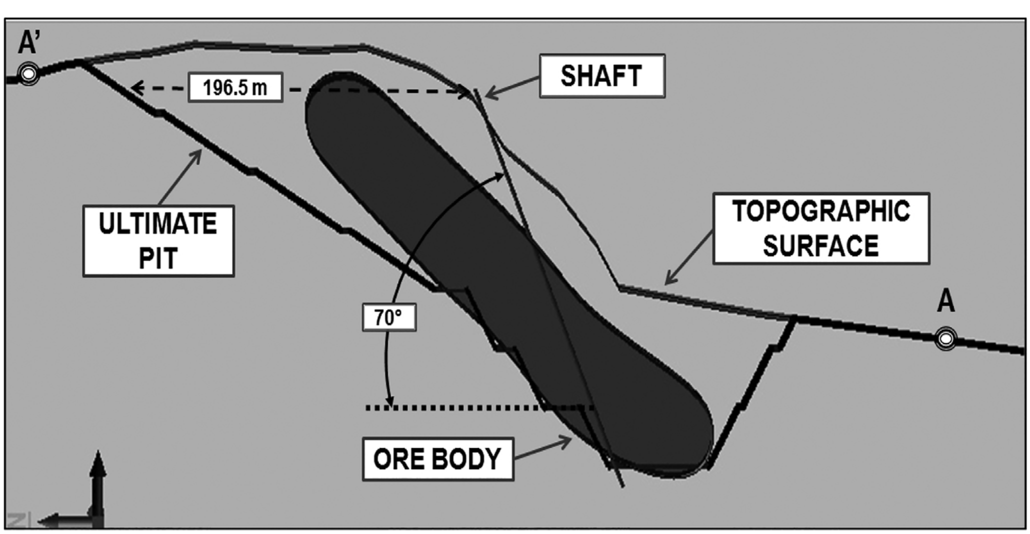

Fig. 2 – Cross-section AA' detailing the shaft position.

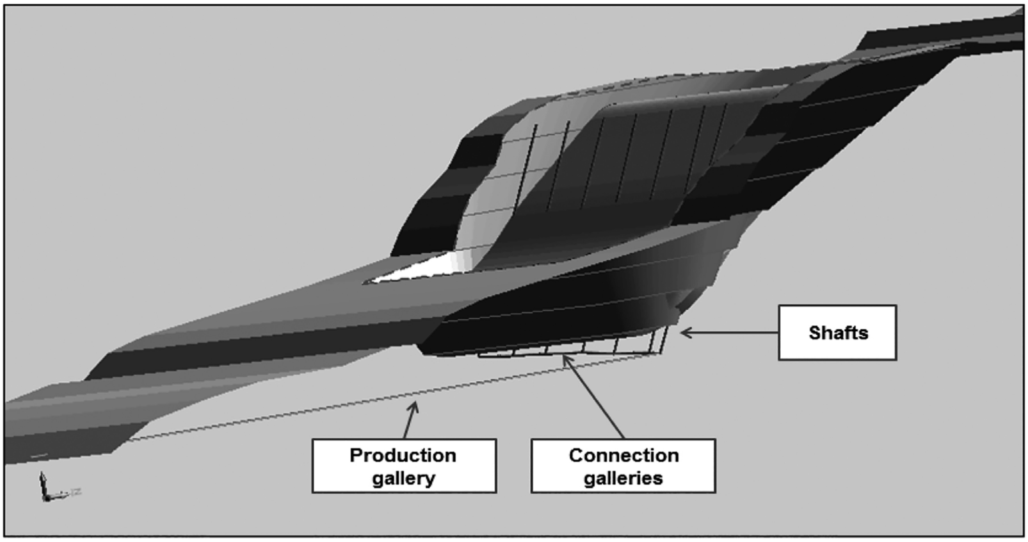

Fig. 3 – Underground structures provided in the project.

Table 1 – Dimensions of the main underground structures.

	Position	Length (m)	Volume (m^3)	Semicircular section (m)		Inclination (degrees)
				width (x)	height (y)	
Shafts						
1	17NS	223	1765	4.5	4	70°
2	257NS	224	1776	4.5	4	70°
3	517NS	227	1802	4.5	4	70°
4	757NS	228	1804	4.5	4	70°
5	1017NS	233	1848	4.5	4	70°
6	1257NS	235	1867	4.5	4	70°
7	1417NS	241	1914	4.5	4	70°
Galleries						
Connection	644EW	1402	11106	4.5	4	0.7° (1%)
Production	1417NS	636	5041	4.5	4	0.7° (1%)

veying system links all galleries and the mineral processing unit.

4.1. *Geotechnical notes*

As the project considers various underground structures and routes, it is worth mentioning some factors to be determined. These factors have a core importance in project routines and support sizing [19]. The author recommends basic aspects to be determined:

- Mechanical strength features of the rock mass.
- Calculation of rock mass strains on the support, as a result of the strength redistribution surrounding the excavation.
- Calculation of the effective resistance stresses acting on the supporting structure to ensure the excavation stability.

In most mining enterprises that include underground routes there are complex lithological structures [20]. This feature generates a great challenge to engineering projects. The main challenge is the uncertainty attributed to the geological structure configuration and the geomechanical conditions. The authors also state that the experience of similar operations becomes an important factor to be considered during the project development. Therefore, this work considers the experience of the mine in Gualcamayo, Argentina. As described by Ward et al.,[6] this enterprise uses shafts for the material passage and galleries for the crushed rock haulage with conveyor belts. In that study, the authors report that operations are developed with economy and safety, despite the mentioned challenges. The authors also report that concrete projected on metal frames was identified and used as a support of underground excavations.

Considering the hard itabirite mines, it is important to carry out proper structural geological mapping of the mining areas. This investigation is aimed at identifying discontinuities and other structures such as fault zones, joint set and other fractures. These results will drive the selection of shaft structures associated to the blasting method to be used.

5. Operational project and mining scheduling using underground structures

The shaft operation basically requires bulldozers for the material cutting and haulage, in short distances, up to its

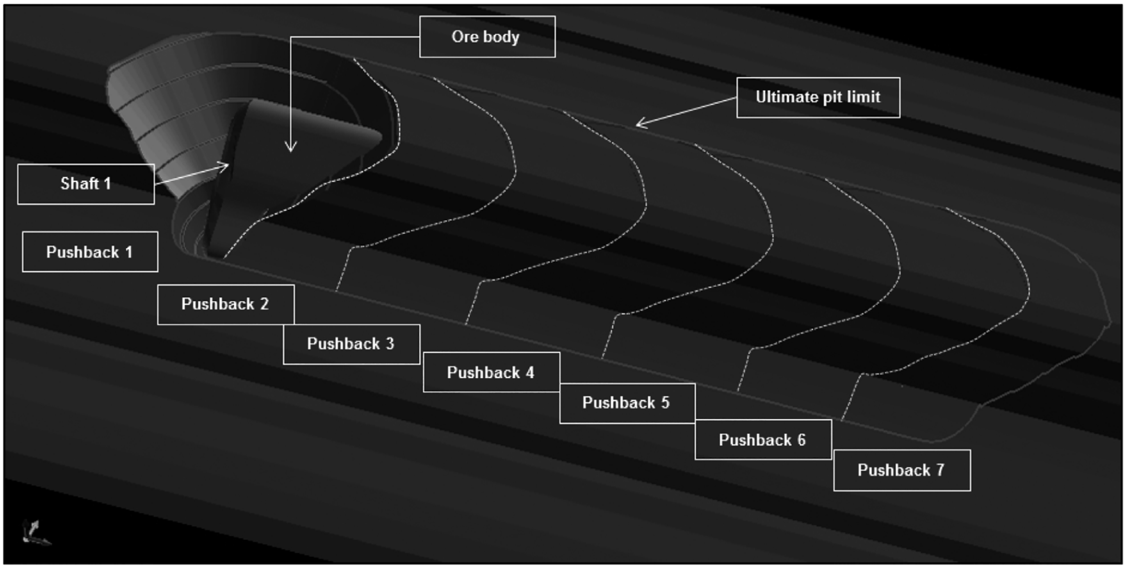

Fig. 4 – Open pit design and long-term production scheduling.

surroundings. Due to the resistance of hard itabirities, it was required that drilling and blasting operations produce an efficient fragmentation, without generating blocks with sizes above the specifications. The shaft feeding can be performed with the use of front-end loaders that deposit the material in a hopper. This structure conducts the material to a rack that prevents large blocks from passing through the shaft. The operational features are critical because they determine the composition of the mining costs. Considering the ore body and the topography of Fig. 1, it is possible to perform the pit optimization rounds to define the economically mineable portion of the mineralized body. The execution of this routine also considers operating factors such as the mining costs. Various pit optimization techniques can be applied in the ultimate pit limit identification. Dimitrakopoulos[21] applied different pit optimization techniques, which generated different results regarding the net present value (NPV). Considering the author's contribution, it is possible to leverage even more the economy and sustainability of mining projects.

Once the ultimate pit limits are defined, it is necessary to establish a mining scheduling strategy. Fig. 4 shows the ultimate pit limits and each of the seven pushbacks to define the final geometry. The pushback design depends on the geological variability, mining operation capacity and the specifications required by the mineral processing. Meagher et al.[22] claim that one of the main deviations related to pushback design is the suboptimal geometries. The authors state that some optimization techniques do not ensure the NPV maximization in each of the scheduling periods. Therefore, it is possible to obtain economic results that are even more positive with the development of optimization techniques applied to the mining scheduling.

Fig. 5 shows the ultimate pit geometry after the mining of all pushbacks. In most iron mines, there is a considerable variability regarding the metal grades and other elements. Moreover, these operations require multiple mining faces to ensure flexibility in the production process. In view of these conditions, it is possible that more than one pushback starts its operations at the same time. Therefore, it is required that two or more shafts are able to operate simultaneously. The remaining shafts can be built during the mining of the first pushbacks. This assumption makes the operations more flexible, because it allows blending with materials from different areas. Another advantage is the possibility to stop the activities in one of the shafts for maintenance, while the other is still in operation. As the mining progresses in a given pushback, the shaft is consumed by the vertical advance, as presented by Fig. 5. In this geometry, the benches are 30 m high. The inclination of the slopes near to the surface is 30° due to the altered rock layer. Hence, it is recommended that shafts surrounded by altered rocks have reinforced supports during the development. As the mining progresses vertically, the slope faces become more inclined up to 60° due the high rock quality index. Table 2 shows the total volume considering the use of underground structures. This table details the estimated production for each pushback, the ore density, waste and the SR.

6. Traditional project

Considering the topographic surface, the ore body described in Fig. 1 and the use of conventional equipment to apply the open pit mining method, it is possible to generate new optimization results. This optimization considers mining costs referring to the operations that use trucks and shovels for the pit development. The result of this analysis generates an ultimate pit and a report that present the total mass of ore and the removed waste rocks.

Fig. 6 represents the final surface of the operational ultimate pit. The operating geometry includes haul roads for large trucks, ramp switchbacks and plain sections. As shovels will be used, the benches require a geometry compatible with the equipment dimensions. To meet this geometry, it is necessary to provide benches 10 m high, slope angles of 50°, roads 20 m

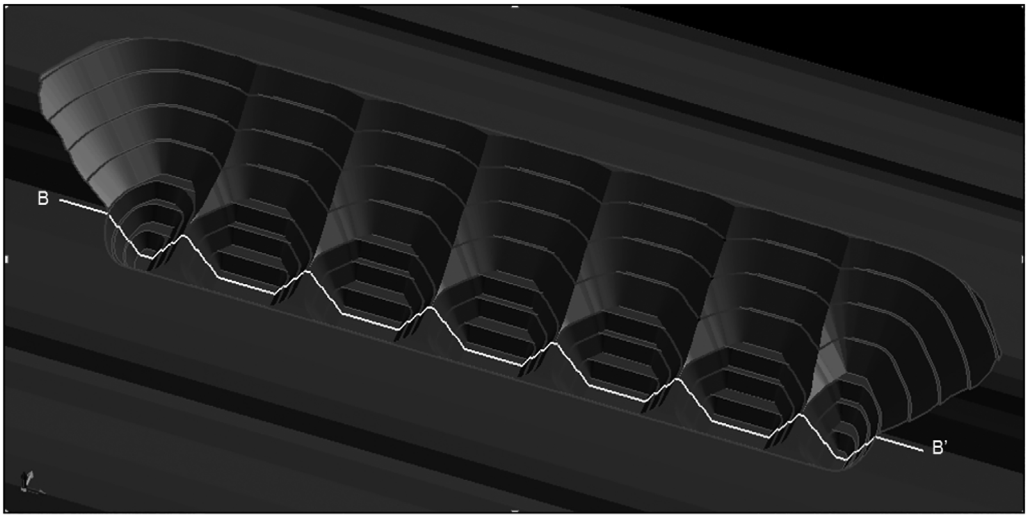

Fig. 5 – Ultimate pit design using underground structures.

Table 2 – Report of open pit design and long-term production scheduling.

Pushback	Volume (m^3)		Density (t/m^3)		Mass (t)		Strip Ratio
	Ore	Waste	Ore	Waste	Ore	Waste	
1	1,799,251	5,362,649	2.9	2	5,217,828	10,725,298	2.1
2	2,773,669	3,539,630	2.9	2	8,043,640	7,079,260	0.9
3	2,963,342	3,870,977	2.9	2	8,593,692	7,741,954	0.9
4	2,960,542	3,867,477	2.9	2	8,585,572	7,734,954	0.9
5	2,963,192	3,870,477	2.9	2	8,593,257	7,740,954	0.9
6	2,960,692	3,867,977	2.9	2	8,586,007	7,735,954	0.9
7	755,120	3,292,353	2.9	2	2,189,848	6,584,706	3.0
Total	17,175,808	27,671,540	2.9	2	49,809,843	55,343,080	1.1

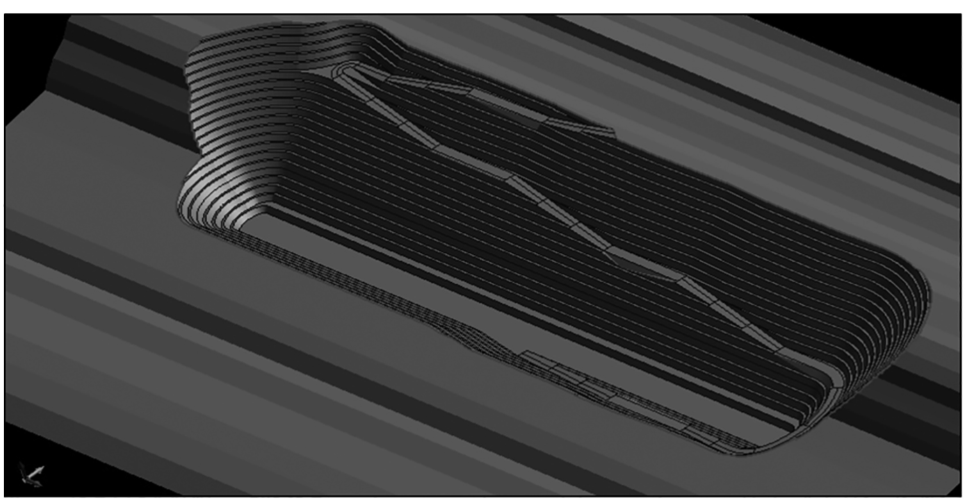

Fig. 6 – Ultimate pit for the traditional method.

Table 3 – Final report of the traditional open pit design.

	Volume (m^3)		Density (t/m^3)		Mass (t)		Strip Ratio
	Ore	Waste	Ore	Waste	Ore	Waste	
Traditional Method	22,209,209	38,036,990	2.9	2	64,406,706	76,073,980	1.2

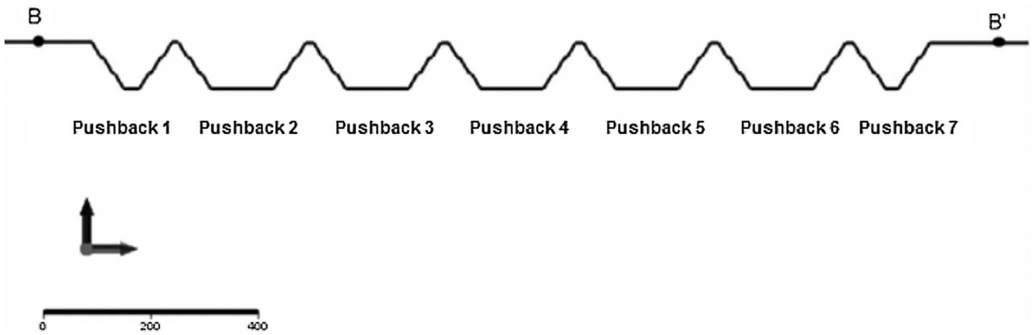

Fig. 7 – Final geometry profile BB' with mined pushbacks.

wide and berms 5 m high. To carry on the haulage operations safety, it is required to provide plain sections every 30 m of ramp. Table 3 shows the final volumetric report regarding the traditional project.

7. Results and discussion

The validation of the new mining method proposed in this research is based on the comparative analysis between the two projects previously discussed. The first aspect to be evaluated is the strip ratio of each ultimate pit geometry. In addition, it is necessary to discuss the use of mined areas of each pushback for the waste and tailings deposition because it is essential that new mining projects promote a greater sustainability.

Tables 2 and 3 present the final SR of each operational ultimate pit. Analyzing these data, the geometry using underground structures achieved a reduction of 8.3% in relation to the traditional design. This result indicates that the proposed method is able to ensure the ore production with less waste removal. This result makes this type of enterprise more sustainable because it demands a smaller area for new waste piles. The economic aspect is also heavily enhanced because no expense is generated with the waste removal. Regarding the total ore tonnage, there is a significant loss due to the new method assumptions. However, mining recovery may be improved with further investigations related to the geomechanical conditions of the mined-out areas.

Among the underground routes, the shafts are temporary structures. The pushback developments start in the higher positions, near to the surface, toward the pit bottom. Therefore, the shafts are consumed as the vertical advance takes place. In addition, there is an average distance of 200 m between the shafts. These characteristics favor the safety and applicability of underground structures in the surface mining development. To evaluate each of the pushbacks after the mining, the cross-section BB' is shown in Fig. 5. Hence, Fig. 7 shows the cross-section BB' detailing the mined areas according to the method proposed by the present study. By geometry analysis, it is possible to use the mined pushbacks for waste deposition, dewatered tailings stacking or both. The stacking of these materials can begin during the development of other pushbacks. This assumption makes the operation more flexible and sustainable because it reduces the need for environmental licensing and the need of new tailings dams or new areas for waste piles.

8. Conclusion

As the present study adopted a typical condition for many metallic deposits, represented by hard mineralized rocks, to discuss a new mining method, it is important to highlight a few points. In the last two decades, there have been many mining projects to be developed near communities and cities. Due to the expansion of urban areas, mining companies are constantly questioned and held accountable for their actions regarding environmental aspects. Besides, the licensing process for new mining units, new wastes piles and new tailings dams became more complex.

Even the mining companies which have carried out operations for four or five decades face many constraints in expanding their operations. This situation is mainly attributed to the need of large areas for the waste piles and tailings dams. Hence, the possibility of using mined areas for stacking waste rocks and tailings, before the ultimate pit, can ensure the business expansion. This study demonstrates that this practice is feasible and can be applied in the mining industry. In addition, the surface mining method combined with underground structures reduces the SR by 8.3% compared to traditional projects. This result represents a significant contribution to make mining enterprises more sustainable.

On the one hand, there is a need for large investments for underground structures regarding the proposed mining method. On the other hand, this practice eliminates investments for road infrastructure, trucks and shovels. Therefore, the continuing research should have three major aspects. The first would be the environmental aspect, where it is necessary to measure the fuel consumption by the method proposed in this research compared to the traditional methods. Then, a deep geomechanical characterization of rock masses able to be mined is recommended. And finally, it is necessary to perform the full economic analysis comparing the proposed method against the traditional one. In these studies, the investments, operational costs and ore losses in each method should be evaluated.

Conflicts of interest

The authors declare no conflicts of interest.

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