Simulation and Optimization of Bench-Mining Sequences Using Fully Mobile In-Pit Sizer and Conveyor Systems

Josué González and Nelson Morales
Advanced Mining Technology Center, Universidad de Chile

ABSTRACT

In-Pit Crusher and Conveyor Systems (IPCC) have received an increasing interest in the mining industry due to the reduction in haulage costs, lower personnel and fuel requirements, and less environmental impact in comparison with traditional truck-shovel operations. However, contrarily to the usual shovel-truck case, there is not a well-established methodology for planning IPCC extractions and, in particular to analyse the optimal bench extraction sequence.

In this paper, a methodology to evaluate Fully Mobile In-pit Sizer and Conveyor System´s (FMIPSC) application and performance is proposed. The FMIPSC system configuration is modelled using discrete-event simulation to assess its productivity, availability, utilization, and its interference with drilling and blasting stages. We analysed different loading methods such as back-up (single and double sided), drive-by and fixed crusher loading methods and they were combined into two mining sequences.

The methodology proposed may be usefully implemented to analyse the behaviour of FMIPSC systems and optimize its performance, through combining high productive loading methods into longitudinal and transversal mining sequences applied to different bench sizes scenarios.

According to the numerical experiments conducted, the drive-by method was the most productive of the loading methods due to shovel's lower average swing angle and less conveyor relocations. However, its application requires lateral areas to be previously mined due to space requirements to sizer and conveyor allocation. The fixed crusher and back-up methods can be applied to carry out these mentioned areas and box cut. Simulation´s results demonstrates that as wider benches are mined combinations of loading methods could be made, increasing the productivity of the system and enabling the possibility of mixed sequences where selective mining could take place.

INTRODUCTION

The uncertainty in the prices of minerals, the high price of fuels, and increasing operational costs, mainly haulage costs due to the deepening of the pit, have made the use of In-pit Crushers and Conveyor Systems (IPCC) one of the most intriguing alternatives for mining companies to reduce these costs and remain competitive.

IPCC systems may have different configurations, chosen according to the production requirements of the mining company and the characteristics of the mineral deposit. Depending on the crusher used, the IPCC systems can be classified into fixed, semi-fixed, semi-mobile and fully mobile (Oberrauner, Turnbull, & Systems, 2012). In this paper, a Fully Mobile Sizer and Conveyor System (FMIPSC) configuration is modelled which integrates a high capacity rope shovel that discharges the material directly into the hopper of a double roll mobile crushing unit. Once the material has been crushed it is transported using a conveyor system that includes a horizontal conveyor and a set of super portable conveyors.

The FMIPSC´s productivity is limited by the shovel's performance. Therefore, the system´s highest productivity is reached by implementing loading methods where the shovel completes low average swipe angles to feed the sizer unit, hence achieving short loading cycles. The relocation frequency also impacts the productivity of the system and it is dissimilar for each loading method. It is defined as the number of advances that the shovel and sizer make before the horizontal conveyor must be moved. The placement and movement of the shovel around the sizing unit directly impacts the average swing angle. Therefore, an excavator moving in arc will be able to excavate a wider bench at a lower average swing angle than the same equipment placed in a fixed position (Atchison, 2011).

Due to the complexity of the system discrete-event simulation (DES) is used. DES has been widely applied to model mine operations where deterministic models fail to predict uncertain behavior accurately (Upadhyay & Askari-Nasab, 2017). This tool is extensively accepted to assess the performance of mine operations because it makes it possible to incorporate inherent variability and complexity of operational uncertainty (Torkamani & Nasab, 2015). In this research, DES is used to estimate operational indexes as productivity, availability, utilization, and the operational interferences between parallel mining operations.

This work aims to propose a methodology to evaluate the application of FMIPSC systems and maximize their productivity. Evaluating different configuration of loading methods and mining sequences applied to dissimilar bench sizes scenarios using DES. It is important to mention that, in this research, mining benches are conformed completely of ore material. Geological uncertainty in terms of material type and ore grade were not considered. FMIPSC's behavior applied to varied mineral distribution scenarios will be evaluated in future work.

METHODOLOGY

The methodology used for this research is summarized in Figure 1. The simulation model replicates the FMIPSC system's behavior. The input for the simulation is a plan that includes the allocation coordinates of the shovel, sizer, and conveyor system; and loading, dumping, and discharge coordinates for each position of the equipment on the bench. The model uses probability density distribution for event occurrence and its corresponding duration. The information of capacity, breakdown frequency, mean time to repair, and other technical data are collected from bibliographic review and interviews with engineers experienced in FMIPSC systems.

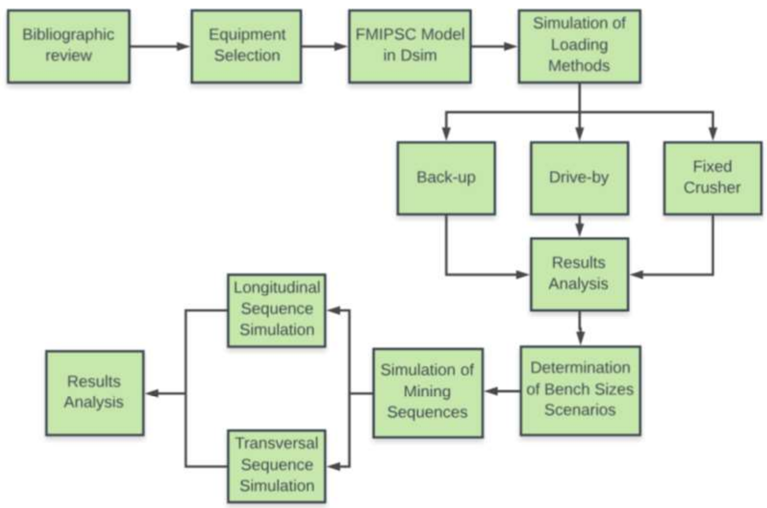

Figure 1 Methodology scheme

NUMERICAL EXPERIMENTS

FMIPSC Equipment

The equipment selected for this study includes a P&H 4100XPC electric cable shovel as loading equipment, an MMD mobile crushing station, a super portable conveyor system from Terra Nova Technologies (TNT), and a Caterpillar MD6540 drilling machine.

The P&H 4100XPC electric rope shovel has a bucket nominal capacity of 52.8 to 62.7m^3 achieving an estimated 99 to 110t per loading cycle. Given the dimension of floor level radius of 16m and a digging radius of 22m, considering a bench height of 15m, it allows the shovel to mine a 6m advance. (Komatzu, n.d.)

The MMD mobile crusher unit incorporates a 1500 MMD series twin shaft mineral sizer with an average capacity of 9,000tph, a receiving hopper of 175m^3 capacity, and a transfer and discharge conveyor. It is designed to be a compact and light-weight unit (44m x 15m x 14.5m / 1170tons) reaching speeds of 12m/min. (Mining Machinery Developments (MMD), n.d.)

Terra Nova Technologies super portable conveyor system includes an 86m-long horizontal conveyor with a full-length receiving hopper, which allows the sizer unit to discharge material at any point on the conveyor; and a set of 13 interchangeable super portable conveyors mounted on tracks, each one of 76m long and fully adaptability to horizontal conveyors. These super portable conveyors were designed to replace shiftable conveyors (Figure 2) that are placed at the face of the bench and need to be moved several times by a dozer to relocate, reducing downtime. (Terra Nova Technologies, n.d.)

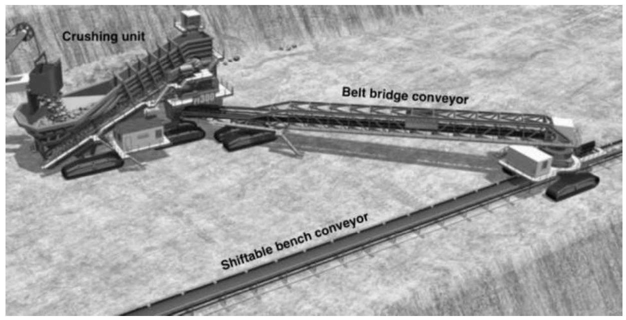

Figure 2 Fully mobile crushing system (Oberrauner et al., 2012)

Loading Methods

The loading methods evaluated include back-up (single and double-sided), drive-by and fixed crusher loading methods, which are described below. Parameters like fill factor, operator efficiency, swipe factor, and swell factor are considered to estimate the effective bucket capacity for copper ore. Safety distances between the FMIPSC system´s equipment to the bench wall or/and pit are respected to ensure the correct maneuverability and operation of the system.

Back-up Loading Methods

This loading method has two variants: single and double sided. In the single-sided method the horizontal conveyor is placed behind the shovel while the sizer is located on one side of the shovel slightly behind it (Figure 3).

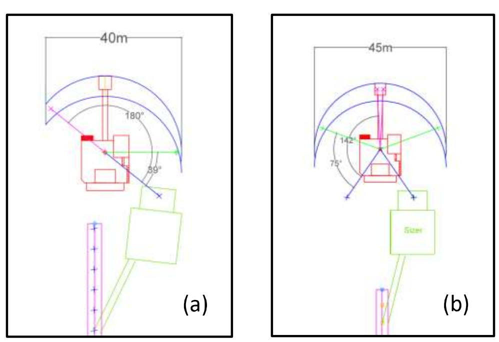

Figure 3 Back-up loading method. **(a)** single sided **(b)** double sided

The shovel rotates 40° to 180° to complete the loading cycles in a 40m width working face. The double-sided method allows to reach a 45m operational width using the entire shovel's digging radius Figure 3 (b). The equipment has the same allocation as the single sided alternative, however, in this alternative just half of the working face´s material is extracted by the shovel while performing 75° to 145° swipe angles, then, the sizer moves to the opposite side of the shovel and the process is repeated.

Drive-by Loading Methods

Drive-by methods are generally applied to long and straight benches where shovel and sizer have parallel trajectories to each other and move parallel to the bench face (Instituto Tecnológico GeoMinero de España, n.d.). Two operational widths are evaluated for this method, 20m and 24m, respectively. The shovel rotates 35° and 98° (Figure 4 a and b) to complete the loading cycles. It is important to mention that these methods require lateral areas (developments are shown in yellow, Figure 5) to be previously mined to allocate the sizer and the conveyor system.

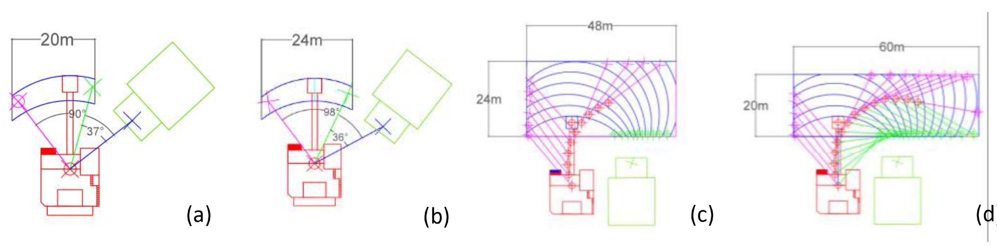

Figure 4 Drive-by loading methods **(a)** 20m working face width **(b)** 24m working face width. Fixed crusher loading methods **(c)** 48m working face width **(d)** 60m working face width

Fixed Crusher Loading Methods

Two alternatives are evaluated for this method where the shovel excavates 48m x 24m and 60m x 20m blocks (Figure 4 c and d) while performing 30 ° to 165° rotations to load the sizer unit along the arc movement around it and followed by the borders extraction where remnant material has been left behind.

Bench Size Scenarios and Mining Sequences

Depending on spacing requirements different loading methods can be applied to the box cut, lateral developments, and production areas within the bench, and they can be combined into longitudinal and transversal mining sequences to improve the overall productivity of the FMIPSC system. The simulation model incorporates drilling and blasting events. The extraction operations need to stop in order to move the equipment to a safe area so blasting can take place, affecting the utilization of the system. Drilling and blasting plans require a distance of 120m between the equipment and the blasting area to insure safety. Blasting parameters were calculated by Lopez Jimeno methodology (INSTITUTO TECNOLOGICO GEOMINERO DE ESPAÑA, 1994) using a drill diameter of 311mm.

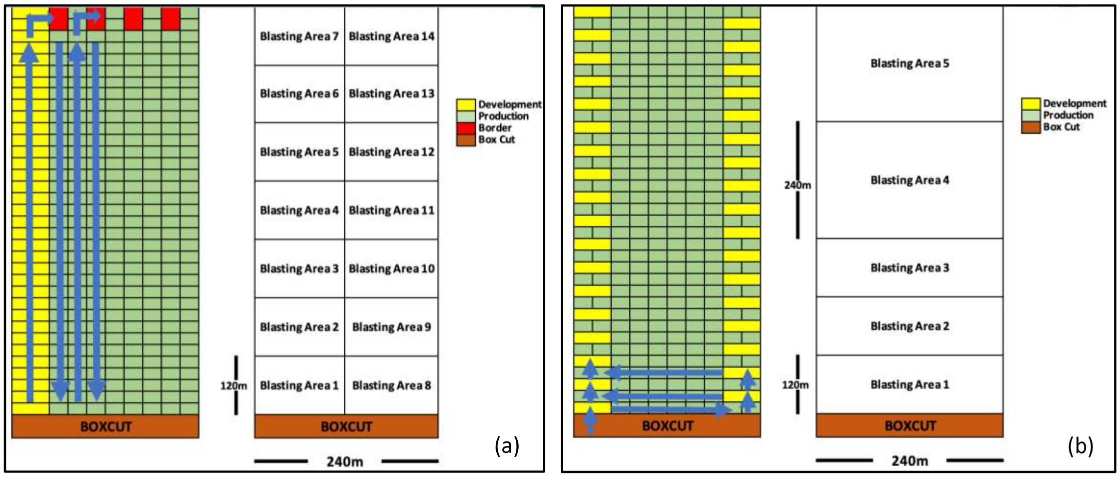

Figure 5 Bench mining and blasting plans sequences. **(a)** longitudinal sequence **(b)** transversal sequence

Two scenarios of bench sizes are evaluated considering a constraint in the number of super portable conveyors available per bench a total of 13 super portable conveyor. The first bench scenario has a bench width of 120m and a length of 1000m, and the second has a width of 240m and a length of 880m. A 120m bench is the minimum width necessary to allocate the shovel, sizer unit, and horizontal conveyor and allow the extraction of the bench by the FMIPSC system.

Model Inputs

The simulation inputs about event distribution were mainly obtained from Morriss, 2008; and adapted to a triangular probability density distribution, according to the criteria of the mine planning engineers. Table 1 and 2 show the data used for each programmed event simulated. Blasting and equipment's maneuver delays are results from the simulation to assess the utilization of the FMIPSC system.

Table 1 Failure event distribution

		Triangular distribution					
		MTBF			MTTR		
Equipment	**Units**	**Minimum**	**Maximum**	**Mode**	**Minimum**	**Maximum**	**Mode**
Shovel	hrs	20	26	22.4	1.6	2.2	1.8
Crusher	hrs	19	25.1	20.7	0.6	1.5	0.8
Horizontal Conveyor	hrs	20	26	21.7	0.4	1	0.5
Drill	hrs	51	53.3	52.1	1.8	2.5	2.2

Table 2 Cyclical event distribution

		Triangular distribution		
Event	**Units**	**Minimum**	**Maximum**	**Mode**
Shift Change	min/shift	9.8	10.2	10

Meal break	min/shift	50	70	60
Geological Inspection	min/day	18	22	20
Fuel *	min/day	12.5	17.5	15
Equipment Inspection	min/shift	8	15	10
Re-Induction	min/week	25	35	30
Other delays	min/week	10	20	15
Bad weather losses	days/year	2	4	3
Scheduled relocations	min/week	10	20	15
Industrial losses	days/year	3	5	4
Daily Service	hrs/day	0.8	1.2	1
Weekly Maintenance	hrs/week	6.2	6.8	6.5
Shovel and Drill Annual Maintenance	hrs/year	2.7	2.9	2.8
Sizer Annual Maintenance	hrs/year	5.5	5.7	5.6

*Non-electric equipment only

RESULTS AND DISCUSSION

One hundred simulation replicas were run in order to obtain accurate results. Each replica running time was approximately 6 to 10 minutes.

Loading Methods

The results presented in Fig. 6 (a) indicate the percentage of time that the shovel and sizer are maneuvering or waiting for the conveyor system to relocate, and the Fig. 6 (b) shows the loading cycle times for each loading method evaluated. The results indicate that the single sided back-up methods have lower percentage time in equipment relocation with 4.7% while also having the highest average loading time. Its double-sided variant has a 4% increase in equipment relocation due to the time needed to move the sizer unit from one side of the shovel to the other. The drive-by methods have the lowest average loading cycle time with 35.6 and 37 seconds, the 20m width working face alternative has 10.9% of its time dedicated to equipment relocation When 4 meters wider working faces are excavated this percentage is reduced by 1%, and the average loading time increases by 1.5 seconds. The methods with the fixed crusher have the highest percentage of time allocated to equipment maneuvering due to the amount of movements performed by the shovel around the sizer unit. These methods have an average loading time of 40 seconds.

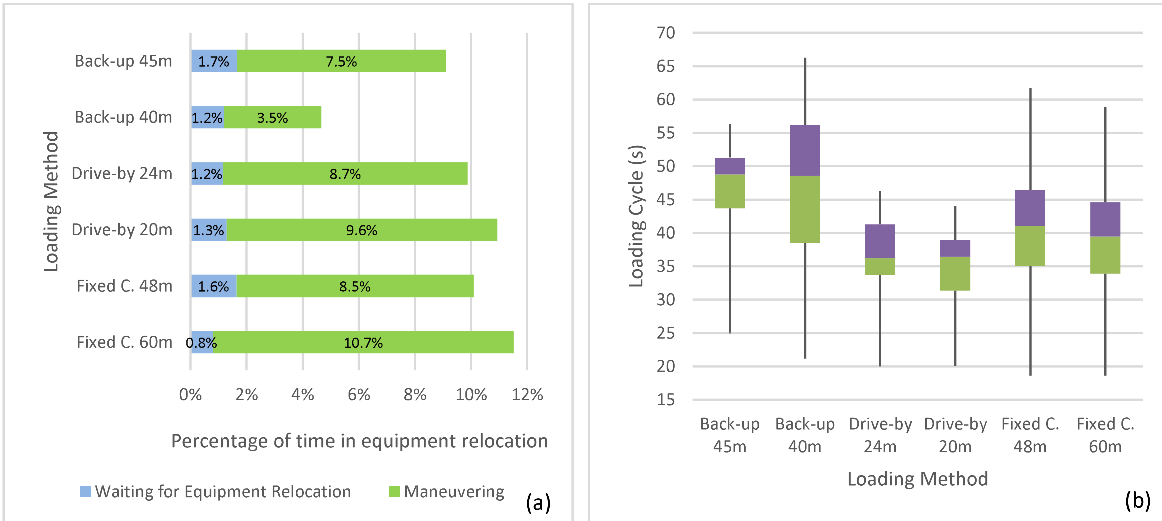

Figure 6 Loading methods simulation results. **(a)** percentage of time in equipment relocation **(b)** loading cycle time

Figure 7 indicates the production rate of each loading method studied. Drive-by methods were found to be the most productive methods reaching 11,800tph followed by the fixed crusher method at 10,150tph. Even though the back-up methods have the lowest time in equipment relocation, they are the less productive methods due to the higher average loading times. Nominal production rates where the system´s relocation time is considered follows the same order and tendency.

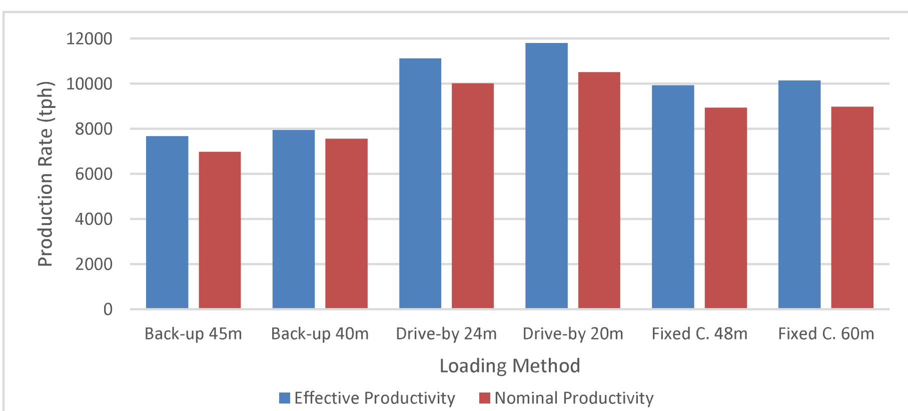

Figure 7 Production rate by method

Due to the required developments needed to preform drive-by methods they cannot be implemented on their own in a mining sequence, so it is required to combine them along with back-up or fixed crusher methods. Table 3 shows the best combination of loading methods that can be applied based on the production rates obtained from the loading methods simulations. Three options are evaluated for two bench size scenarios, option 1 combines back-up single sided and drive-by methods, option 2 and 3 combine fixed crusher and drive-by method with different working face widths.

Table 1 Loading methods combination options

	Number of Strips Extracted						
	Back-up 40m	Drive-by 20m	Drive-by 24m	Fixed C. 48m	Fixed C. 60m	Bench Width (m)	Average Production Rate (tph)
Option 1 (back-up & drive-by)	1	4				120	10516
Option 2 (fixed crusher & drive-by)			3	1		120	10642
Option 3 (fixed crusher & drive-by)		3			1	120	10977
Option 1 (back-up & drive-by)	1	10				240	11161
Option 2 (fixed crusher & drive-by)			8	1		240	10878
Option 3 (fixed crusher & drive-by)		9			1	240	11391

Mining Sequences

Results of the simulations of the mining sequences applying the aforementioned combinations to two bench size scenarios are showed in Figure 8. It is important to mention that the same availability of the system is considered for all options, bench scenarios, and sequences because the model uses the same failure distribution and programmed maintenance frequency in all the simulations. The average value of availability estimated at 72.7%. Other cyclical events such as meals, shifts changes, geological inspections, and equipment inspections are also similar, averaging all the replicas of each alternative simulated. Having said this, the system´s utilization is only affected by the relocation time of the equipment and blasting delays.

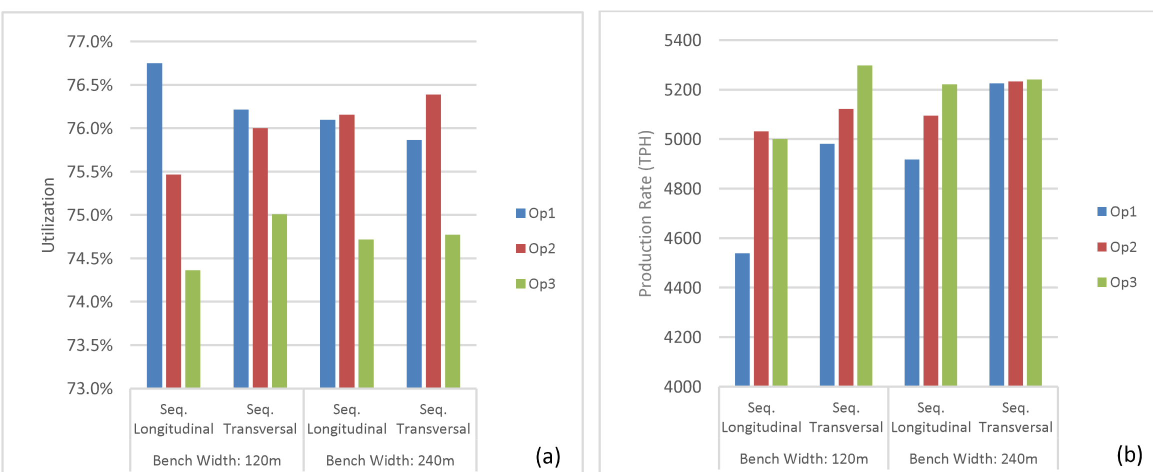

Figure 8 Simulation results. **(a)** FMIPSC utilization **(b)** FMIPSC production rate

The system's utilization for option 1 is the highest due to the lower equipment relocation time of the back-up loading methods. In this option the utilization declines while the size of the bench increases, since more of the bench's tonnage is extracted by drive-by methods where the relocations are more frequent, but it increases productivity. In options 2 and 3 (longitudinal) utilization increases as wider benches are mined because of the longer maneuvering times of the fixed crusher methods are countered by drive-by method´s shorter movement times. The opposite happens with option 3 using a transversal sequence in a 120m width bench where the horizontal conveyor only needs to be relocated once after the complete transversal strip has been mined, making of it the most productive option at 5,298tph.

The simulation's results demonstrate that transversal mining sequences are more productive than longitudinal sequences due to less equipment maneuvers and the elimination of the border areas in the back of the bench that are created with longitudinal sequences. As wider benches are mined a larger percentage of material is extracted using drive-by methods, increasing the FMIPSC system´s productivity until it potentially approximates to the drive-by methods average productivity.

CONCLUSION

In conclusion, FMIPSC's are one of the most interesting alternatives to be implemented as material handling system due to its reduced operative costs, high productivity, and less fuel and personnel requirements.

Drive-by methods are the most productive of the loading methods evaluated, however, its application requires previous developments due to spacing requirements. The fixed crusher methods are the best option to carry out these developments.

As wider benches are mined the system´s average productivity increases approaching to the productivity of the drive-by methods since a bigger part of the bench is mined by this higher productive method.

It was found that the methodology proposed may be usefully implemented to analyse the behaviour of FMIPSC systems and optimize its performance, through combining high productive loading methods into longitudinal and transversal mining sequences applied to different bench sizes scenarios.

ACKNOWLEDGEMENTS

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