Comparison between the application of the conventional mine planning and of the direct block scheduling on an open pit mine project

http://dx.doi.org/10.1590/0370-44672017710037

Pedro Henrique Alves Campos
Mestrando
Universidade Federal de Ouro Preto - UFOP
Escola de Minas
Departamento de Engenharia de Minas
Ouro Preto – Minas Gerais - Brasil
phacampos@gmail.com

Ivo Eyer Cabral
Professor-Adjunto
Universidade Federal de Ouro Preto - UFOP
Escola de Minas
Departamento de Engenharia de Minas
Ouro Preto – Minas Gerais - Brasil
cabralmg@uol.com.br

Carlos Enrique Arroyo Ortiz
Professor-Adjunto
Universidade Federal de Minas Gerais – UFMG
Escola de Engenharia
Departamento de Engenharia de Minas
Belo Horizonte – Minas Gerais - Brasil
carroyo@demin.ufmg.br

Nelson Morales
Professor
Universidad de Chile
Department of Mining Engineering
Investigator – Delphos Mine Planning Laboratory
Advanced Mining Technology Center
Santiago - Chile
nelson.morales@amtc.cl

Abstract

Historically, since the 60's, traditional mine planning consists of several distinct stages:

1) Definition of the ultimate pit - the portion of the blocks that results in the greatest total value;

2) Pushback selection - based on the generation of nested pits, obtained with the change in the value of the ore price;

3) Long-term production scheduling.

Although considered quite satisfactory, this methodology presents some flaws: The stages, even if considered individually optimal, may not be when put together. The opportunity cost is not considered and the cut-off is fixed.

Due to the recent computational advances, a new technique has been growing and is more reliable: the direct block sequencing. In this methodology, the steps are consolidated into only one process, improving the economic results, reducing the total execution time and obtaining, in fact, an optimal planning.

The aim of this work is to compare the results of the two planning methods applied in a database of a Brazilian iron ore mine and to show the real advantages and disadvantages of each one. To solve the direct block sequencing technique, *Doppler* was used, a tool developed by Delphos Mine Planning Laboratory, located at the University of Chile. The traditional methodology was executed through *Whittle* software. Lastly, a medium-term scheduling was performed using *Deswik* software.

Keywords: mine planning, production scheduling, direct block scheduling.

1. Introduction

Open pit mine planning is the process of defining and scheduling mine production with the objective of obtaining a maximum possible Net Present Value (NPV) for the project, subject to capacity and operational constraints. For this, mine planners represent the geology data by a set of regular three-dimensional blocks, also known as economic block model, and must decide what and when to extract each block, as well as decide its destination. (Morales *et al*., 2015)

There have been two main broad methodologies for optimizing this problem, and these methods have been broadly classified as “block level resolution” and “aggregation” approaches. The “aggregation” approach splits the global problem into several smaller sub-problems, which include, for example, the optimization of the ultimate pit, intermediate pushback selection and scheduling, and is known as the conventional planning. (Elkington and Durham, 2011).

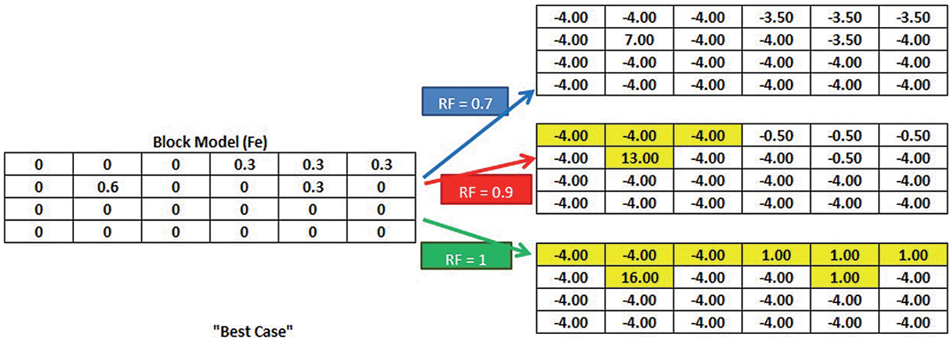
The final ultimate pit is the volume of material economically viable to be extracted and which returns the largest possible profit. An optimum pit contour can be determined by setting economic values on the blocks and slope angles. An increase in the values of the blocks results in wider pits, while an increase in the slope angles enables deeper pits.

The second step is the creation of pushbacks. Hustrulid and Kuchta (2006) state that pushbacks are also known as sequences, expansions or phases and are an attempt to relate mining geometry to the ore distribution geometry. To aid in the pit limit definition, Lerchs and Grossmann proposed a technique for generation of nested-pits. This technique uses revenue factors that penalize the economic value of the blocks, thus resulting in several nested-pits of different sizes. The smaller the pit, the higher is the economic value, and, therefore, should be extracted first to maximize the NPV.

Finally, long-term production scheduling can be understood as the sequence in which the blocks contained in the optimal final pit must be removed in order to maximize profit.

The "block level resolution" optimization approach, on the other hand, is a mathematical formulation proposed by Johnson in 1968 and is now known as Direct Block Sequencing (DBS). DBS is a production scheduling technique that consists of solving mathematical equations by means of mixed integer programming (MIP), whose objective is to maximize the NPV, subject to particular constraints during the production period.

These mathematical equations are related to the block model and their solutions consist of answering, at the same time, what and when the blocks should be extracted and which destination they should have. This procedure is not incremental, that is, all decisions are taken observing their implication in other periods. Thus, this method emphasizes the temporality of the problem and the opportunity cost, as opposed to the traditional methodology by nested pits. As a result, DBS is able to deliver better results than traditional methodology. Figure 1 shows one case where the DBS NPV is higher than the traditional 'Best Case'.



Block Model (Fe)

0	0	0	0.3	0.3	0.3
0	0.6	0	0	0.3	0
0	0	0	0	0	0
0	0	0	0	0	0

RF = 0.7

-4.00	-4.00	-4.00	-3.50	-3.50	-3.50
-4.00	7.00	-4.00	-4.00	-3.50	-4.00
-4.00	-4.00	-4.00	-4.00	-4.00	-4.00
-4.00	-4.00	-4.00	-4.00	-4.00	-4.00

RF = 0.9

-4.00	-4.00	-4.00	-0.50	-0.50	-0.50
-4.00	13.00	-4.00	-4.00	-0.50	-4.00
-4.00	-4.00	-4.00	-4.00	-4.00	-4.00
-4.00	-4.00	-4.00	-4.00	-4.00	-4.00

RF = 1

-4.00	-4.00	-4.00	1.00	1.00	1.00
-4.00	16.00	-4.00	-4.00	1.00	-4.00
-4.00	-4.00	-4.00	-4.00	-4.00	-4.00
-4.00	-4.00	-4.00	-4.00	-4.00	-4.00

"Best Case"

$$NPV = -4 + \frac{-4}{(1.1)} + \frac{-4}{(1.1)^2} + \frac{16}{(1.1)^3} + \frac{1}{(1.1)^4} + \frac{1}{(1.1)^5} + \frac{1}{(1.1)^6} + \frac{1}{(1.1)^7} = 3.46$$

DBS

$$NPV = 1 + \frac{1}{(1.1)} + \frac{1}{(1.1)^2} + \frac{1}{(1.1)^3} + \frac{-4}{(1.1)^4} + \frac{-4}{(1.1)^5} + \frac{-4}{(1.1)^6} + \frac{16}{(1.1)^7} = 4.22$$

Figure 1
Difference between DBS
and 'Best Case' sequencing results.

However, according to Morales *et al.*, (2015), although this approach is theoretically better, it presents computational complexity involved in solving very large mathematical problems. Many papers involving this technique, its application and its variants have already been published (for more detail, see Chicoisne *et al.*,2012; Cullenbine *et.al.*, 2011; Jélvez *et al.*, 2016; Guimarães and Marinho, 2016).

Although already tested in small, simplified or fictitious problems, it is also important to check the feasibility of applying this technique to large real problems.

2. Materials and methods

The development of this work consists of applying, with the same block model and under the same parameters, both the direct block sequencing methodology and the traditional methodology for the resolution of the open pit mine production plan. Being a consolidated software in the industry, *Whittle* was chosen to be used as a representative of traditional planning. Using the DBS technique, the program *Doppler*, developed by Delphos Lab at the University of Chile, was used. In the sequence, the projects were operationalized and the annual planning for the first five years was carried out, both stages performed by *Deswik* mining design software. All the programs used are available in the laboratories where this study was done. Figure 2 exemplifies the work methodology.

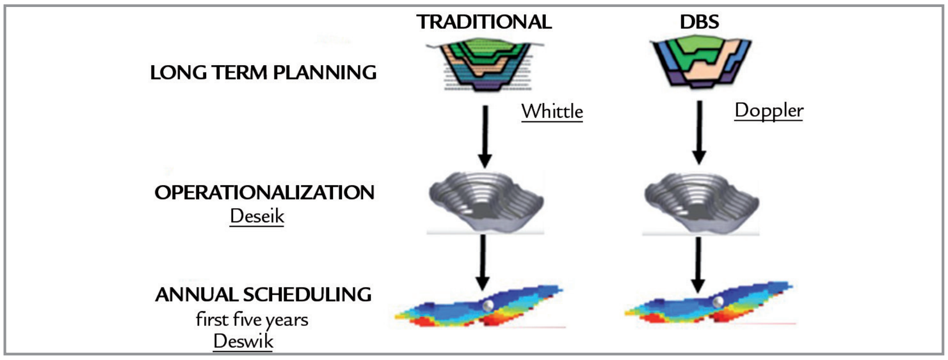


Figure 2
Methodology developed.

The block model used corresponds to an operating iron ore mine, located in Brazil. It consists of 38,172 regular blocks of dimensions 50 x 50 x 20m. For each block, in addition to the coordinates, there are relevant attributes such as tonnage, iron grade and grade of contaminants, possible destinations and their corresponding economic values. The technical and economic parameters applied can be seen in Table 1.

Parameter	Value	Unit
Iron Ore Price	70	US$/ton
Iron Recovery	0.9	-
Selling Cost	18	US$/ton
Processing Cost	9.45	US$/ton
Mining Cost	4.5	US$/ton
Discount Rate	0.1	-
Mining Capacity	55	MTPY
Processing Capacity	36,5	MTPY
Slope Angle	Bearing	Slope
	0 – 120°	45°
	120-240°	35°
	240-360°	30°

Table 1
Technical and economic parameters.

Subsequent to the long-term planning, the operationalization of the projects and the medium-term scheduling were proceeded. The operationalization consisted in designing the feet and crests of the banks, the access ramps, safety berm, etc. (Table 2) that allow the efficient and safe development of mining operations. Some attempts were performed, so that the ones that presented the greatest adhesion with the mathematical ultimate pits were selected to proceed.

		Bearing	Slope
Bench	Face Angle	0 – 120°	60°
		120-240°	45°
		240-360°	40°
	Height(m)	20	
	Berm(m)	10	
Ramp	Width(m)	30	
	Grade(%)	10	
	Radius of curvature(m)	20	

Table 2
Operationalization parameters.

Then, five-year periods were defined, and only the first 5-year pit was operationalized and sequenced in order to verify the operational feasibility of the medium-term annual planning. (As pointed out in the discussion section, DBS tends to pick up blocks in several different regions, which can be harmful to a good medium-term planning). This scheduling was done with great concern in respect to the operational parameters of mining: access to banks closer to the ramp and higher bench levels were considered when defining the mining priorities. Other restrictions considered were: maximum number of excavation resources, their mining and utilization rate and maximum number of mining fronts, as seen in Table 3. For the creation of dependencies, face angle constraints were used and the final objective was to maintain the mining rate at 55 MTPY, with 36.5 MTPY being sent to the processing plant.

Parameters	Value
Number of excavators	4
Excavator mining rate (ton/hour)	1570
Utilization	100%
Maximum mining fronts	4

Table 3
Parameters for medium-term scheduling.

3. Results

As a result of Whittle's strategic planning, a 43-year production plan was obtained with 1.56 billion tons of ore mined, 86 million of waste, and NPV of $ 2.88 billion (Figure 3).

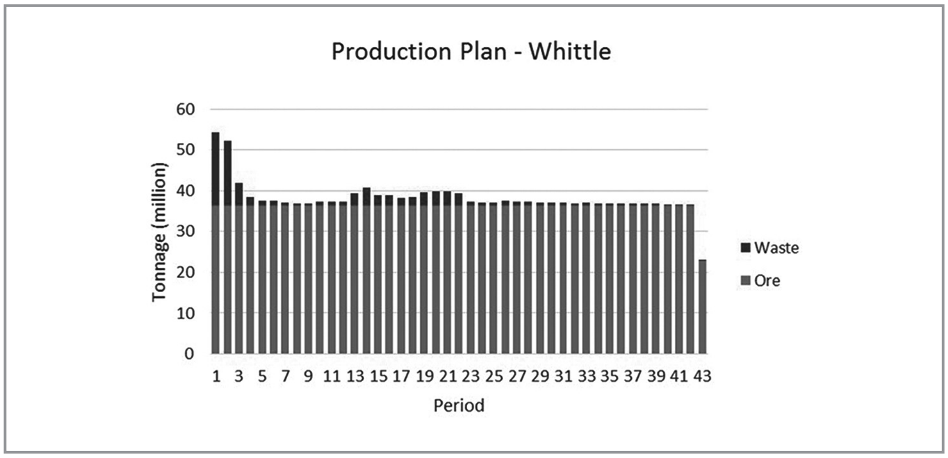


Figure 3
Production Plan developed with Whittle.

The operationalization of the final pit had a 95.4% adhesion with the optimal mathematical pit. In relation to the first five years, the operationalization had adherence of 100.7% and the annual scheduling presented a NPV of 1.01 billion dollars.

Direct block sequencing yielded a 50-year production plan, 1.70 billion tons of ore and 220 million tons of waste, with a NPV of 3.70 billion dollars.

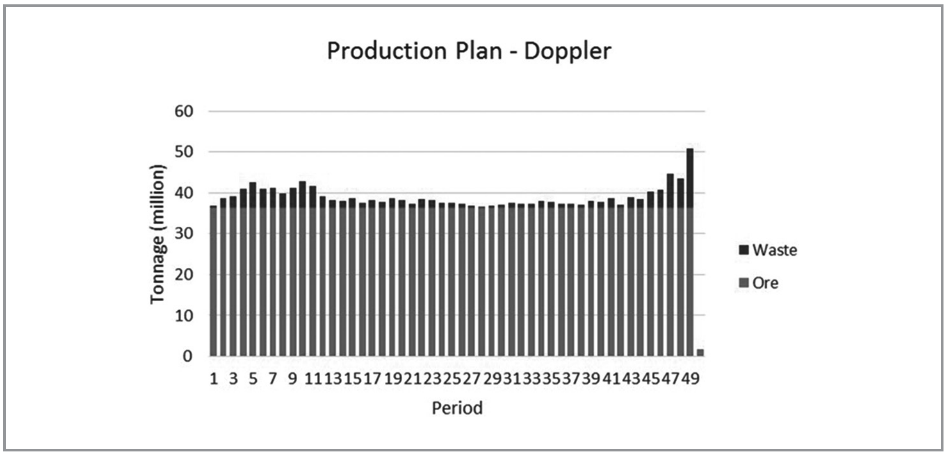


Figure 4
Production Plan with Doppler.

The operationalization of the pit had a 97.7% adherence with the optimal mathematical pit. In relation to the first 5 years, the operationalization had adherence of 83.7% and the annual scheduling presented a NPV of 1.48 billion dollars.

4. Discussion

The production plan generated with Whittle was developed according to what is done by the mineral industry, that is, accomplished through the analysis and experience of the planner, where a feasible production plan with satisfactory economic results was sought. In this case, after generating the nested pits based on revenue factors, the planner opted for a specific set of pushbacks and for the use of the Milawa Balanced algorithm implemented in the software, which always seeks to optimize the use of mining resources. Its operationalization, both of the final pit and for the 5 initial periods, was very satisfactory, with differences due to the inclusion of access ramps and other operational requirements. Finally, the tactical scheduling was performed without many problems, obtaining the result already mentioned. This process follows the standard procedures performed by the mineral industry today.

On the other hand, the technique of direct sequencing of blocks was also used to perform mine planning. The production plan generated by Doppler is based on mixed integer programming and provides the best possible result, respecting the constraints imposed. This means that this process is completely independent of the planner's experience and it is not necessary to find a production plan through trial and error. The result is a greater life-of-mine, higher amounts of ore and waste mined and a higher NPV than the other one. Although there are constraints of maximum slope angle and annual mine and processing capacities, there are still no operational constraints implemented in the software such as maximum horizontal and vertical rate of advance, minimum working width and pit bottom. As a consequence, the result is the scheduling of blocks widely dispersed from one another (Figure 5). If on the one hand this dispersion is economically beneficial, on the other hand it is operationally damaging.

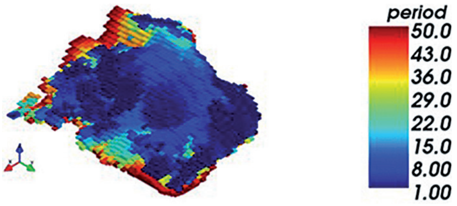


Figure 5
Blocks to be extracted
in each period according to DBS.

Subsequently, the operationalization of the final pit and of the 5 initial periods was performed. Although a satisfactory operation for the final pit was obtained, the 5-year-period pit did not show adequate adherence. This was due to the fact that blocks to be extracted in this period range are distant from each other, making this operation difficult. In Figure 6, one can see the difference in the 5-year operationalization after traditional long-term planning (left) and DBS (right).

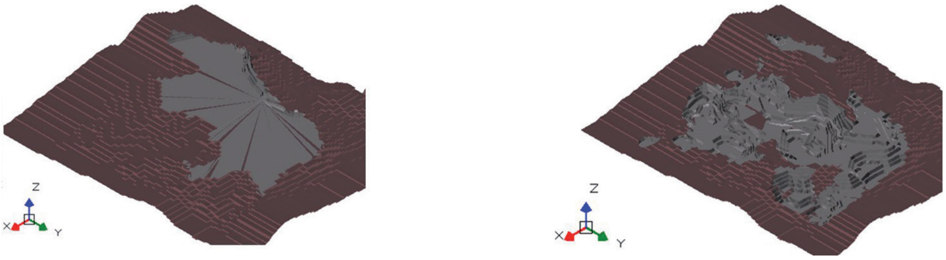


Figure 6
Difference in the 5-year
operationalization. Traditional
long-term planning (left) and DBS (right).

In order to overcome this problem of the dispersed blocks, the tactical sequencing was developed, which has more operational parameters to be obeyed. The operationalized mass resulted in a 7-year sequencing. However, to provide a comparative basis, sequencing was restricted only for the first 5 years, resulting in a higher NPV than the first. It is noted, however, that this is not an adequate practice.

5. Conclusions

The direct block sequencing methodology is capable of providing optimized results and therefore, is economically better than the results provided by the traditional methodology. The reason for this is that its methodology is based on the resolution of representative mathematical equations of the mining planning problem, whose reflex is to obtain results in a single step, without the need for fragmentation into sub problems and, consequently, dependence on the planner's experience in obtaining good results. However, one of the main challenges for the DBS technique is to maintain the resulted sequencing within the minimum operational constraints. For its results to be realistic, mathematical formulations must be adequate, including all types of constraints within a mining operation, and still have to be solved computationally in a timely manner.

Another issue presented was the difficulty of operationalizing the result of the first five years of *Doppler,* which presented questionable adherence despite several attempts. The reason for this is the absence of operational constraints, such as maximum horizontal and vertical rate of advance, minimum width of working bench and minimum depth of pit bottom, which are complex to be modeled and implemented in equations. It is believed, however, that soon this issue will be adequately addressed, given that the development of this technology is recent and that advances are being made exponentially.

Finally, a tactical sequencing of the first five years was carried out, in order to develop a truly operational medium-term planning. While the sequencing of *Whittle's* strategic result was natural, *Doppler* presented an obstacle: the mass to be sequenced over a period of 5 years was a little longer, resulting in a period of 7 years, a fact resulting from the bad operationalization mentioned before. The solution was then to exclude the result of the last 2 years so that it was possible to compare the results of the first 5 years between the two techniques. Once this was done, it was observed that the results obtained from the sequencing of DBS planning presented better economic results, and this time, operationally feasible.

In short, the technique of direct block sequencing still encounters obstacles, but presents a great potential that has been used by researchers in the area. Many advances and discoveries are occurring gradually, and soon it will be ready to play the leading role in the development of mining projects by the industry. While this does not occur, any attempt to take advantage of this technique is valid. In this work, some adjustments had to be made, but in the end the result was satisfactory.

Acknowledgments

To CNPq – Conselho Nacional de Desenvolvimento Científico e Tecnológico and to AMTC – Advanced Mining Technology Center for the financial support.

References

CHICOISNE, R., ESPINOZA, D., GOYCOOLEA, M., MORENO, E., RUBIO, E. A New algorithm for the open-pit mine production scheduling problem. ***Operations Research,*** p. 517-528, 2012.

CULLENBINE, C., WOOD, R. K., NEWMAN, A. A sliding time window heuristic for open pit mine block sequencing. ***Optimization Letters,*** p. 365-377, 2011.

ELKINGTON, T., DURHAM, R. Integrated open pit pushback selection and production capacity optimization. ***Journal of Mining Science***, v. 47, n. 2, p. 177-190, 2011.

GUIMARÃES, O., MARINHO, A. Sequenciamento direto de blocos. In: CONGRESSO BRASILEIRO DE MINA A CÉU ABERTO, 8. 2014.

HUSTRULID, W., KUCHTA, M. ***Open pit mine planning & design.*** Rotterdam: A.A.Balkema, 2006.636p.

JÉLVEZ, E., MORALES, N., NANCEL-PENARD, P., PEYPOUQUET, J. Aggregation heuristic for the open-pit block scheduling problem. ***European Journal of Operational Research,*** p. 1169-1177, 2016.

JOHNSON, T.B. ***Optimum open-pit mine production scheduling.*** Berkeley: Operations Research Department, University of California, , 1968. (PhD Thesis).

LERCHS, H., GROSMANN, I. Optimum design for open pit mines. ***CIM Bulletin,*** v. 58, p. 47–54, 1965.

MORALES, N., JÉLVEZ, E., NANCEL-PENARD, P., MARINHO, A., GUIMARÃES, O. A comparison of conventional and direct block scheduling methods for open pit mine production scheduling. ***Application of Computers and Operations Research in the Mineral Industry,*** p. 1040-1051. Fairbanks, AK: Society for Mining, Metallurgy & Exploration, p. 1040-1051, 2015.

Received: 2 March 2017 - Accepted: 17 October 2017.