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OPTIMUM SEQUENCING OF UNDERGROUND ORE RESERVES FOR DIFFERENT MINING SYSTEMS.

TESIS PARA OPTAR AL GRADO DE MAGÍSTER EN

MINERÍA

MEMORIA PARA OPTAR AL TÍTULO DE INGENIERO CIVIL DE MINAS

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ABSTRACT

Currently, mine plans are optimized by using many criteria, such as profit, life of mine, concentration of some pollutants, mining costs, confidence level or mineral resources, while attending constraints related to production rates, plant capacities and grades. Whilst this approach is successful in terms of producing high value production schedules, it uses a static sequence of production units (for open pit and underground mine) and therefore the optimization is performed within the level of freedom left by the original opening schedule and is far from the optimal value of the project according to the objective function. This approach is often used in the industry and therefore the value addition that is involved when optimizing the mining sequence is disregarded.

This thesis summarizes a research that includes applying a model to optimize the NPV value, as the objective function, in a panel cave mine and evaluating this model with different mining systems, to study the drawpoints opening sequence and the NPV variations. The emphasis is in the precedence, geometrical and production constraints that are required to produce meaningful operational drawpoints opening sequences considering the exploitation method (panel caving), physical considerations and logical rules. Further on, while it applies the standard approach of maximizing NPV, other targets for optimization, such as the mining material handling system, are considered. The idea is to consider the drawpoints opening sequence as an output of the problem and to select the best sequence considering different mining systems.

The results indicate that the selection of the mining system is important when comparing the results of the objective function or the grade. The results can vary up to 18% as shown in the following table (Table 1):

Table 1. Statistics results for all cases studied.

	1 LHD per crosscut	2 LHD per crosscut	Global
Max NPV [MUS$]	1,201	1,181	1,201
Min NPV [MUS$]	986	979	979
Difference [MUS$]	215	202	222
Percent. Diff. [%]	17.9	17.1	18.4

RESUMEN EJECUTIVO

En la actualidad, los planes de producción mineros son optimizados usando diferentes criterios como el beneficio económico, la vida de la mina, la concentración de contaminantes, los costos mina, el nivel de confiabilidad o las reservas mineras, atendiendo a restricciones relacionadas a la producción, capacidades de planta y leyes. Si bien esta aproximación es eficaz en términos de producir planes de producción de alto valor agregado, usa una secuencia de las unidades de producción estática (tanto para minería a cielo abierto como para minería subterránea) y por lo tanto la optimización es realizada con un grado de libertad menos, debido al uso de la secuencia predefinida (secuencia original) y esto está lejos de ser el valor óptimo del proyecto, de acuerdo con la función objetivo utilizada. Esta aproximación se usa a menudo en la industria y por lo tanto, cuando se optimiza la secuencia de explotación de las unidades de producción, el valor agregado involucrado no se percibe.

Esta tesis resume una investigación que incluye la aplicación de un modelo para optimizar el VAN como función objetivo, en una mina de *Panel Caving* y evaluando este modelo para distintos sistemas mineros, de tal forma de estudiar la secuencia de apertura de los puntos de extracción y las variaciones del VAN asociadas. El énfasis se encuentra en las restricciones de precedencia, geométricas y de producción, que son requeridas para producir secuencias de apertura de puntos de extracción significativas considerando el método de explotación (*Panel Caving*), consideraciones físicas y reglas lógicas. Entonces, mientras se aplica la aproximación estándar para maximizar el VAN, se consideran otros *inputs* para la optimización como por ejemplo el sistema minero. La idea es considerar la secuencia de apertura de puntos de extracción como un *output* del problema y seleccionar la mejor secuencia dados distintos sistemas mineros.

Los resultados indican que la selección del sistema minero es importante, ya que los resultados de la función objetivo son muy distintos (así como la ley media) para cada sistema considerado. Los resultados pueden variar hasta un 18% como se muestra en la siguiente tabla (Tabla 1):

Tabla 1. Estadísticas de los resultados para todos los casos estudiados.

	1 LHD por calle prod.	2 LHD por calle prod.	Global
Max. VAN [MUS$]	1.201	1.181	1.201
Min. VAN [MUS$]	986	979	979
Diferencia [MUS$]	215	202	222
Porcent. Dif. [%]	17,9	17,1	18,4

To my mother Cecilia, my father Antonio and my sister Geovanella.

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1. INTRODUCTION

As the mining industry is faced with more and more marginal reserves, it is becoming imperative to generate mine plans which will provide operating strategies and make the industry more competitive (Chanda, 1990). To obtain these strategies, it is important to consider many factors, like mining and processing capacity, geotechnical conditions, precedencies (for activities or exploitation units), grades, pollutants, geology, among others. The mining and processing capacity indicates the maximum production in the mine and in the plant, so these values are determined according to the equipment and the mine scale to achieve. The last one depends on the strategy company and is related with the maximization of the project value, the investments, the profit per year, reserves, among others interests of the owner (company). Geotechnical conditions could be a limitation to achieve the desired production rate and it is not possible to ignore the consequences that could occur if some structure interacts with the extraction. The mine planning should anticipate that effects. Precedencies should be very clear and this set of rules determines the mining method for the exploitation units. In case of activities, it is more logic. For example: If a block has not been blasted, in no case the block could be charged. Grades and pollutants are factors that normally are maximized or minimized to get the best mine plan. All of those factors can be considered to open pit and to underground mining.

In the last 20 years mathematical optimization has been incorporated to the mine planning, to obtain the best solutions for mine planning. The mining business is modeled theoretically, considering mining units. Each mining units has a group of characteristics that are defined as attributes. The model contains components as variables, parameters, objective functions and constraints. The variables normally have been defined by the state of the mining units (mined, processed, or in situ). In some models there are more than one variable, depending on the attribute of mining unit that is necessary to model. The next described component was the parameters that are attributes that don't change in the mining units (eg. grade, tonnage, etc.). The objective function includes the company strategy. In most cases the objective function is NPV, however, this function could be another such as to maximize reserves, to maximize a lineal combination of grades, etc. Finally the constraints permit to model all the factors such as geotechnical, productivity (global and by components), grades, among others. All of them can be written as inequalities.

The construction of the optimization problems has required rational studies of which mining constraints are applicable in each case (Rubio and Diering, 2004). These constraints are important, because they limit the objective function and define the set of feasible solutions. The objective of this construction is to get the best solution using an optimization engine that could search throughout all the feasible solutions that are constrained by the mine design and the geotechnical constraints of a given mining method. Depending on the mining method, the constraints and variables are purposed.

This thesis proposes a novel form to apply the optimization for underground mine planning. Nowadays the mine planning is made considering all the factors mentioned using the optimization as basis. To mine the reserves, a sequence and a system are required and they are the two critical components in the mine planning. Normally these components are selected before the optimization and not necessarily using criteria related with the optimization. This thesis shows the importance of sequence and the mining systems (specifically handling systems) in the objective function results, that is to say, how some changes in this both components influences the objective function result. To find the best solution considering these factors sounds very attractive, because these changes could generated added value (for case of NPV as objective function). The studied method was Panel caving, but it is possible with little changes to obtain results for other mining methods. Panel caving is a good example to demonstrate the importance of the sequence and the mine system in the mine planning. The objective function was NPV. At this point, an important concept that should be explained is the scheduling. The scheduling is the distribution of sequence in periods, that is to say, the sequence only indicates the order, but the scheduling indicates when each block will be extracted respecting the precedencies given by the sequence. To solve the problem, scheduling should be used to make the optimization, because the NPV requires the information about periods extraction. It is important to mention that the objective function does not consider differences for the drawpoints extracted in a period, because they are pondered by the same factor in the objective function.

An example using NPV as objective function is shown in Figure 1. In this example three schedules to extract blocks are evaluated considering the same layout. The layout is represented by the set of blocks and each block has a value that represents its economic. To evaluate the NPV, it is necessary to define periods of time, and which blocks can be extracted in each period, so each different color block represents period of the block extraction. The three NPV are shown and also the variation percentage.

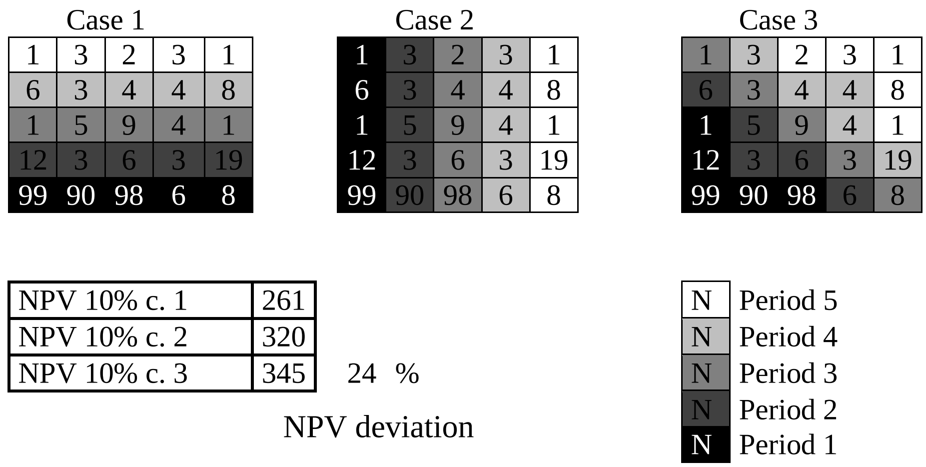

Figure 1. Alternative sequences for a given 2D fixed value block model.

The last example shows for the same set of blocks (layout) important differences for the objective function because the scheduling (also the sequence) is changed.

1.1 Objetives

- Constructing a mathematical optimization model with logic, precedence and capacity constraints for underground mining for panel cave mine.
- Incorporate the sequence as a variable to select the optimal result within the other constraints and variables. Sequence is a result of optimization.
- Incorporate the possible changes to the mining system also with the sequence and find the best combination, as a result of optimization.
- Demonstrate that the sequence changes if some changes in the mining system are made.

1.2 Scopes

- Testing different mining material handling system for the same layout mine.
- Testing the proposed model for Panel Cave mine, considering a real case.
- The objective function will be the NPV without considering investment.
- The material handling components to generate systems are: Crushers, LHDs, chutes (production and vertical transport)

1.3 Methodology

1. Review of existing optimization models for underground mine planning.
2. Pose a new model with new constraints set and variables for underground mine planning, thinking in panel cave mine.
3. Select case study, in this case a Panel cave mine.
4. A real layout for tests is selected and the material quantity and quality per column are an input for the proposed model. The information derived from Best HOD run of a known mine with Gemcom® Software GEMS® 6.1.4, PCBC® module.
5. Case study Block/panel cave mines system.
6. Define the material handling mining systems to evaluate the real layout, based on case study.
7. Testing each mining system considering sensitivity in mining system: number of components, global capacity and capacity per component. For each generated scenario only the best sequence or result is reported according to the objective function, because the model tests all drawpoints as the start point.
8. Results analyses and conclusions.

2. BACKGROUND

2.1 State of the art.

In the last decades tools has been included by mine planning that permits to optimize the results and to get the best result for the objective function, subject to the problem constraints.

A problem close to the one considered in this paper is studied by Chanda (1990), who uses a computerized model for short-term production scheduling, combining simulation with mixed integer programming. The paper studies the problem of scheduling draw points for production, the goal being to reduce as much as possible the fluctuation between periods in the average grade drawn. This model does consider geometric constraints between drawpoints. (For example: precedence).

Jawed (1993) used another model with the same objective function but focused on operational constraints, manpower requirements, extraction capacity, ventilation requirements, plant capacity, and lower bounds on extraction quantity. It was for a room and pillar mine.

Trout (1995) presented a model to optimize the mine production schedule. The model maximized NPV, and it was applied for sublevel stopping with backfill. The model considered the sequencing but the geometric constraints for sequencing of sublevel stoping permit more geometries than panel or block caving.

For panel or block caving, this model is a good start point, but the precedence constraints and capacities should be modified. Also Carlyle and Eaves (2001) carried out a similar study for the Stillwater Mining Company.

Rahal et al. (2003) used a mixed integer linear programming for block caving, to solve an optimization problem. The model used as an objective function the deviation from the ideal draw profile. The model considered constraints of capacity, precedence, material handling and maximum and minimum levels of drawpoint rates.

Kuchta et al. (2004), presented an optimization model to determine an operationally feasible ore extraction sequence that minimizes deviations from planned production quantities. The model used aggregation to optimize long-term production planning at an underground mine. The solution applied for a sublevel caving mine (Kiruna) and geometric precedencies were defined in one direction in the horizontal (enough for sublevel caving, but not enough for block caving or sublevel stopping).

Rubio and Diering (2004) solved another optimization problem, because they maximized NPV, for block caving. The model used two slices to simulate columns in a discrete vertical model and tested the same objective function as in the Rahal paper. The model used precedence constraints, defined only for immediate neighbors. Anything about geometrical precedence does not appear, considering the time, which the predecessors drawpoints are mined.

Sarin and West-Hansen (2005) solved a planning optimization problem with mixed integer linear programming. The model used maximizing NPV as an objective function and adds penalties for deviations for production and quality. It was developed for room and pillar and longwall mining. The model contained constraints of capacity, sequence (constraints for immediate neighbors), and construction.

Queyranne et al (2008) presented a model for block caving that maximized the NPV and used the capacity constraints of mine production, maximum open and active, drawpoints, and neighbor drawpoints. The model considers binary variables, and the drawpoints only can be active in a determined number of periods. Also, the constraints of neighboring drawpoints do not consider a range of time to mine them, but all neighbors are mined in the same period. The model uses a predefined quantity extraction per drawpoint.

Bilbao et al (2009) presented a model that maximizes the NPV. This model incorporates the sequence and can calculate the best sequence to get the optimum. The model considered the following aspects for constraints: laws of physics, connectivity, subsidence, production capacity, rock mechanics, caving speed, drawpoints lifetime, vertical speed and many geometric constraints. The model is a very good approximation, for the optimal solution, but it does not consider the material handling system in the optimization.

Epstein et al (2009) presents a model that includes open pit mining, underground mining and processing plant. The paper shows a network flow representation to represent the relation between components in the model. The model uses a drawpoints as the exploitation unit for underground. The drawpoint is represented as a column composed by a discrete number of blocks. In the model the sequence is an input for a constraint in the model. Others constraints that appear are: Capacity production, max extraction rate per drawpoint, maximum allowed horizontal extraction per sector, planted in terms of areas, not shapes, regularity in heights, interaction with neighborhoods (considering interactive draw). The objective function was to maximize NPV.

This thesis attempts to incorporate sequencing and capacity constraints, locating the sequence in time. To this end, the sequence needs to be limited geometrically. Also it will compare different capacities of mining. The model is based on BOS2 (Vargas et. al, 2009), which is a development of Delphos laboratory for open pit mining. BOS2 is a short-medium term tool for open pit mines, that defines which mining units (blocks) should be mined and how should be mined to maximize the NPV (objective function), considering a processing system (crushers, transport, so the costs and profits for each block). The main constraints are related to slope, connectedness and blending. Obviously it was necessary to adapt the model for underground mining, and add some more constraints.

2.2 Mining systems

A case study of different mining systems (with emphasis in material handling system) from different mining system Block/Panel caving in the world was performed. Below are the studied cases:

2.2.1 Henderson Mine: Level 7.210.[1]

Henderson Mine is located 80 kilometers west of Denver Colorado and 1500 m below the original peak of the overlying Red Mountain. This mine has been producing from the 7210 Production Level since January 2005. The history of Henderson mine production is summarized as follow: In 1976 the production started with the 8,100 production level until 1993. The next level 7,700 was mined from 1992 lasting until 2006. Currently, 7,210 is the level that is mining and all the production of Henderson Mine is scheduled from it. The production of this level is 32,000 tpd. A 150 m by 300 m panel (7700 level Southwest) remains to be developed on the 7700 Production Level.

The 7,210 level layout is similar to the previous two levels, but was designed with several improvements. The 7,210 draw level is located 18.3 m below the undercut level. The drawpoints have an entrance angle of 56 degrees, and are mined in 15 m from both sides leaving a 2 m pillar

[1] The information of this part was obtained from Massmin 2004 (Keskimaki et. al, 2004) and Massmin 2008 (Callahan et. al, 2008)

for added strength. Draw bells are developed by a pattern of 76 mm diameter holes drilled from the undercut level. A “vcut” drill pattern, also composed of 76 mm diameter holes, is drilled from the draw level.

In production level there are 6.7 meter cubic LHDs that feed bins that transfer the ore from this level to the truck haulage level located 44 m below. The LHD production varies between 270 to 300 tph (6,400 to 7,000 tpd). The ore is transferred by 2,1 m bored orepass raises. The raises has 18.5 m long, with an inclination of 60°. The space of ore pass varies from 102 to 130 meters. A single grizzly rail is installed at the top of the orepass raise, limiting rock size running through the orepass to 0.5 m by 1.2 m. In the truck haulage level there are remote controlled trucks that load 72 tonne side dump haul trucks, with a production of 560 tph for the truck fleet, considering an average distance of 1.000 m. These trucks transport the ore to an underground crusher. The haulage level was originally designed as loops with drive-through chutes. This design is currently used in the 11 chutes for the 7210 Production Level that has been constructed to date. Ore is then conveyed to the mill via a three-stage 24 km conveyor system. The haulage roads are constructed of mine muck mixed with cement to create a cost-effective, long lasting and gradable roadway. Dewatering drifts are mined under the haulage level to allow drainage from the truck level and to ventilate the haulage chutes.

A picture of the global mining material handling system is shown in Figure 2. A schematic diagram of unitary handling system is presented in Figure 3. This system considers one chute per two production cross-cuts. Figure 4 and Figure 5 show transport and production levels plans that permit to understand the mine size.

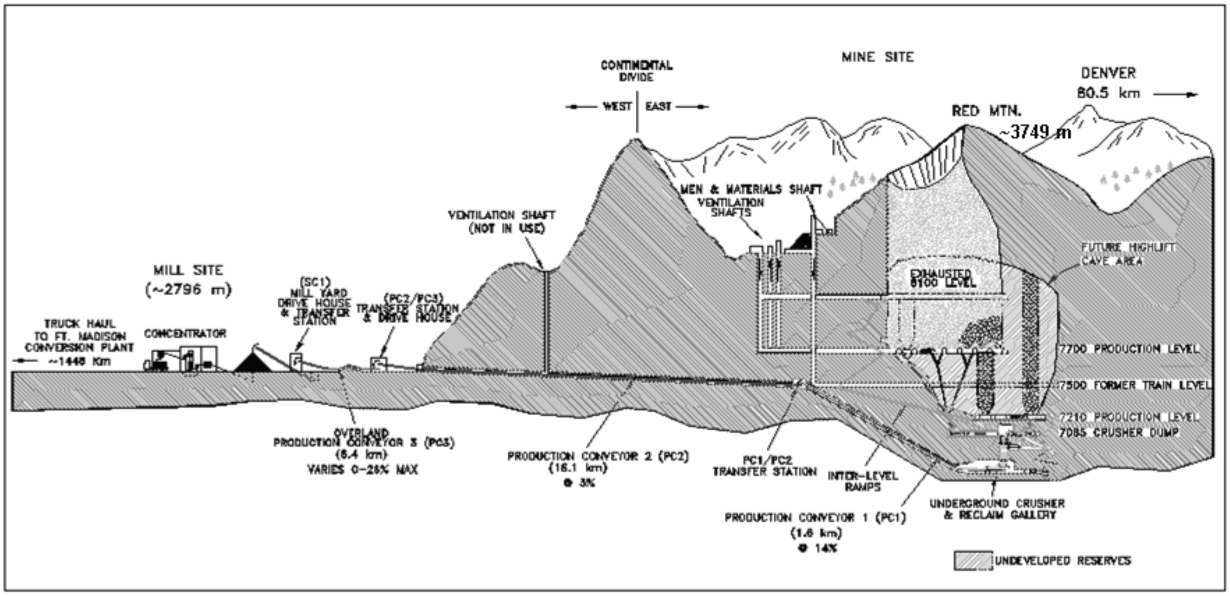

Figure 2. Henderson cross selection.

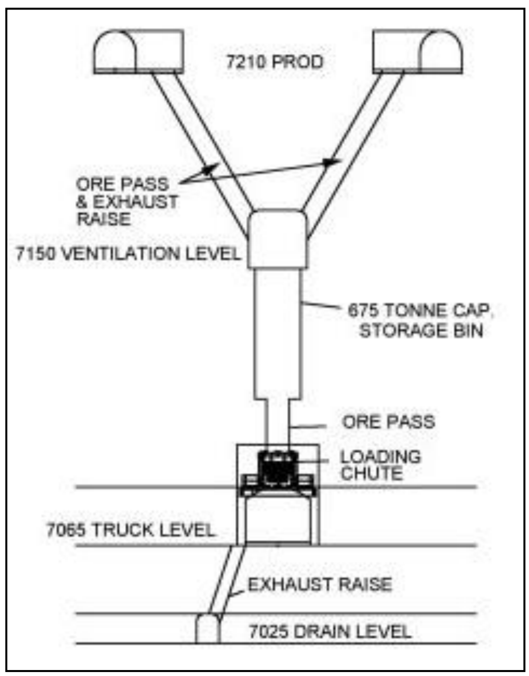

Figure 3. Henderson level 7,210 Mining system.

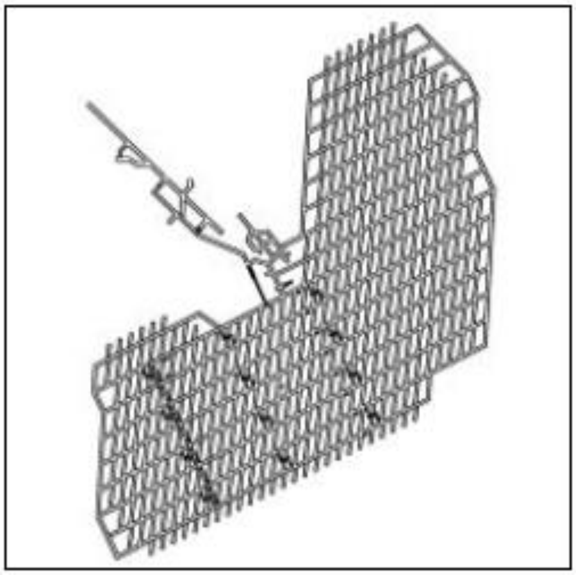

Figure 4. Production level plant Henderson 7.210.

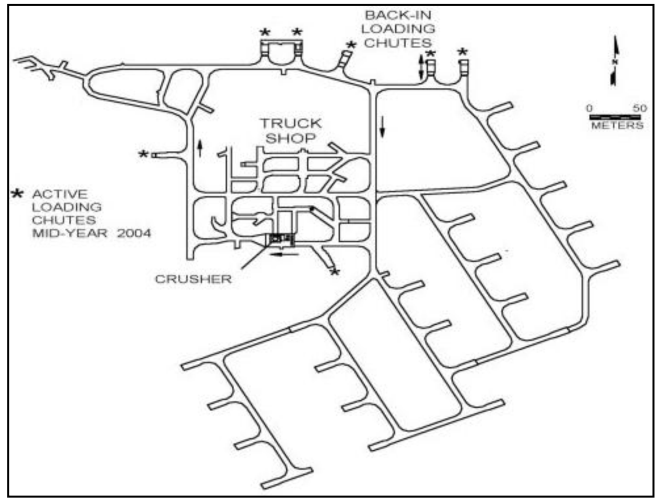

Figure 5. Haulage level plant 7,065 Henderson.

A summary table is presented with the main material handling system parameters: (Table 2)

Table 2. Parameters of material handling system of Henderson Mine.

Distance between undercut and draw level	18.3	[m]
Distance between production level and truck haulage level	44	[m]
LHD capacity	6.7	[m^3]
Number of cross-cuts production	16	
Diameter orepass between bin and production level	2.1	[m]
Orepass spacing	103 to 130	[m]
Transport level	Trucks+conveyor	
Number of loops in transport level	5	
Truck Capacity	72	[tonnes]
Number of chutes	11	
Number of crushers	1	
Conveyor large	24	[Km]
Production mine	32,000	[tpd]

This mine has the principle of having much receipt units and after, by a batch method, continues to a unique receipt unit. This transition does not appear in other mining systems, so testing this system as an alternative to select the best mining material handling system is interesting, because it should be compared with another with less receipt units. For this system only until before the truck level is considered to study with more detail the behavior of production with a lot of units receipt that should comply a production rate individual and global.

2.2.2 Grasberg Mine (2008)[2]

The Grasberg copper-gold deposit is located in the Ertsberg Mining District, in the province of Papua, Indonesia. Current operations in the district include the Grasberg open pit (200 ktpd ore) and the DOZ block cave mine (40 ktpd). The Grasberg open pit is the flagship operation in the district, and when the pit is concluded in 2015[3], the Grasberg block cave mine (GRSBC) will be the primary source of mill feed.

The diluted mineable reserve established for the feasibility study is 983M tonnes @ 1.06% copper, 0.85 g/t gold, and 3 g/t silver (as of January, 2008). The reserve was established using the PC-BC© block cave planning software. PC-BC simulates the block caving process and produces a schedule of predicted mined tonnes and grade (Diering, 2000). The cut-off grade (assuming $1.20/lb Cu, $450/oz Au, and $7.50/oz Ag) was roughly 0.70% copper equivalent (value of gold and silver calculated as copper percent).

The primary access to the mine will be via twin adits, each eight kilometers in length that will be developed from surface at the 2,600 meter level. The tunnels are named the Ali Boediardjo (A.B.)

The mine will be a mechanized block caving operation with a planned peak production rate of 160,000 tonnes per day. Undercutting is initiated in 2016, peak production is forecast by 2023, and closure estimated in about 2037. Maximum drawbell opening rates are eight drawbells per month; maximum draw rates are 0.20 m per day. The sequence has been designed to maximize grade and minimize dilution effects from the toppling of the pit material.

The mine will utilize an advanced undercutting system. Expected draw column heights average 460 meters. A room and pillar advanced undercut is proposed for the mine. Lateral crosscuts are driven over the top of every minor apex. The narrow undercut removes only a narrow opening (4.0 m) between undercut level and cave back.

The extraction level (2,815 m) is based on an "El Teniente" style of layout. Spacing of the panels is 30 meters with drawpoint spacing of 20 meters. The current mine layout is a very large footprint with a diameter of about one kilometer (700,000 m^2) and 2,400 drawpoints. The overall footprint is divided into four Production Blocks, each about 260 meters wide. Ore is delivered to

[2] The information of this part was obtained from Massmin 2004 (Brannon et. al, 2004) and Massmin 2008 (Brannon et. al)
[3] http://www.infomine.com/companies-properties/reports/propertyreport.aspx?pid=21384&part=2&part=5&Submit=View+Report

the haulage level by a series of 4.0m diameter bored raises; the material will pass through the grizzly, with a 1.0m opening, to the haulage level.

The haulage train level (2,775) has four loops and associated with each one of those four crushers. In this level, each train has two 40 ton locomotive sand six trains were considered.

The simulation with Arena ® gave the follow results: 41 LHD operating, 1,100 active drawpoints, 6 trains and each one with 24 wagons (20 ton each one) and four 60” x 89” crushers.

In Figure 6 the production level layout is shown. The layout has 32 production cross-cuts. The transport loops are not parallel to cross-cuts but to the drawbells (Figure 7 shows the loops). In Figure 8 is the material handling system from transport level to bottom. The ore is emptied to the trains to conveyors.

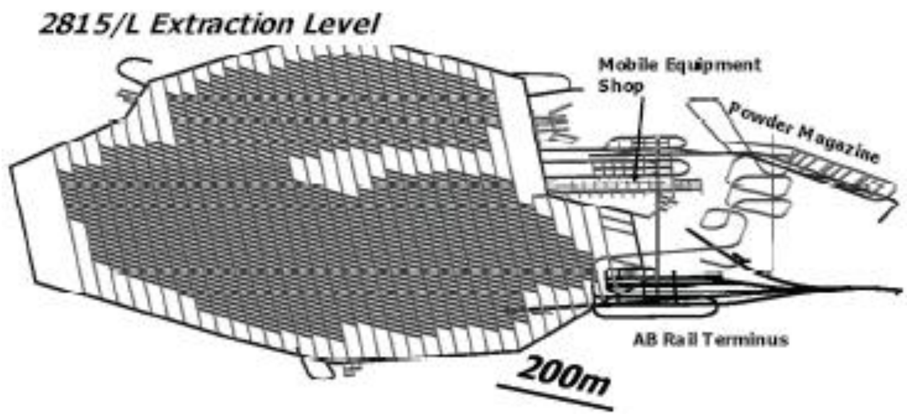

Figure 6. Layout production level with modification Grasberg mine, project 2008.

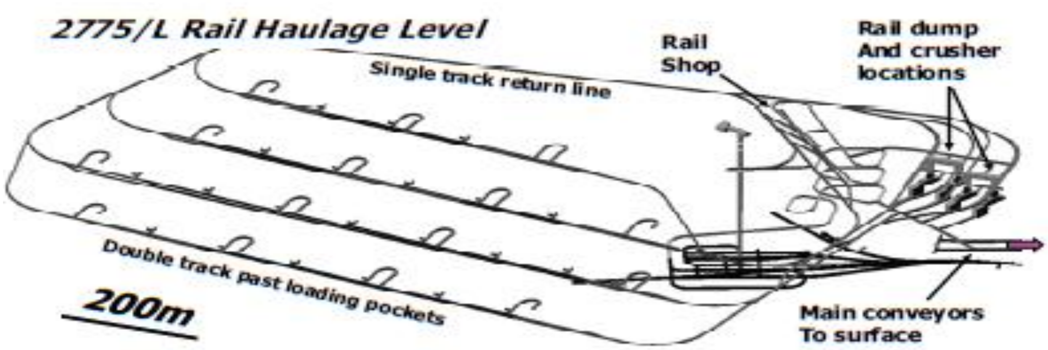

Figure 7. Layout haulage level Grasberg mine, project 2008.

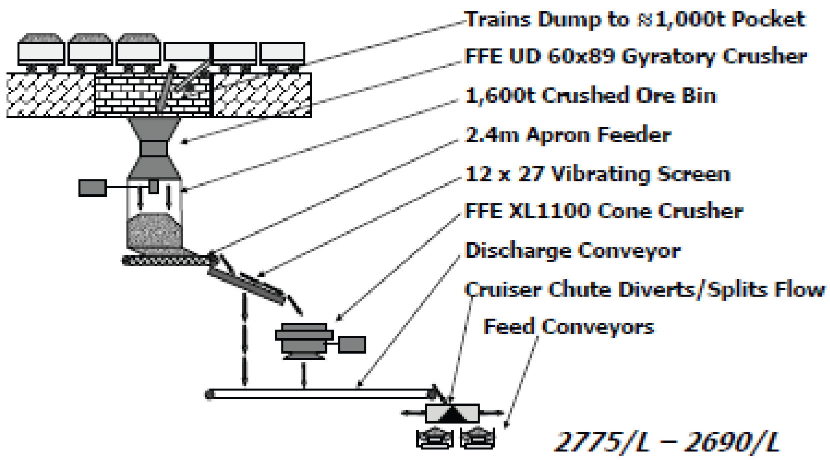

Figure 8. Material handling system Grasberg mine, project 2008.

In the following table (Table 3) there is a summary of the parameters of the mine:

Table 3. Parameters of material handling system of Henderson Mine.

Distance between production level and truck haulage level	40	[m]
LHD capacity	17	[tonne]
Diameter orepass between bin and production level	4	[m]
Transport Level	Train+conveyor	
Number of loops of transport	4	
Bottom-dump muck cars capacity	20	[m^3]
Locomotive capacity	40	[ton]
Locomotives per train	2	
Bottom-dump muck cars per train	24	
Number of trains	6	
Number of chutes	103	
Number of crushers	4	
Crushers	60” x 89”	
Production mine	160,000	[tpd]
Number of drawpoints	2,400	
Drawpoints spacing	20	[m]
Column height average	460	[m]
Draw rate	0.2	[m/d]
Footprint area	700,000	[m^2]

2.2.3 Palabora[4]

Palabora Mine is located in the Northern Province of South Africa about 560 km north east of Johannesburg. Elevation of the pit rim is about 400 m above sea level. Palabora Mining Company

[4] The information of this part was obtained from Massmin 2000 (Calder et. al, 2000).

was originally established as a joint venture between Rio Tinto (formerly RTZ) and Newmont Mining Corporation in 1956 to exploit the copper resource identified around a hill known as Loolekop, where there was archaeological smelting evidence from the 8th century.

Analyses during the feasibility study determined that the optimum grade boundary is 0.8 per cent Cu (Kear, 2000). This cut-off resulted in a mineable reserve of 245 Mt at 0.68 per cent Cu.

Palabora mine is an open pit and an Underground mine. The Underground mine is exploited using block caving.

The drawbells are rectangular with inclined walls and offset between production drives spaced at 34 m and the distance between drawpoints is 17 m. The section for this level is 4.5 m x 4.2 m. In Figure 9 a perforation diagram with these measures is shown.

The undercut level is located at 1,200 m below surface and 460 m below the open pit. The production level is located 18 m below the undercut level. 11 diesel-powered LHD with a 14 t payload muck from the drawpoints directly to four Krupp 1700 mm x 2300 mm jaw crushers located along the northern periphery of the cave. The material is reduced to minus 200 mm. The average one-way length of haul is 175 m. The crushers discharge onto conveyors of 2,000 tph delivering the material to two 5,000 t capacity production shaft silos. The ore is hoisted out the mine using four 32 t payload skips located in the production shaft. The production shaft has a diameter of 7.4 m and a 106 m high concrete headframe. Maximum hoisting capacity is 42,000 tpd. The production level and the sequence are shown in and Figure 10 and Figure 11.

The extraction has a velocity 200 mm/day and the footprint has 126,000 m^2.

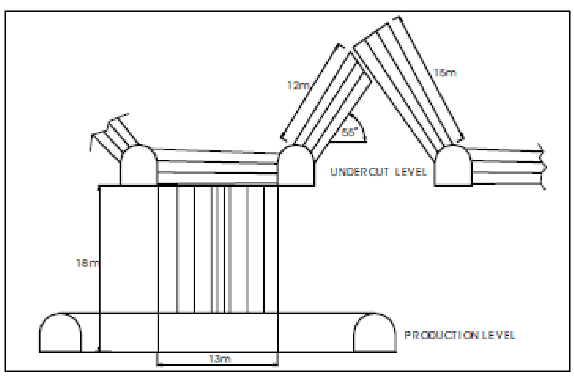

Figure 9. Palabora perforation diagram.

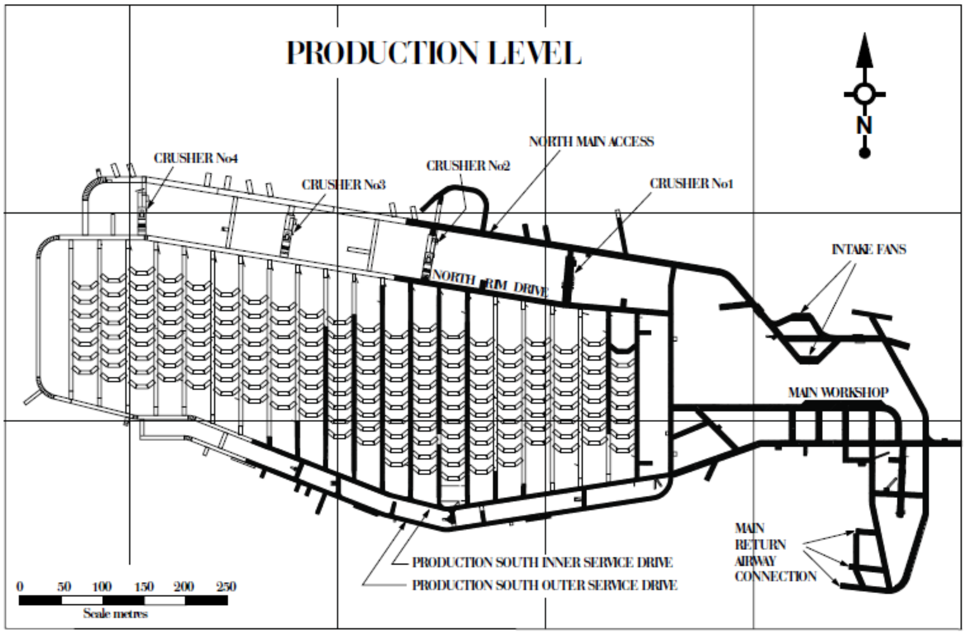

Figure 10. Palabora production level.

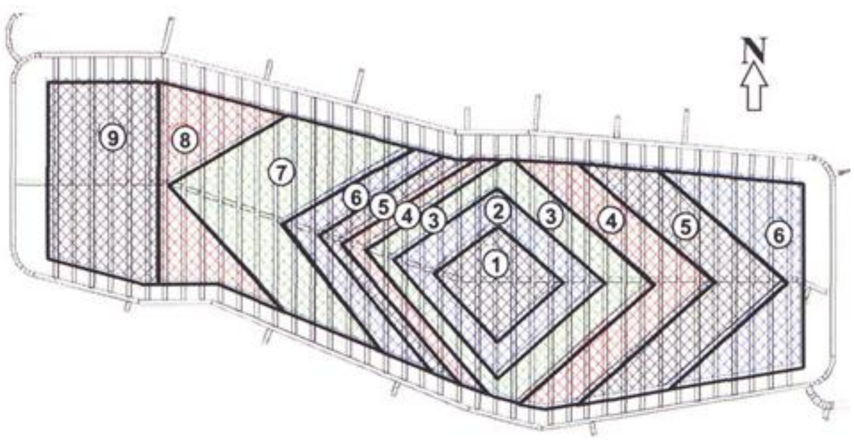

Figure 11. Palabora sequence.

In the following table (Table 4) there is a summary of the parameters of the mine:

Table 4. Parameters of material handling system of Palabora Mine.

Distance between production level and undercut	18	[m]
LHD capacity	14	[tonne]
Number of cross-cuts production	20	
Number of crushers	4	
Crushers	Krupp 1700 mm x 2300 mm jaw crushers.	
Transport system	Conveyor+shaft	
Conveyor capacity	2,000	[tph]
Shaft capacity	42,000	[tpd]
Production shaft diameter	7.4	[m]
Number of skips per shaft	4	
Skip capacity payload	32	[ton]
Production mine	30,000	[tpd]
Number of drawpoints	332	
Drawpoints spacing	17	[m]
Column height average	460	[m]
Draw rate	0.2	[m/d]
Footprint area	126,000	[m^2]

These three cases has been studied because systems are very different in production and in components, so the idea is to generate cases for selecting the material handling system. The variety in mine system is not big, and the other mines has systems very similar to one of the presented systems.

2.3 The program schedule optimization.

This problem has been studied using different techniques to solve it with mathematical programming, but all of these have a common denominator: the constraints. Rubio and Diering (2004) identified which constraints should be included in optimization of scheduling for block caving, which are presented below:

• ***Development rate:*** states the maximum feasible number of draw points to be open at any given time within the schedule horizon. Depends on the existing construction capacity.

• ***Precedencies:*** defines the order in which the draw points will be open. This constraint usually acts on the draw point status, activating those that are at the front of the production face.

• ***Maximum open production area*** at any given time within the production schedule has to be constrained according to the size of the ore body, available infrastructure and equipment availability.

• ***Draw rate*** controls flow of muck at the draw point. Draw rate will define the capacity of the draw point and it needs to be fast enough to avoid compaction and slow enough to avoid air gaps.

• ***Draw ratio*** defines a temporary relationship in tonnage between one draw point and its neighbors. It is important to control dilution.

• ***Capacity constraints:*** forces the mining system to produce the desired production usually keeping it within a range that allows flexibility for potential operational variations.

In this model the ***precedencies constraints*** are a set of two constraints that indicate the maximum number of drawpoints it is possible to advance between two periods in some direction, defining a ratio. Also it defines the number of neighbors drawpoints that is necessary to mine, in a determined time in order to mine any drawpoint. The last two also limit the ***open production area*** in a period and the ***Draw Ratio*** and also guarantee the ***connectivity*** between drawpoints year to year.

The ***draw rate*** constraint corresponds to the production capacity of each drawpoint.

The ***capacities constraints*** limit the mine capacity and subunits of the mining system such as cross-cut capacity.

The ***development rate*** also is considered as a constraint considering the number of constructed drawpoints in a period.

The variables can be integers or real. Normally, the integer variables are used to indicate the state of a point, specifically, if the point is open or not. The real variables are used to specify how much tonnage of a draw point has been extracted. The logical constraints allow these two variables to coexist.

This model will use the maximization of NPV in ranking the scenarios. Every drawpoint of layout will be evaluated and the idea is to determine the best sequences. Obviously, the objective function could be changed. For example: To maximize reserves, to maintain in a range the grades, etc.

3. THE MODEL

The model formulated in the research has been conceptualized for a panel cave mine having several capacity constraints at the production cross-cuts. The model integrates the individual value of a draw point derived from a pre-mixing algorithm that simulates the vertical flow as well as the economic benefits of withdrawing a draw point and its column. There are geometric constraints that can be applied to the neighbors, so that the advancing front results similar to the ones present in a panel caving mine. Although the model has been designed for panel caving, this model could be applied to any underground mine.

Some concepts should be introduced before continuing with the model description:

Drawpoint: Is the mining unit for panel caving. A drawpoint has an associated infrastructure as a drawbell to collect the material and this material is recollected by an LHD or another system. The drawpoint contains all the fractured material after blasting, and the material fracture is produced by the propagation of the initial blasting. After the fracture (by propagation) the material falls gravitationally. The term column is used to refer to the material associated with the drawpoint.

Horizon: Corresponds to the total time considered for the mine planning. According to the size of the time, horizon can be classified in three types: Long-term (for mine planning for long interval times), medium-term (for mine planning for medium interval times) and shot-term (for mine planning for short interval times). It is a measure of how far in time it is wanted to plan.

Period: Corresponds to a unit of time that the mine planning is done. The selection depends on the detailed knowledge that the mine planner wants to know. Examples for periods are: years, months, semester, day, etc. The selection also is related with the mine planning horizon level: long term, short term or medium therm. For the long term the preferred units are big as years, decades, etc. For short-term mine planning period considered can be day, month, etc.

Front cave line: Corresponds to the contour of the mined drawpoints set, geometrically in plant in some moment. The line should be studied in different times.

Advance: Corresponds to the movement of the front cave line.

Neighbor drawpoints: Correspond to the drawpoints that achieve the proximity condition from a determined drawpoint. This condition is determined by the mine planner with some criteria. The information of the neighbors of the drawpoints can be important to control the dilution and to have a good stability.

Capacity: Corresponds to the maximum production of the some unit of the mining system or the global system.

Ramp Up: Is the part of horizon when the operation is starting, so the production rates should be growing. Normally in this stage the open area is small and this is a limitation for the production rate.

Open drawpoint: Corresponds to the drawpoint that is ready to be mined. The entire associated infrastructure is ready.

Active drawpoint: Corresponds to the drawpoint that is being mined. The drawpoint had to open in a previous period or the drawpoint mining can start immediately after the drawpoint opening.

For the model description is considered a set called B that contains all the drawpoints, and T, the horizon time.

3.1 Variables

The model considers two set of variables. The first indicates when the drawpoint is open. It is a binary variable, that is zero when the drawpoint has not been open and it changes to 1, when the drawpoint is open. The second variable is a real number that represents the percentage of column extracted until period t. Formally:

$$m_{bt} = \begin{cases} 1 & if\ the\ drawpoint\ b\ is\ opened\ at\ 1 \ldots t \\ 0 & otherwise \end{cases} \tag{1}$$

$$e_{bt} = percentage\ of\ column\ mined\ from\ drawpoint\ b\ until\ period\ t.$$
$$p_{bt} = percentage\ of\ column\ processed\ from\ drawpoint\ b\ until\ period\ t.$$

$$e_{bt} \in [0,1], \forall\ b \in B, \forall\ t \in \{1,2,3, \ldots, T\} \tag{2}$$

It is useful to introduce the following notation: $\bar{m}_{bt} = m_{bt} - m_{b,t-1}$, which is equal to 1, if and only if drawpoint b is open exactly at time period t. Similarly, the auxiliary variable $\bar{e}_{bt} = e_{bt} - e_{b,t-1}$ represents the percentage of column b that is extracted at t.

3.2 Logical constraints

These constraints establish the basic relations between the variables and mainly state that drawpoints can be open only once, and that material can be extracted only up to 100%. For each $b \in B, t = 1, \dots, T-1$:

$$m_{b,t} \leq m_{b,t+1} \tag{3}$$
$$e_{b,t} \leq e_{b,t+1} \tag{4}$$

3.3 Production Constraints

Production constraints are related to physical and economical limitations of the mine operation, like the maximum amount of tonnage to be extracted per time period, or the minimum amount of material to extract for an open drawpoint.

The overall mine capacity constraint limits the total amount of mineral to be extracted in the mine for each time period. Considering that each drawpoint has a tonnage $ton(r)$, and an upper limit of M^+ tons for the mine, the constraint reads:

$$\sum_{b \in B} ton(b)\ \bar{e}_{bt} \leq M^+ \quad (\forall t = 1, \dots, T) \tag{5}$$

Similarly, it is possible to constrain the total number of drawpoints to be open at each time period:

$$\sum_{b \in B} \bar{m}_{bt} \ \leq P^+ \quad (\forall t = 1, \dots, T) \tag{6}$$

Notice that these constraints do not consider the ramp up and ramp down. But P^+ could be defined for any period as $P^+(t)$, setting different capacities for any period, resulting the ramp up and ramp down.

Apart from the above mentioned case, the model also considers to constraint the production of subsets of the set of drawpoints. For example: in case of a subset of points of cross-cuts, it is possible to define an upper bound M_c^+ like the capacity per cross-cut c and C is the number of cross-cuts of layout. In this case the constraint is:

$$\sum_{b\in B_c} ton(b)\ \bar{e}_{bt} \le M_c^+ \quad (\forall c = 1, 2, \dots, C)(\forall t = 1, 2, \dots, T) \tag{7}$$
$$\bigcup_{c=1}^{C} B_c = B \ \wedge\ B_c \subset B\ (\forall\ c = 1,2, \dots, C)$$
$$B_i \cap B_j = \emptyset \quad (\forall\ i, j = 1, 2, \dots, C)\ (i \neq j)$$

Where B_C is a set of blocks belonging to cross-cut c, and Based on the last constraint it is possible to define the same constraint for the components of the mining system: crushers and chutes, and overall these constraints model the mining system downstream. In cases of the crushers and chutes, the subsets have to be not necessarily disjoints.

In Figure 12 two examples are shown. The left one shows an example with four cross-cuts, so four subsets: B_1, B_2, B_3 and B_4. Each subset contains a group of drawpoints that will be constrained in production. The right one shows case where the drawpoints are grouped by the crusher where the material is emptied. So all the drawpoints that empties their material into the crusher one, belong to the subset B_1 (The nomenclature is maintained to be consistent). In the example two crushers are shown and each crusher is fed by two cross-cuts, so the subset results as in Figure.

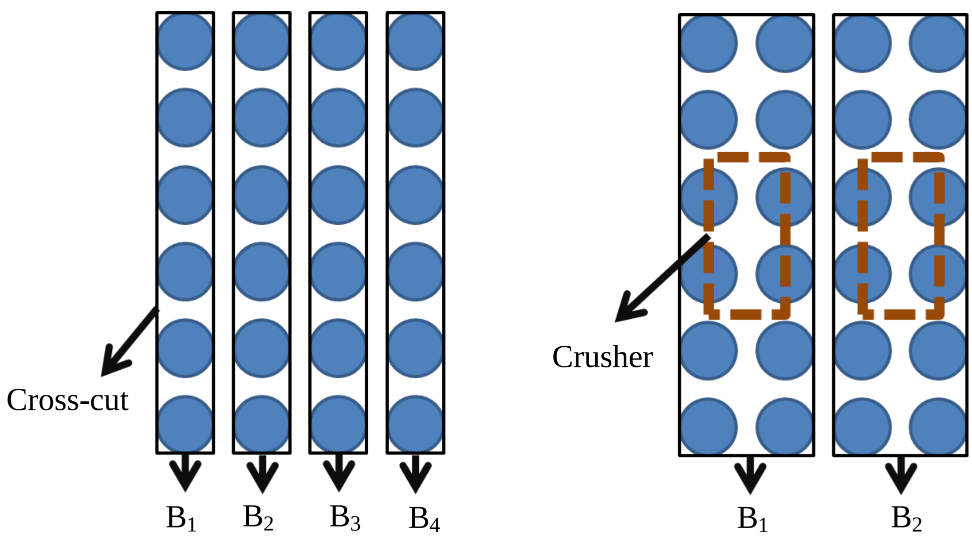

Figure 12. Example of drawpoints subsets to apply production constraints: The left Figure shows the subsets for case of cross-cuts and the right Figure shows case of crushers.

Other constraint considers the capacity limit per drawpoint. This constraint therefore considers a limit M_b^+: the maximum production capacity per drawpoint.

$$ton(b)\ \bar{e}_{bt} \leq M_b^{+} \ \ (\forall b \in B)(\forall t = 1, \dots, T) \tag{8}$$

There is also a constraint limiting the minimum percent $\mathbf{L} \in [\mathbf{0}, \mathbf{1}]$ to extract from a column if the drawpoint is open. Notice that this constraint bounds the final percentage mined from the column (hence the right sight had sub index **T**).

$$m_{bt}L \leq e_{bT} \ \ (\forall b \in B)(\forall t = 1, \dots, T) \tag{9}$$

To explain this constraint Figure 13 shows three possible cases given an open drawpoint. The condition is evaluated in T, the last period in mining. The white rectangle represents a drawpoint and the red part represents the part of drawpoint mined in period T. The percentage L has been marked, to show which case satisfy the condition of to be mined at least L% until period T. The third one (from left to right) doesn´t satisfy this condition.

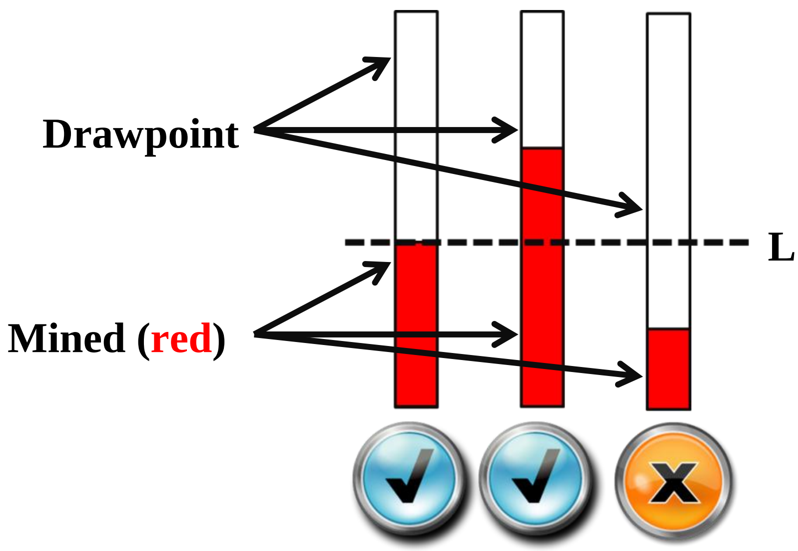

Figure 13. Feasible and unfeasible situations given that a drawpoint is open.

Finally, we consider the lifetime of a drawpoint and as the upper bound A_b in the number of period it can be operational since it is open. This is expressed as:

$$\bar{e}_{b,s} \leq \bar{m}_{bt} \ \ (\forall b \in B)(\forall s = t + A_b, \dots, T) \tag{10}$$

In Figure 14, a cycle of a drawpoint is shown between the drawpoint is open until is closed. The cycle has the same convention than in Figure 13, and indicates how much time should take the drawpoint mining.

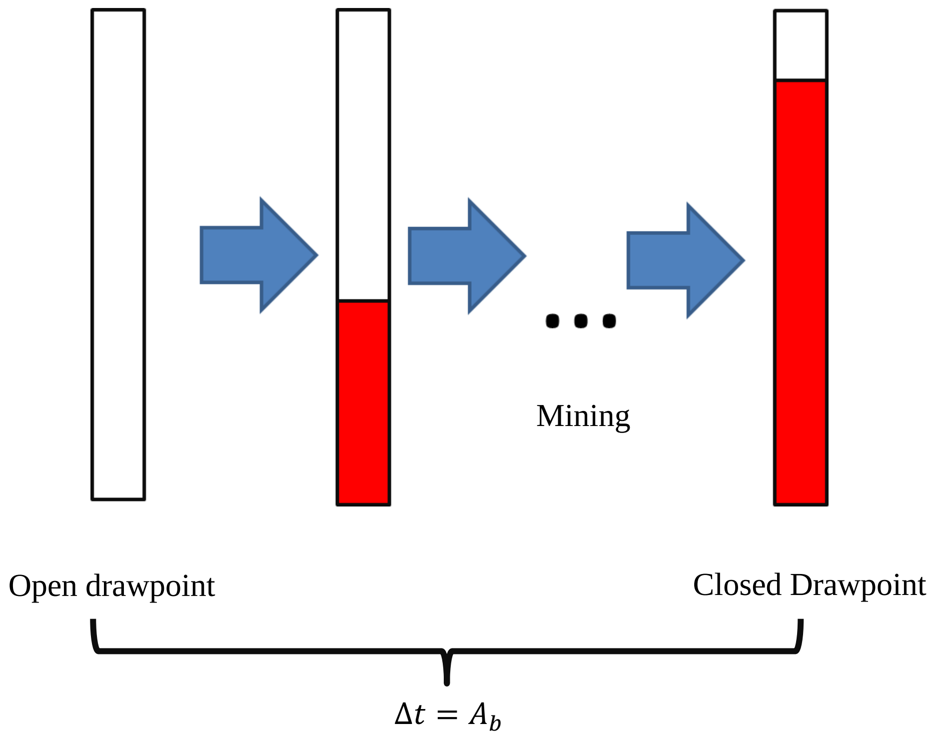

Figure 14. Maximum interval of periods for the activity of drawpoints

3.4 Geometric constraints

This set of constraints limits the order in which the drawpoints are open, so this is consistent with technology and geomechanics. The front cave line behavior in time is constrained to prevent dilution and collapses. To achieve this, the study of front cave line shape in any time is necessary. The model considers two types of constraints in this category: a) connectivity constraints and b) shape constraints.

To impose these constraints, the model considers a graph whose nodes are the drawpoints. Two drawpoints are connected in the graph if they are close enough (for a certain distance tolerance).

The connectivity constraints force the drawpoints to be connected, that is, there are not isolated open drawpoints. This is enforced by considering a set of access points from where to start the exploitation is given, so it is possible to calculate a connected path:

$P(b) = (b_1, b_2, b_3, \dots, b_{k-1}, b_k)$ with $b_k = b$ that goes from the (unique) access of drawpont b to drawpoint b. If $prec(b)$ denotes b_{k-1} in the path, the connectivity constraint is therefore:

$$m_{b,t} \leq m_{prec(b),t} \quad (\forall b \in B)(\forall t = 1, \dots, T) \tag{11}$$

The model considers also two shape constraints. The first one limits the progress of the front cave line. This constraint does not provide case where the front cave line is broken (discontinuities). This case is covered with other constraint that will explain later.

$$\begin{gathered} m_{b+d,t} \leq m_{b,t} \ \ \forall\, t \leq T \\ m_{h,1} = 0\ if\ h > d \end{gathered} \tag{11}$$

Figure 15 shows an example of this constraint. In Figure, the circles represent the drawpoints, and the color represents period in which the drawpoint should be mined. The arrows represent the feasible directions to advance, given the starting point. Yellow circle marks the starting point. Two scenarios are shown: The left one considers maximum advance 1 (drawpoint) per period. This means that given the front cave line of the previous period, in the next period this line should not move more than one drawpoint distance, considering the perpendicular distance between the consecutive font cave lines. The right one shows the front cave line advance, when this line move quicker than in the last case, because the maximum advance is two drawpoints, but not necessarily the advance should be always two drawpoints.

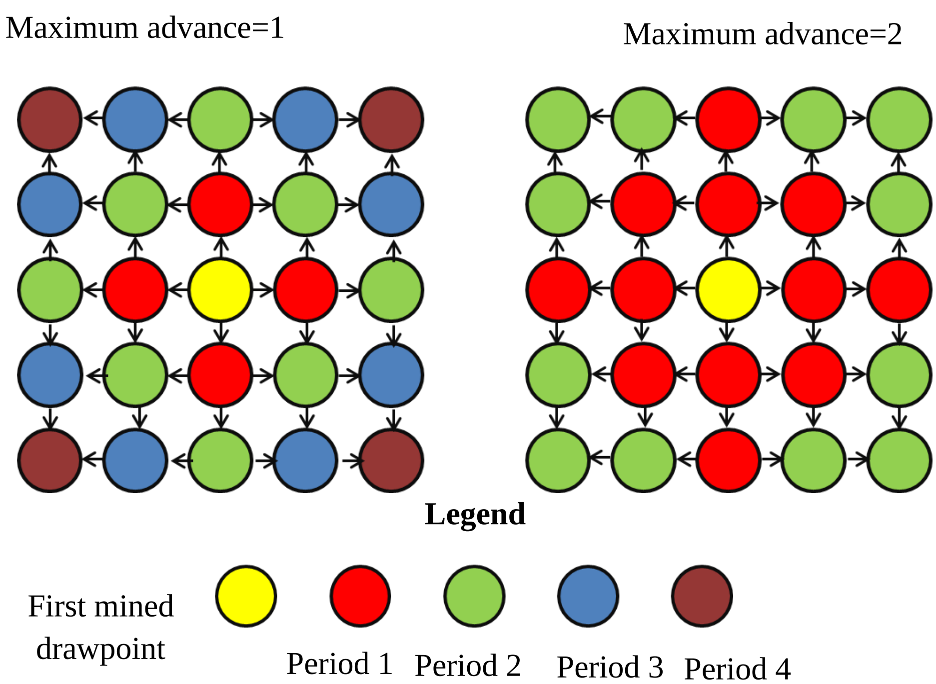

Figure 15. Example of maximum advance constraint.

The second type of shape constraints forces that not only drawpoint cannot in an isolated manner, but also that the opening of a drawpoint forces also neighboring drawpoints to be open too. Again, in the connectivity graph described before, let $\mathcal{N}_N(b)$ be the set of drawpoints that are neighbors of (connected to) b. This constraint takes also two parameters: K, which is the number of neighbors for a drawpoint to be mined, and Δ, that corresponds to an aditionnal time to do the mining of all the neighbors of some drawpoint. The constraint is:

$$Km_{it} \leq \sum_{j \in \mathcal{N}_N(i)} m_{j,t+\Delta} \tag{12}$$

Where $\#\mathcal{N}_N(i)$is number of elements of $\mathcal{N}_N(i)$.

In Figure 16 an example of this constraint is shown. Each circle represents a drawpoint. If the circle is black the drawpoint is mined and if the circle is light blue the drawpoint has not been mined yet. In the example three moments are shown to illustrate the how the constraint operates. The most important moments is the last one, so another combination for mining for the first two moments are feasible, because the constraint permits that the block i to be mined in t, provided that all there neigbours were mined until $t + \Delta$ (before is ok). In this example $t = 2$ does not have importance, because the constraint is applied on $t = 3$. Even it is possible that in $t = 2$ nothing happens, provided that in $t = 3$ all the neighbors are mined.

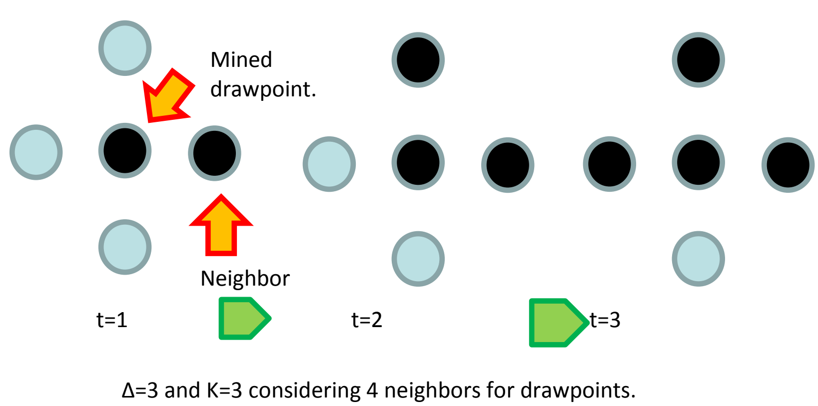

Figure 16.Example of Minimum neighbors constraint.

3.5 Firsts tests: Maximum advance and minimum neighbors.

3.5.1 Maximum advance

In following part the tests related with maximum advance constraints are shown for different values.

The four next Figures (17 to 20) show the changes in the opening sequence when the parameter D is changed. Figure 17 shows an exaggerated case where it is only possible to advance one drawpoint in perpendicular direction to the perimeter of front cave lines. Given that the planning horizon was 13 years after that the drawpoints appears with code “100”, that means that they weren´t open. The next Figures show periods with more open drawpoints, because D value increases. One consequence is that the opening is finished in earlier periods. The idea is to select D value according to the layout and in this case five is a good value because indicates that the layout could be open at least in four years, because the layout has twenty cross-cut (five drawpoints in the east-west direction means 10 crosscuts, the half of twenty, but not necessarily all cross-cut should be open, it depends on to the shape of the cave line).

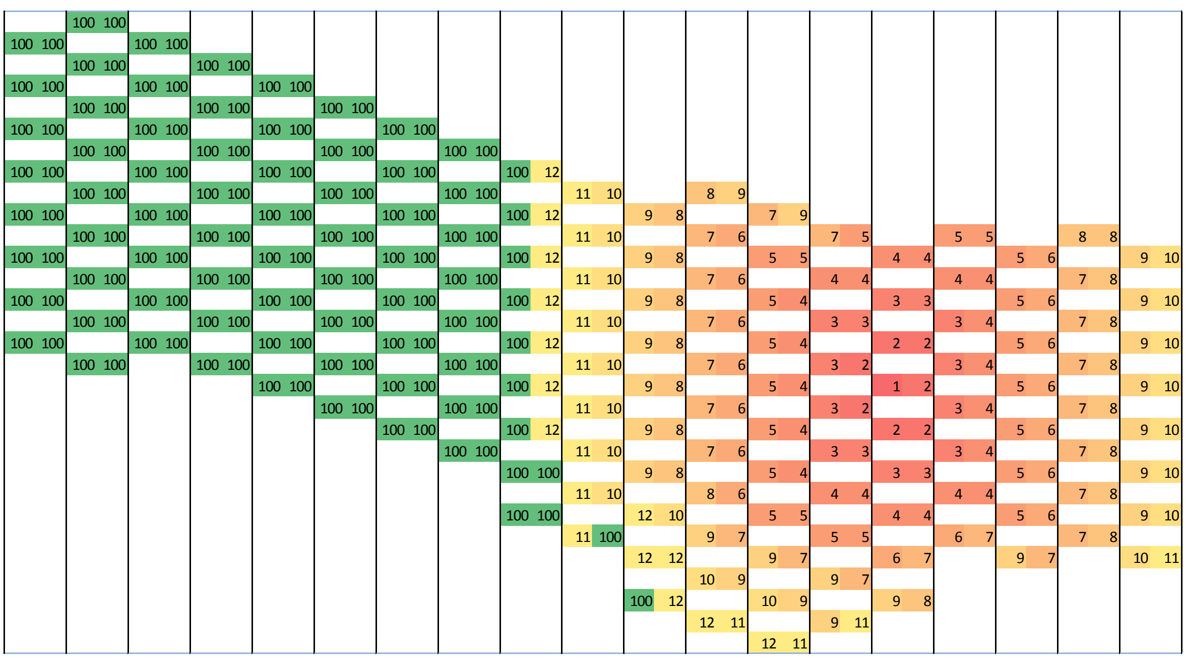

Figure 17. Layout with maximum advance with D=1.

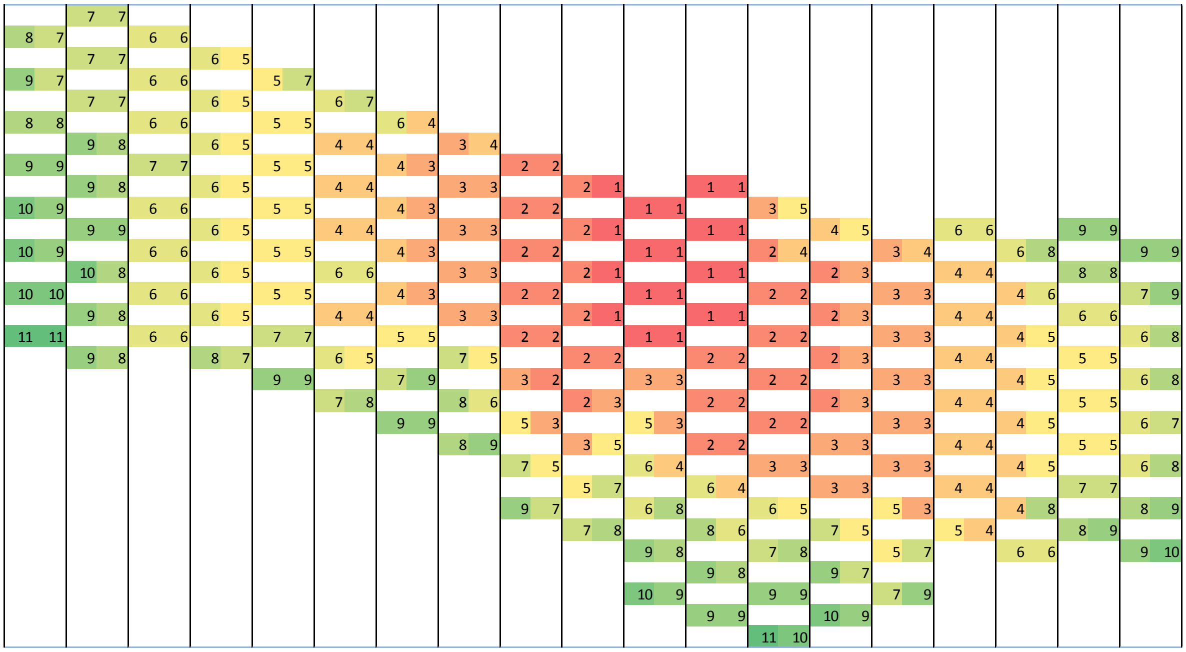

Figure 18.Layout with maximum advance with D=3.

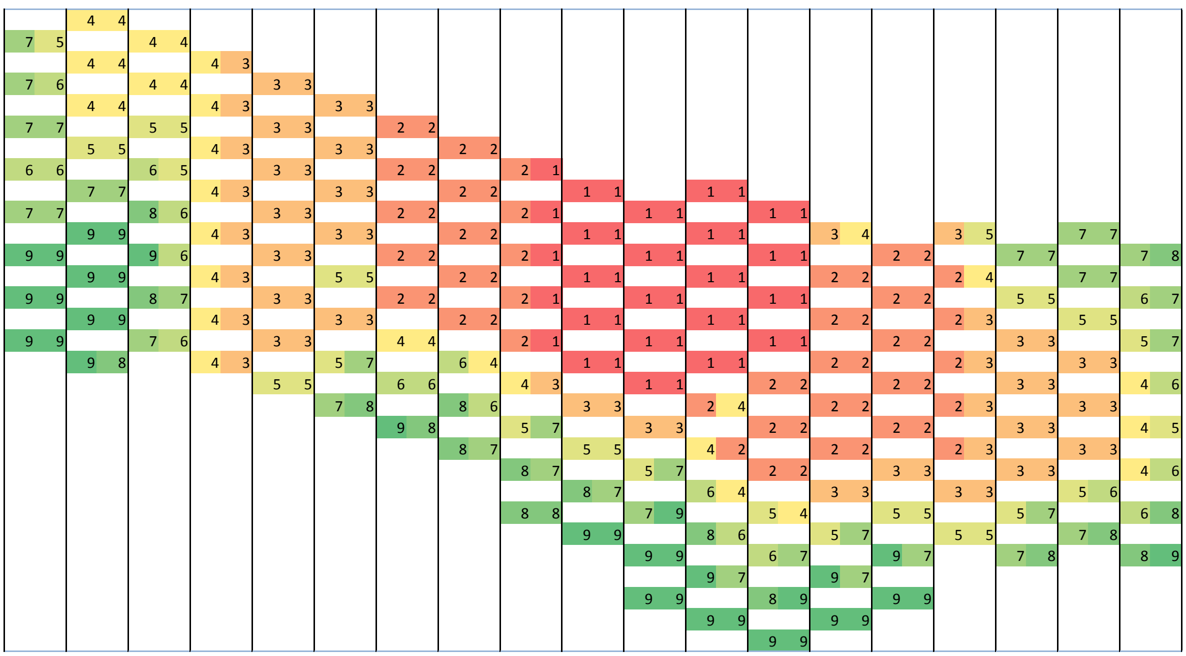

Figure 19. Layout with maximum advance with D=5.

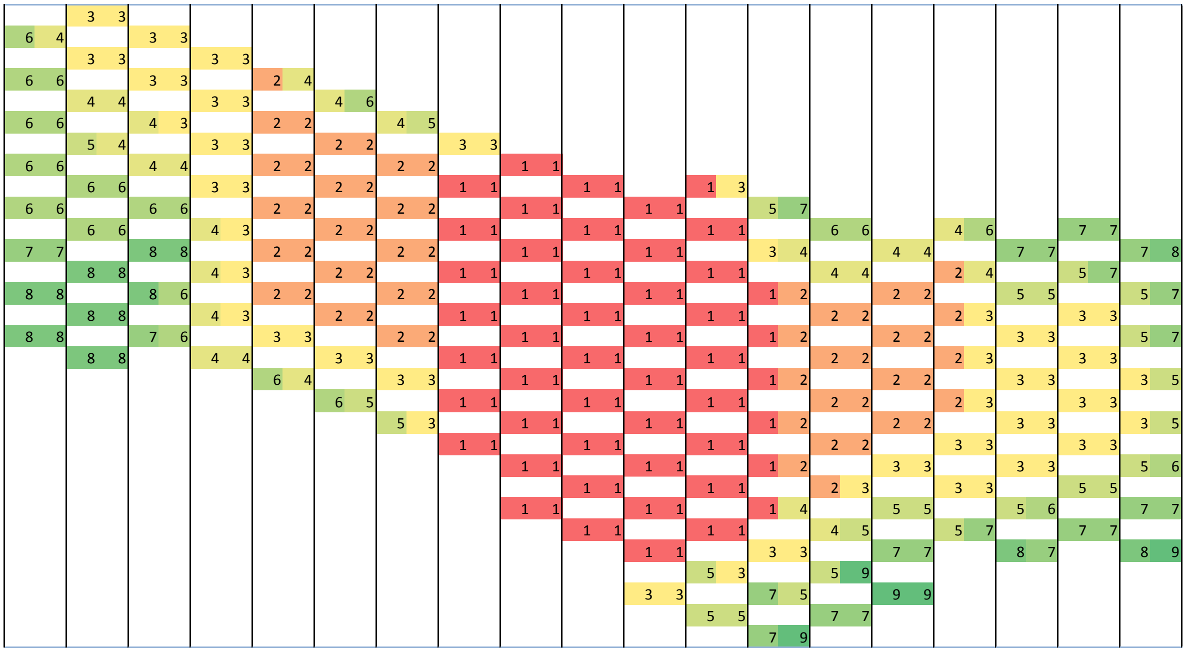

Figure 20. Layout with maximum advance with D=6.

In Figure 21 and Figure 22, polygons that represents the open drawpoints are shown, to demonstrate the difference in the front cave line if the parameter maximum advance is changed. The area tends to grow up when “maximum advance” grows.

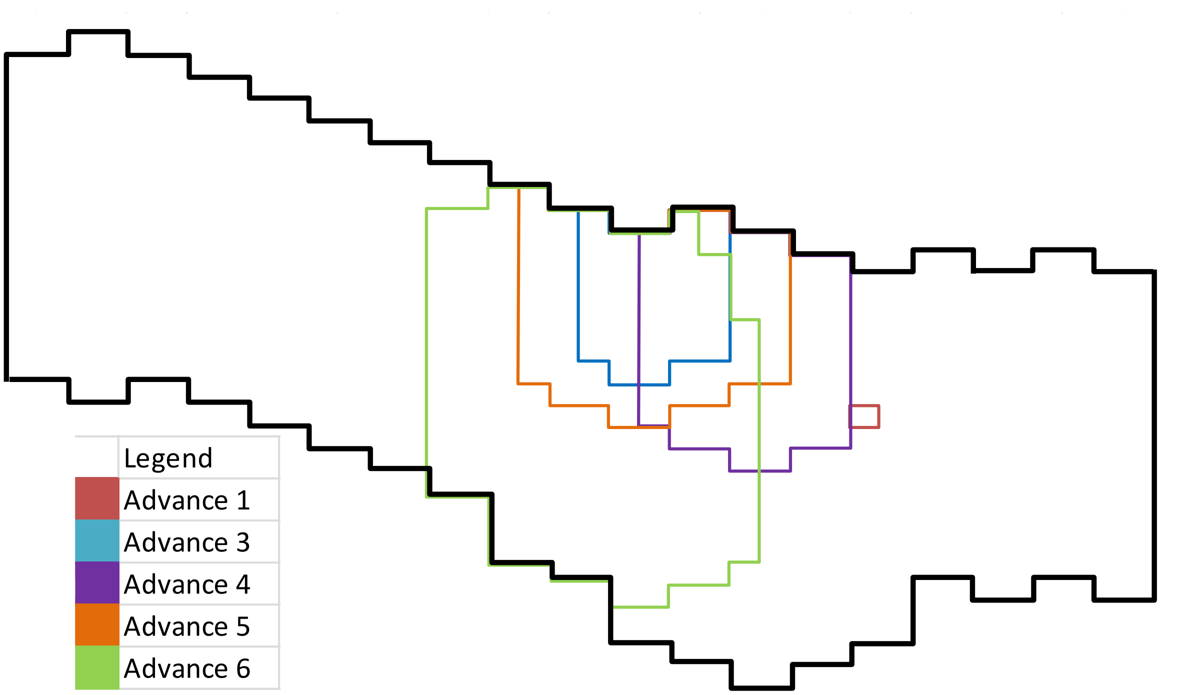

Figure 21. Comparing sequences with different “maximum advance” for year 1

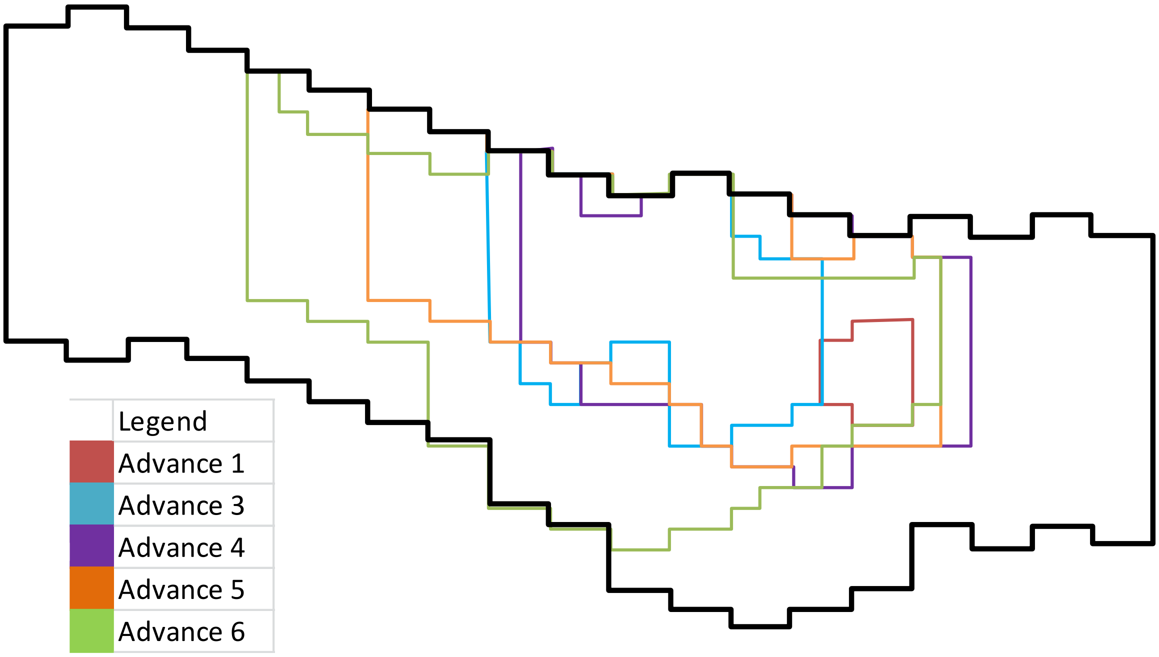

Figure 22. Comparing sequences with different "maximum advance" for year 2.

3.5.2 Minimum neighbors

Figures 23 to 28 show the effects of changing the minimum neighbors value K in the respective constraint. A low K value (K=1) indicates that any drawpoint can be open in any moment. This value is the same to have the case without this constraint. In the next Figures, it is possible to view the behavior of the sequence when K increases. Following the above idea, the high K values permit that the opening is more regular geometrically, and the cave lines are clearer. The transition between regular and irregular shapes is with K greater than three, but less than seven, because seven is the number of neighbors per drawpoint. Seven also is exaggerated, because it implies that is necessary to open ALL the neighbors to open one drawpoint. In this case the value for the test will be K=6, because it warrants regular cave lines and gives more options to complete the minimum neighbors. In Figures 27 and 28 the cave lines have more area when K is smaller, and when K grows the area is smaller. The difference is noted in the first years.

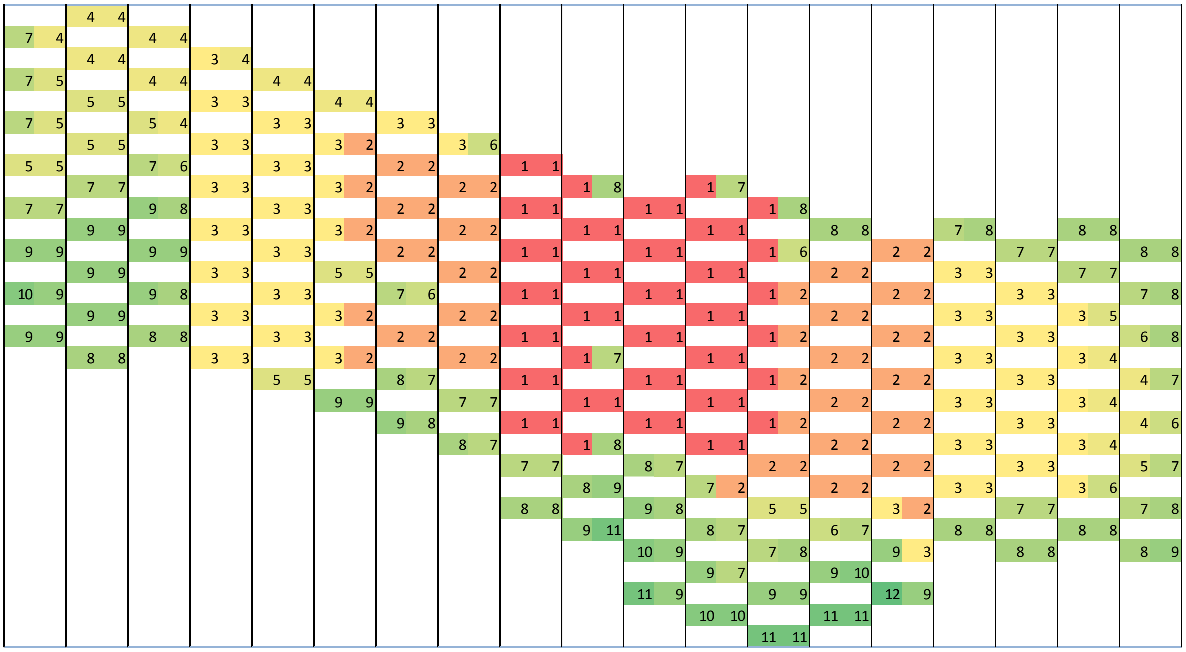

Figure 23. Layout with minimum neighbors set with K=1 and Δ=2.

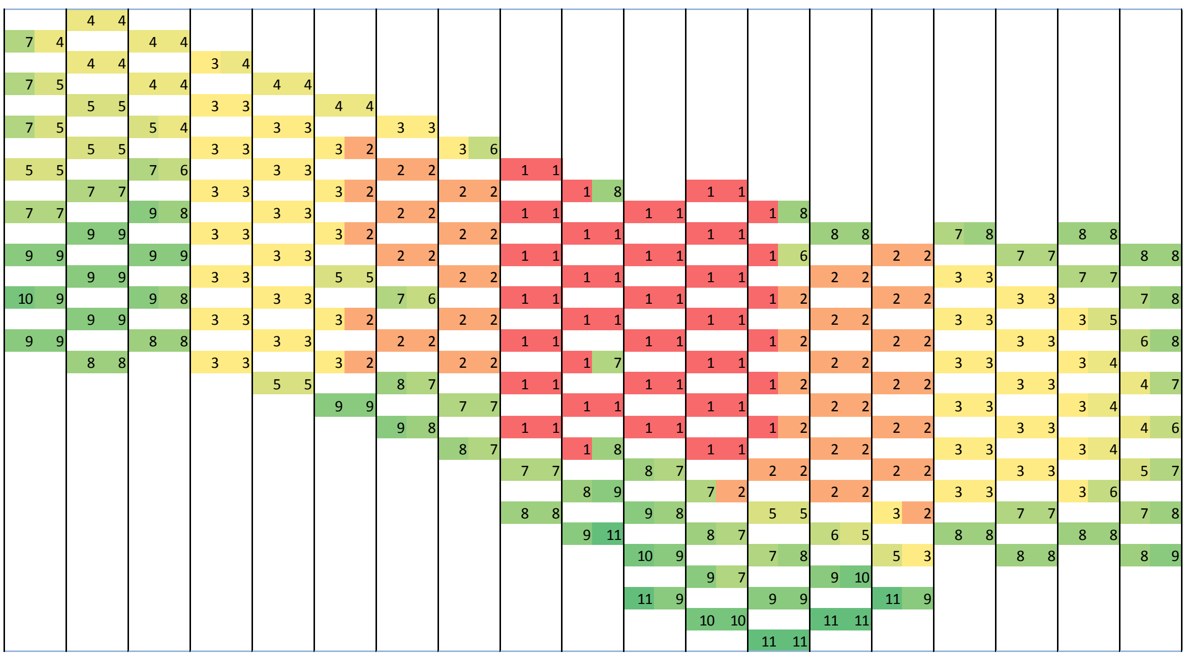

Figure 24. Layout with minimum neighbors set with K=3 and Δ=2.

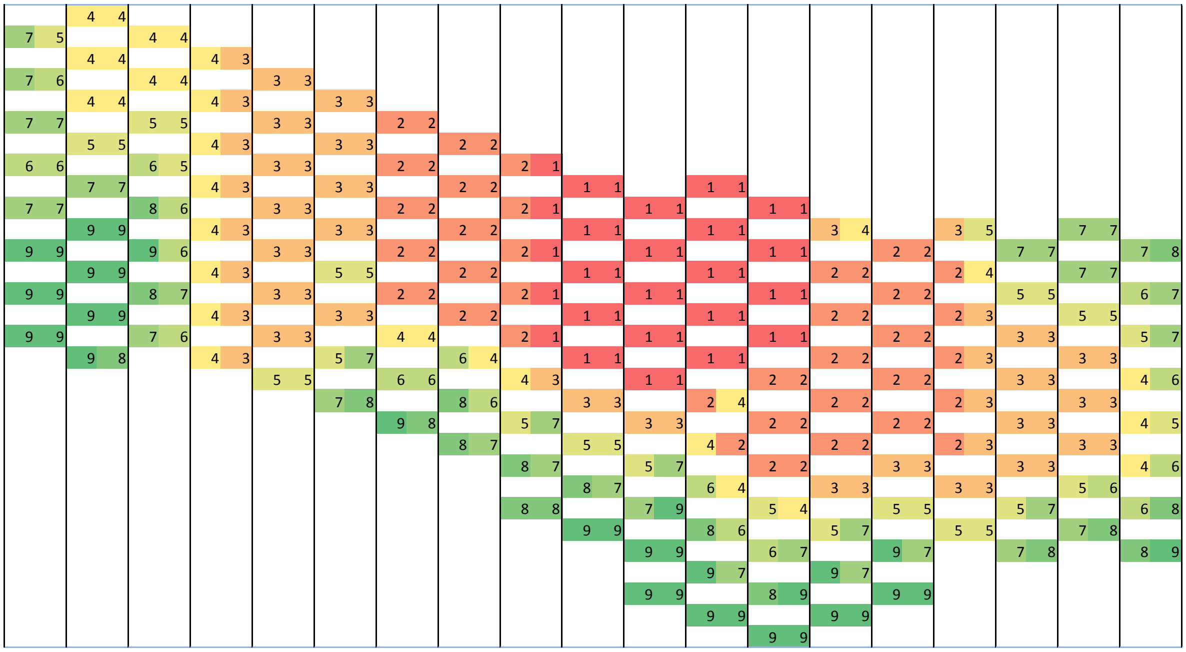

Figure 25. Layout with minimum neighbors set with K=6 and Δ=2.

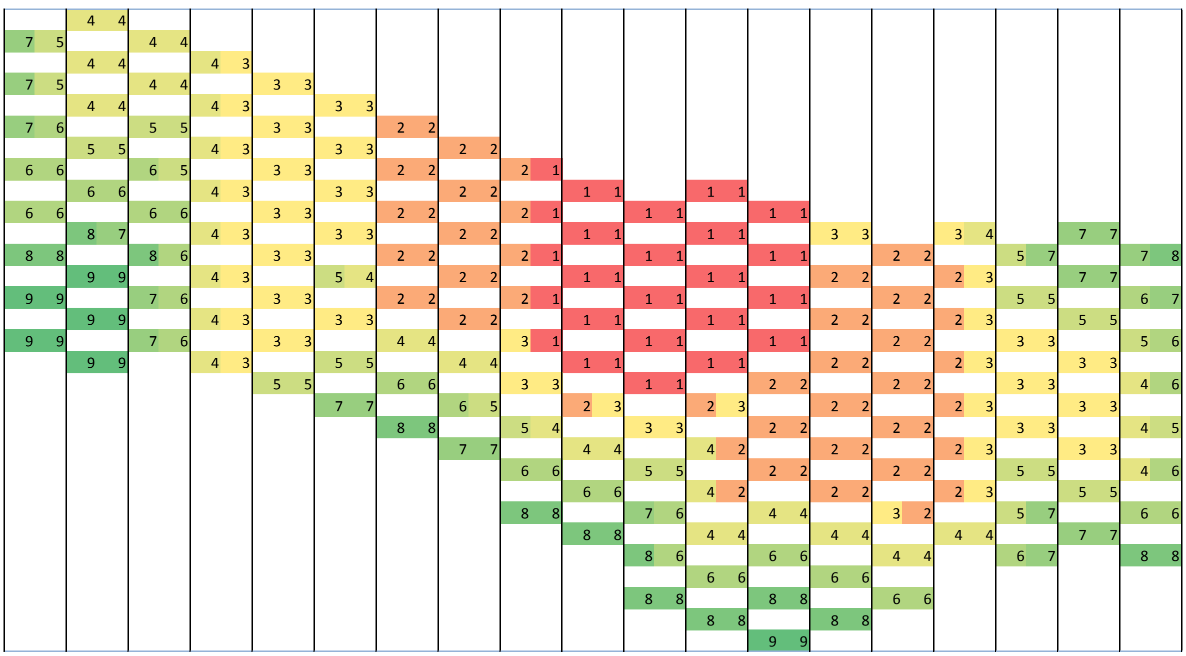

Figure 26. Layout with minimum neighbors set with K=7 and Δ=2.

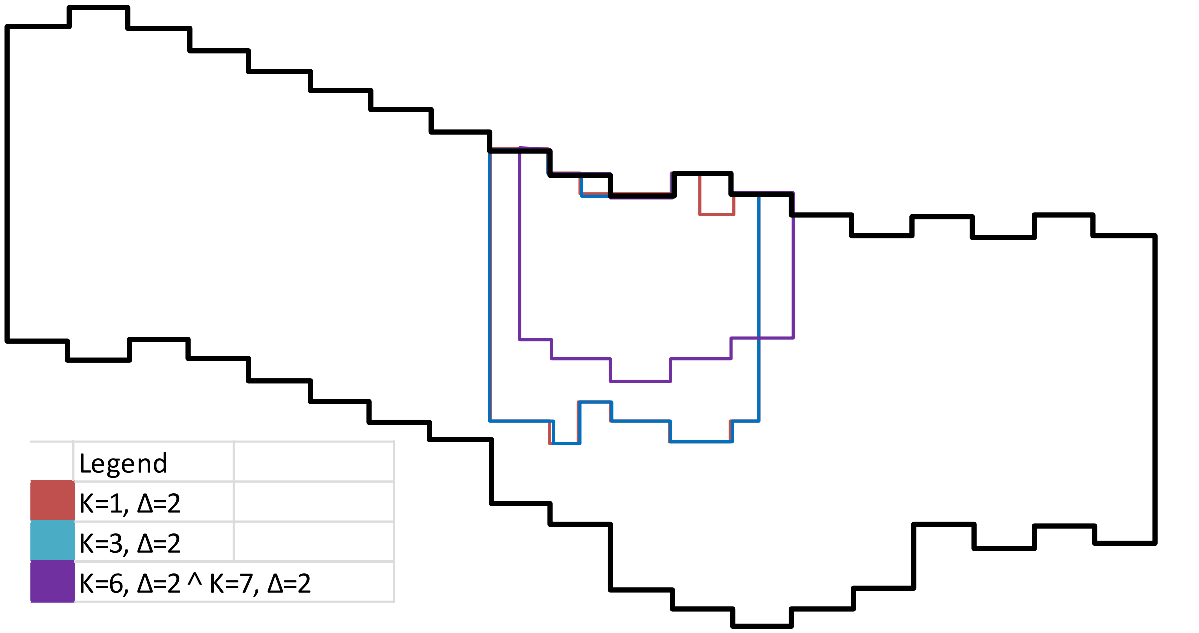

Figure 28. Comparing sequences with different "minimum neighbors" for year 1.

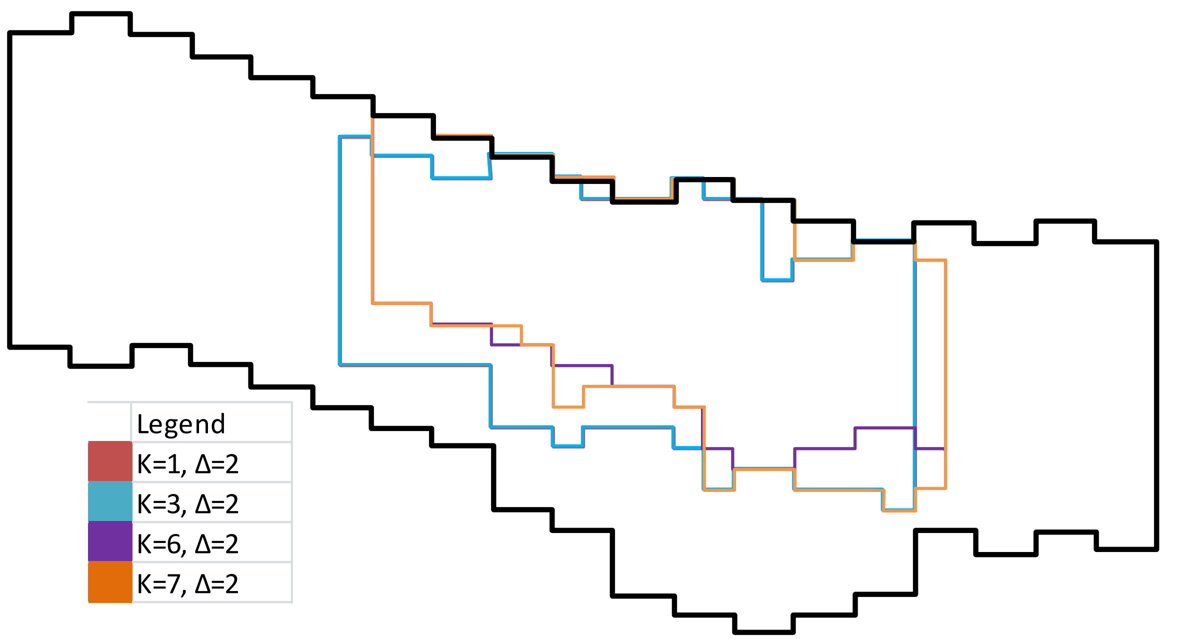

Figure 27. Comparing sequences with different "minimum neighbors" for year 2.

4. CASE STUDY

Case study is a mine that has a 30.000 tpd run of mine production. The layout has 332 drawpoints. Currently the sequence has already been developed, but the idea is to show how it the sequence varies when capacities per drawpoint or capacities per cross-cut production are changed. Production is driven to 4 crushers located on the ore body footwall. A three dimensional view of the mining system is shown (Figure 29). All the parameters previously defined are specified. Figure 15 shows the isometric view of case study.

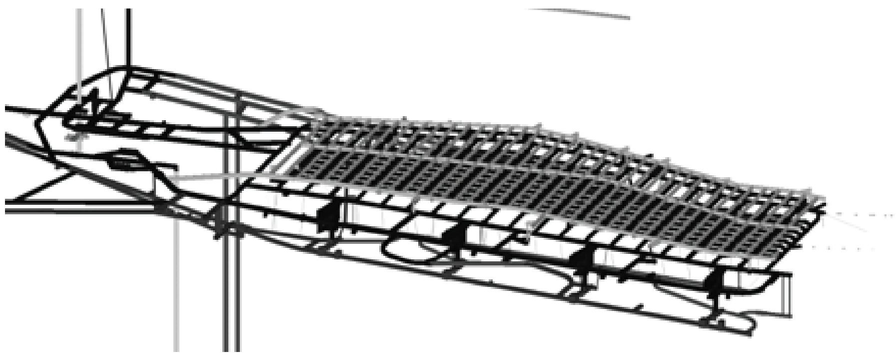

Figure 29. Case study mining system.

4.1 Data for model

To solve this model a run of BHOD of GEMS 6.1.4 ® module PCBC® (Gemcom® Software) is used. The revenue factor used was 1.68 US$/lb , cost 16 US$/ton and recovery 0.8. The data statistics are presented in Table 5:

Table 5. Data statistics.

Number of dpt	332
Tonnage reserve [Mton]	11.76
Average grade [%]	0.82
Total value [MU$]	1,811

4.2 Mining systems

One important factor to studies the changes in the result sequence (scheduling) is the mining system. So, four mining systems will be shown in this section and the model will be run with each one, and also with variants of each one (sensitivity study). These three scenarios were selected because they are very different in regard to the associations and connections in systems. The four systems can represent a lot of similar systems. One of the four systems corresponds to system associated with the layout and from that the others alternatives were proposed. The others systems are based on the sensitivity of quantity of units downstream and each one is based on a real mining system (material handling system): On the one hand a system with a lot of terminals components, that attends to a few drawpoints (cross-cuts) and on the other hand a system with less terminal components and each component attends a lot of drawpoints (cross-cuts). The same layout as in case study is used, but with four different mining systems groups. Each system is tested with one and two LHD per crosscut. The capacity for LHD in the first case is 3.000 tpd, and for the second case is 1.500 tpd (to complete the same production, as in the case with one LHD). In back ground appears production rates for LHD around 6.000 tpd in Henderson, but in this model a lower production rate was considered with one LHD per cross-cut (In Henderson case not specify if it is one or two LHD per cross-cut), because the first test and balances indicate that with a production per cross-cut of 3.000 tpd, it was possible to achieve the production of 30.000 tpd, and this implies a saving in the investment (considering the price of the 6.000 tpd LHDS). In the first case the shafts are out to the crosscut, in the head. In the second case the shaft is located in the middle of the cross-cut. (Figure 30).

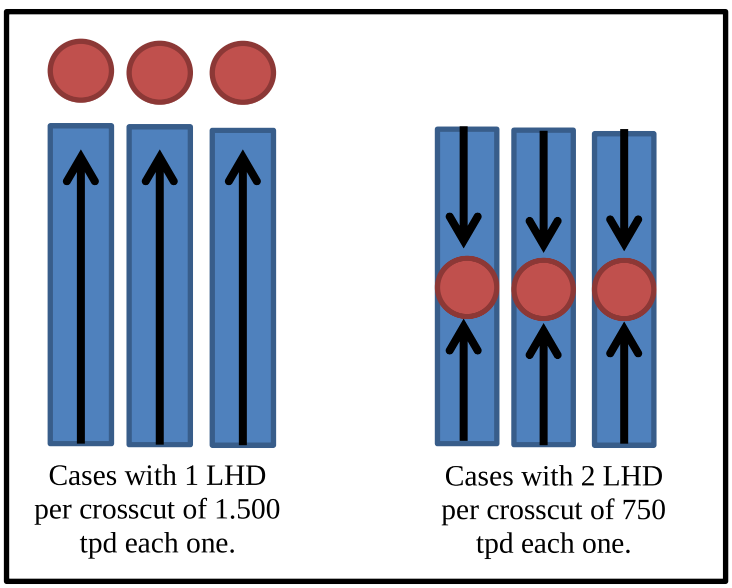

Figure 30. Configuration option for shaft location in the cross-cuts.

The selected mining material handling systems were the following (Based on exposed literature):

4.2.1 System A: Based on Palabora mining system.

The first system, for which the sequencing was evaluated, has 5 cross-cuts per crusher, which gives a total of 4 crushers for the complete layout. The crushers have a production capacity rate of 7.500 tpd each one. This value was obtained considering the global production rate of the mine and the number of the crushers in system. So the minimum production rate per crusher required to reach the 30.000 tpd is a quarter of this value. But, to reach the 30.000 tpd all drawpoints should be active, but in panel caving this normally does not happen, because the front cave line is moving continually, and while this happens the exhausted drawpoints are closing. So this case will show a critical result, where probably the crushers will be the bottle neck. After that the material pass by crusher level, the ore pass by transport level and after the material is driven to the plant. Also, the possibilities to have one or two LHD per cross-cut production were considered. In addition to this variant, the sensitivity in the number of crushers was considered. In this case it is considered four, five and six crushers for the complete layout, each case evaluated for one or two LHD per production cross-cut. The last idea generates 6 mining systems to evaluate.

The modeled systems has been considered modular, so that each module has the same production capacity, except if the result of dividing the cross-cuts production number by the crushers number are not integer. In that case, an integer series is planted, so that the final tonnage can be accomplished. Each crusher could be different capacities production.

Figure 31 shows the three cases. In each case the rate between cross-cuts number and crushers number is not an integer. This value is called “a”. In the first case, where the non-integer part of “a” is greater than 0.5. The indicated series is repeated each three crushers,. In this case, each square symbolizes the cross-cuts number that each crusher attends. The two first crushers attends the integer part of “a” plus one, and the third crusher attend the integer part of “a”.

In case that the non-integer part of “a” is less than 0.5, the first crusher attends the integer part of “a” plus 1 cross-cuts and the second and third attends the integer part of “a” cross-cuts. The last case happens when 0.5 is a non-integer part of “a”, and the crushers attends a crosscuts number turns the part integer of “a” and the part integer of “a” plus 1.

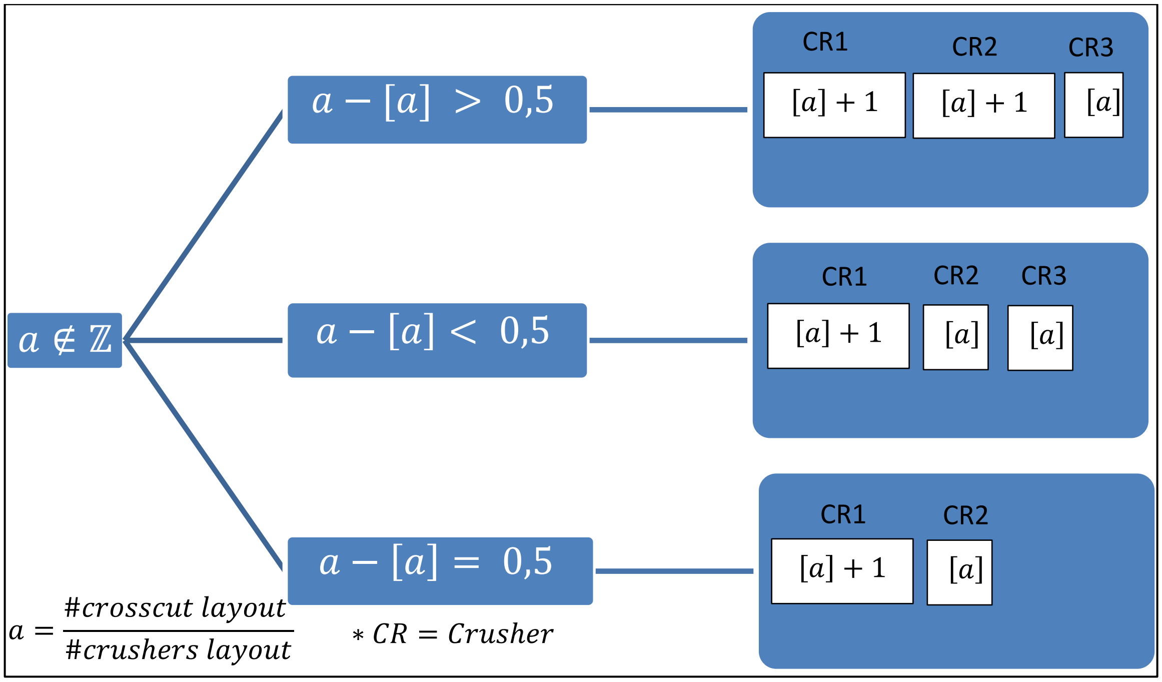

Figure 31. Summary for cases where the ratio between the number of cross-cuts and the number of crushers is not an integer number.

Figure 33 shows the unit for the mining system with four crushers, each one 7,500 tpd. The four crushers satisfy all layout. A transport level was considered with the result capacity, depending on the crushers and cross-cuts constraints. Figure 32 shows case that has 5 crushers (7,500 tpd each one). At the end of optimization process these values will be replaced by the final production rate of each component.

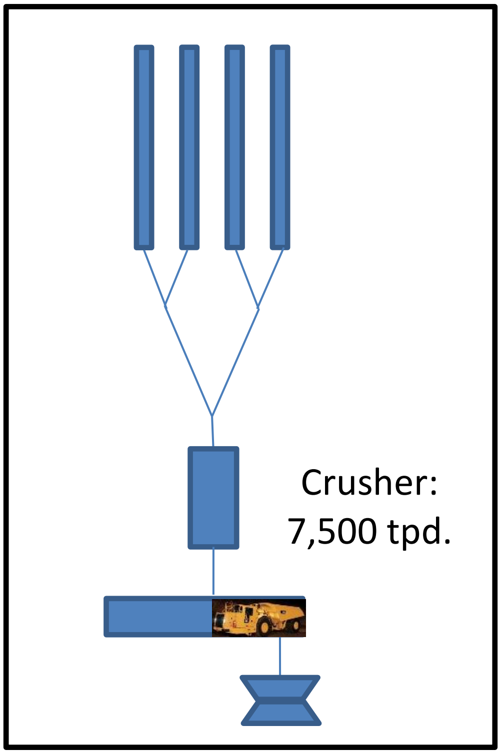

Figure 32. Unitary material handling system for case of 5 crushers.

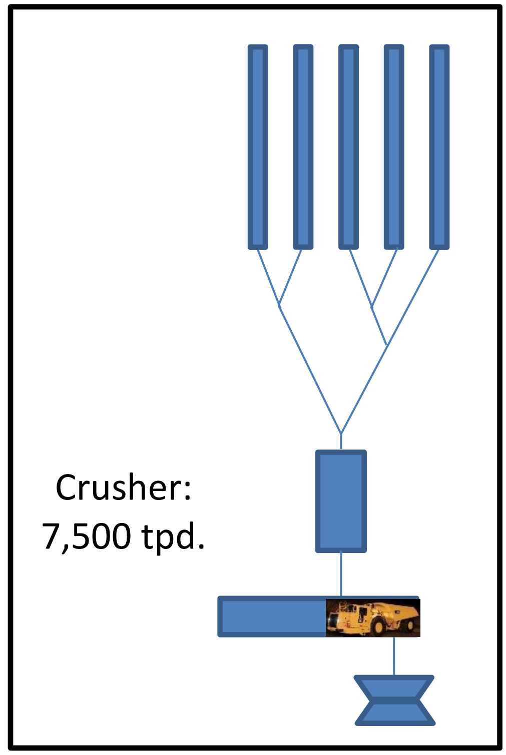

Figure 33. Unitary material handling system for case of 4 crushers.

Figure 34 shows the mining system that has 6 crushers in the layout. Because the ratio between cross-cuts and crushers is not integer, the numbers of cross-cut per crusher are different between crushers. The result combination was: 2 crushers fed by four cross-cuts and four crushers fed by three cross-cuts.

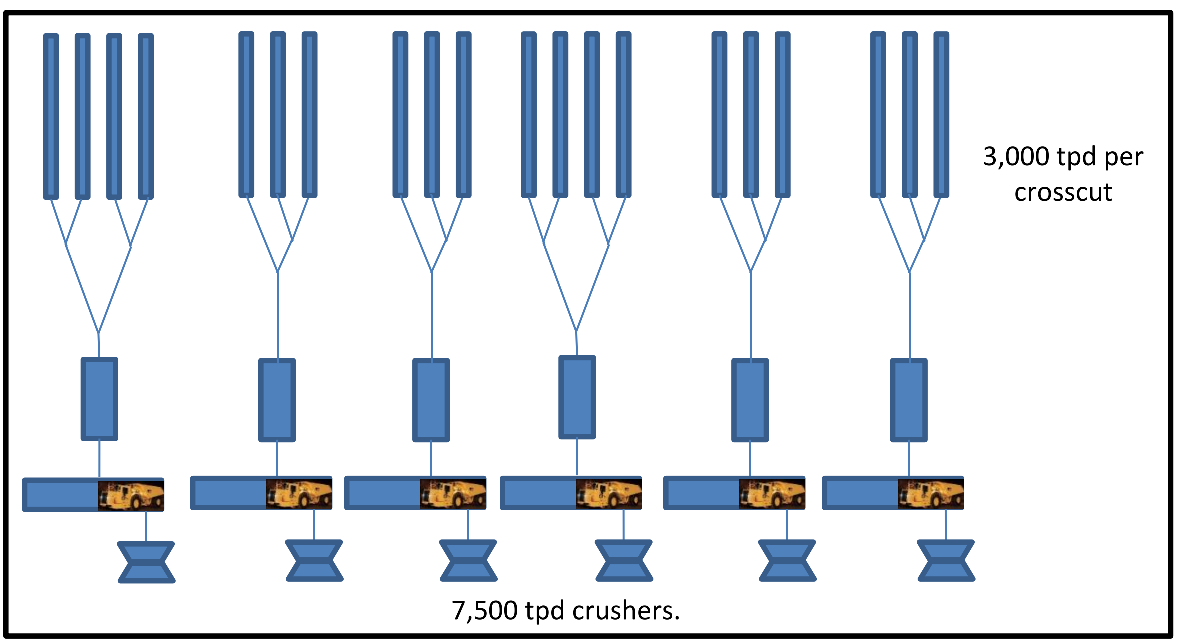

Figure 34. Mining Material handling system for case of 6 crushers.

In Table 6 a summary with the three systems is shown.

Table 6. Summary system A.

Number of cross-cuts	20
Number of drawpoints	332
Capacity LHD	1.500 tpd two LHD/cross-cut 3.000 tpd one LHD/cross-cut
Capacity crusher	7.500 tpd
Cross-cut per crusher	5 (four crushers) 4 (five crushers) 3,4 (six crushers)

4.2.2 System B: Based on Henderson mining system.

In this system, an important number of chutes were considered, and these chutes feed the transport level that consists of trains. This case considers 10, 11 and 12 chutes and each one has capacity rate 3,000 tpd. This system has more terminal units (chutes) than in Palabora case, so each terminal unit has to have more capacity. The capacity is the critical for the basal case, because corresponds to the 1/10 of the capacity and with 10 chutes the global capacity is achieved, but with all the drawpoints in active state. Each chute is fed by two cross-cuts for case of 10 chutes for the layout. In the rest of cases each chute is fed by a different number of crosscuts, because the ratio between the number of cross-cuts and chutes is not integer. Figure 36 and 37 shows the distribution of cross-cuts, for this particular case.

In Figure 35 each square symbolizes the chutes of the each mining system. In the square is a number that indicates the number of cross-cuts that feeds to that chute. This case considers 2 cross-cuts per chute.

Figure 35 and Figure 36 show configurations, where the ratio between the number of cross-cuts and the number of chutes is not integer. The last configuration implies that not all the chutes attend the same number of cross-cuts. Capacities per crusher were considered as 3.000 tpd, but the real production not necessarily will be the purposed capacity. These ten chutes feed a transport level that consists of two transport loop. After that the entire mineral goes to the crusher level, with a unique crusher.

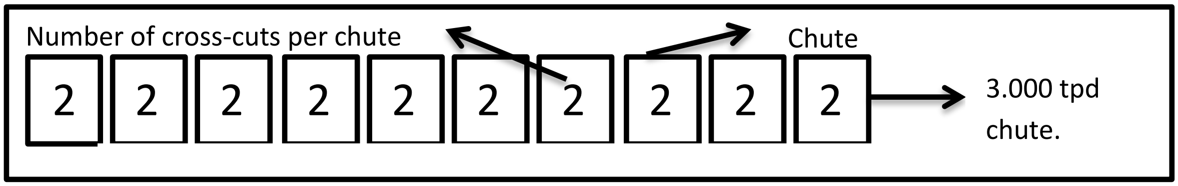

Figure 35. Mining system configuration for the 10 chutes case.

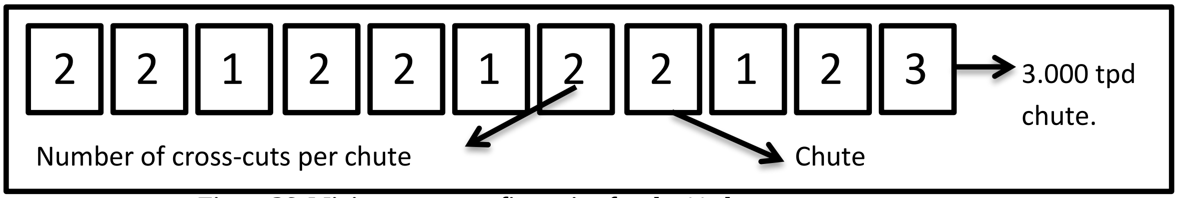

Figure 36. Mining system configuration for the 11 chutes case.

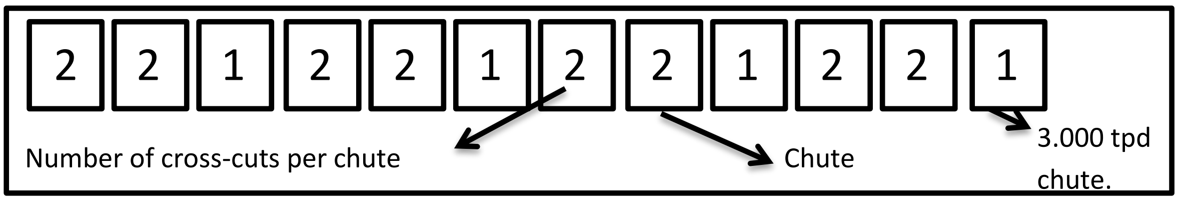

Figure 37. Mining system configuration for the 12 chutes case.

In Table 7 a summary with the three systems is shown.

Table 7. Summary system B.

Number of cross-cuts	20
Number of drawpoints	332
Capacity LHD	1.500 tpd two LHD/cross-cut 3.000 tpd one LHD/cross-cut
Capacity chute	3,000 tpd
Cross-cut per chute	2 (ten chutes) 1,2,3 (eleven chutes) 1,2 (twelve chutes)

4.2.3 System C: Based on Grasberg system.

Three crushers are considered for the handling material system. Each crusher has 10.000 tpd each one. As in the last cases, systems contemplate to have 1 or 2 LHD per cross-cut. This system has less terminal units than in Palabora case, so each terminal unit has to have more capacity.

In this case (Figure 38) each crusher is not associated with the same number of cross-cuts, because the rate between the number of cross-cuts and the number of crusher is not integer. The capacity for the three crushers is the same. The two cases, in Figures 39 and 40, there are the same layout than the first case (20 cross-cuts), and the production per crusher is 10,000 tpd. In the case with four crushers, each crusher is fed by five cross-cuts and in the case with five crushers, each crusher is fed by four cross-cuts.

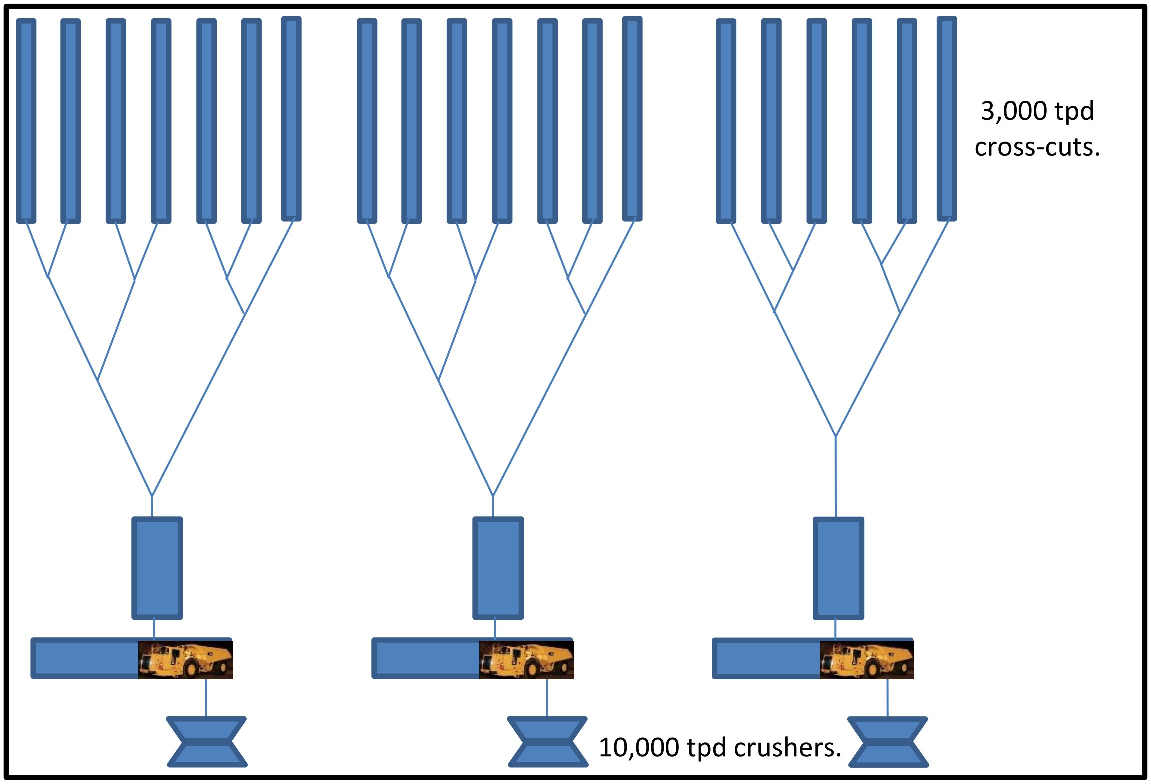

Figure 38. Mining system for case C with three crushers.

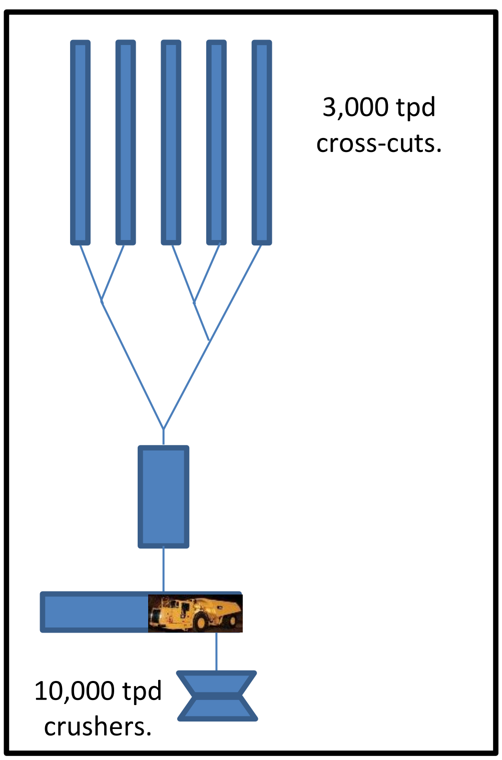

Figure 39. Unit of the mining system for case C with four crushers. (10,000 tpd)

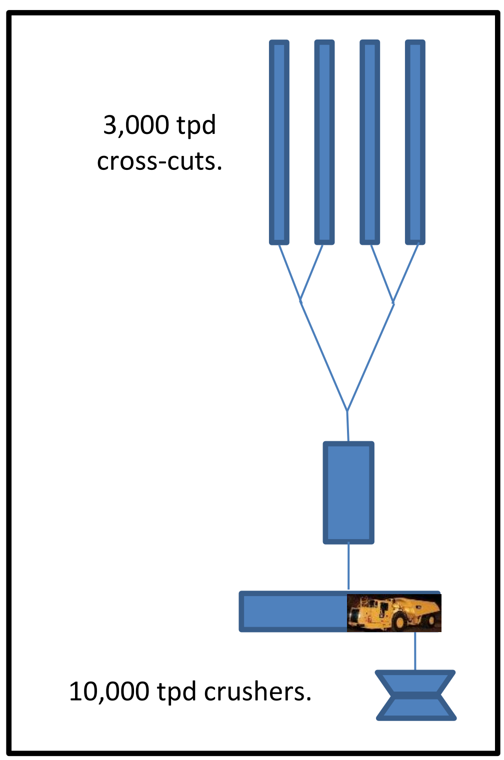

Figure 40. Unit of the mining system for case C with five crushers. (10,000 tpd)

In Table 8 a summary with the three systems is shown.

Table 8. Summary system C.

Number of cross-cuts	20
Number of drawpoints	332
Capacity LHD	1,500 tpd two LHD/cross-cut 3,000 tpd one LHD/cross-cut
Capacity crusher	10,000 tpd
Cross-cut per crusher	6,7 (three crushers) 5 (four crushers) 4 (five crushers)

4.2.4 System D: Based on LHD supported by panzer conveyor.

This system considers continuous mining. Figure 41 shows system composition that consists of the same cross-cuts than in the other systems with 3,000 tpd per cross-cut, because the same layout is tested for different systems. The red circle represents the emptying orepass and the blue rectangle is a crosscut. The half of cross-cuts leaves the material on a 15,000 tpd panzer conveyor. The rest of cross-cuts leave the material on other 15.000 tpd panzer conveyor. The two panzers conveyors leave the material in a 30,000 crusher. (The material could be divided in more crushers, if 30,000 tpd were an elevated value).

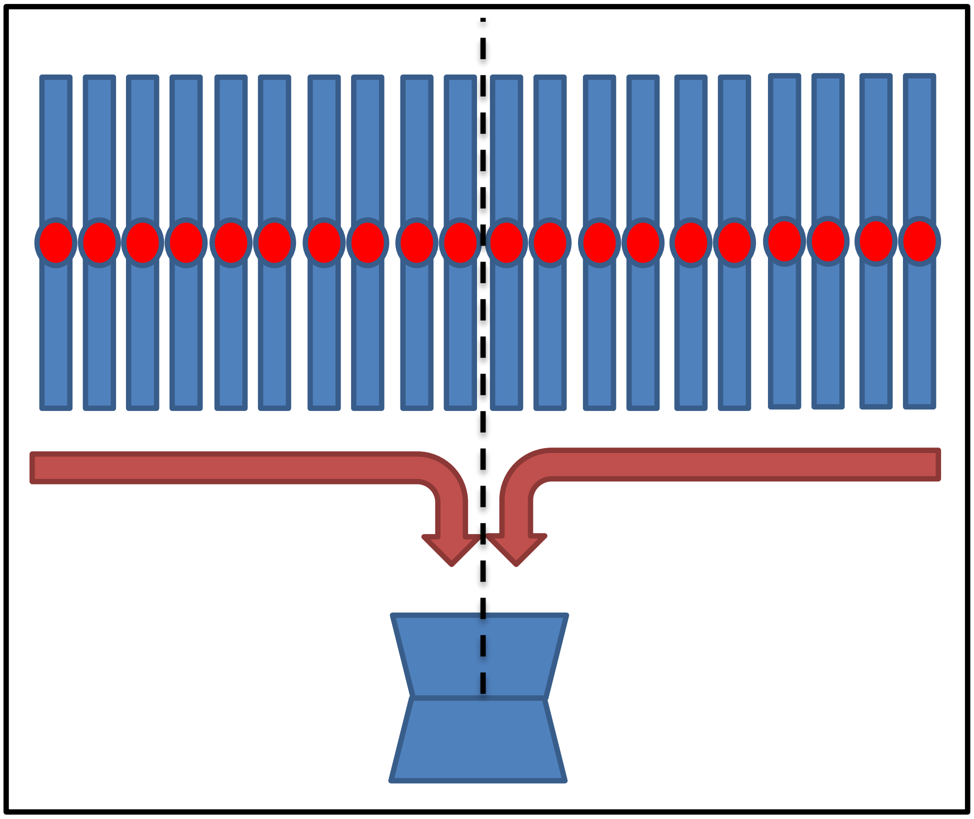

Figure 41. System D LHD supported by panzer conveyor.

In Table 9 a summary with the three systems is shown.

Table 9. Summary system C.

Number of cross-cuts	20
Number of drawpoints	332
Capacity LHD	1,500 tpd two LHD/cross-cut 3,000 tpd one LHD/cross-cut
Capacity panzer	15,000 tpd
Cross-cut per panzer	10

A summary of the material handling systems studied is shown in Figure 42. In Figure 42 is the simplified nomenclature to design system in Tables and graphs. One or two LHDs indicate the number of LHD operating per cross-cut.

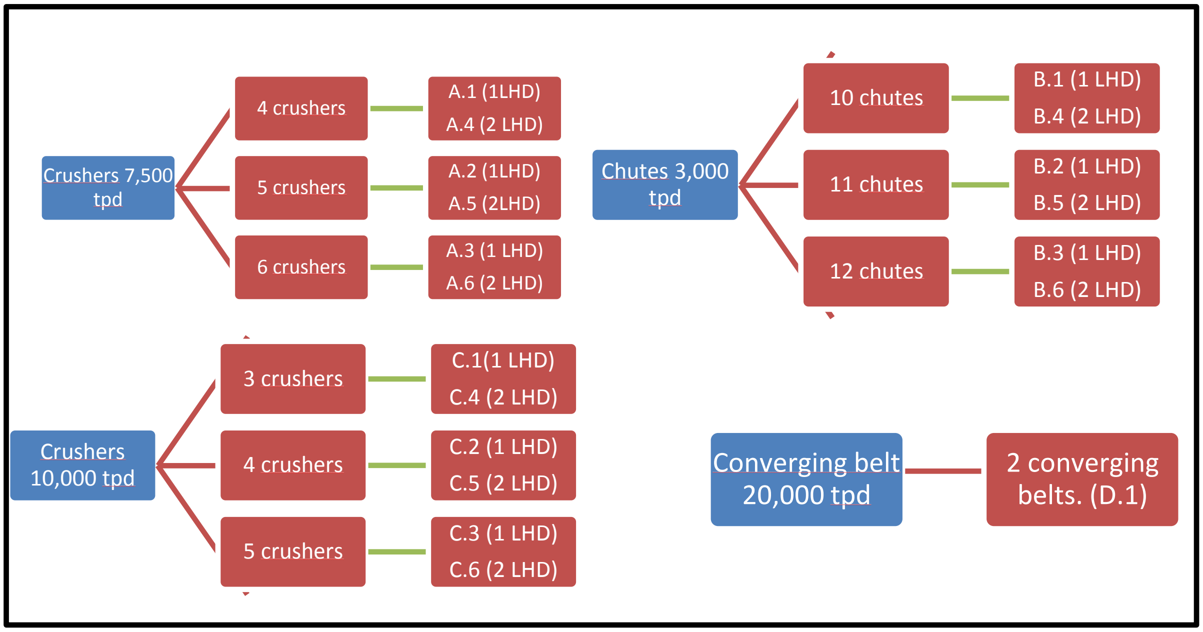

Figure 42. Mining system summary.

Other tests were made, but the idea was to maintain the net for the material handling and only change the capacity per component. In Figure 43, the generated cases, with the first variation in capacities are shown:

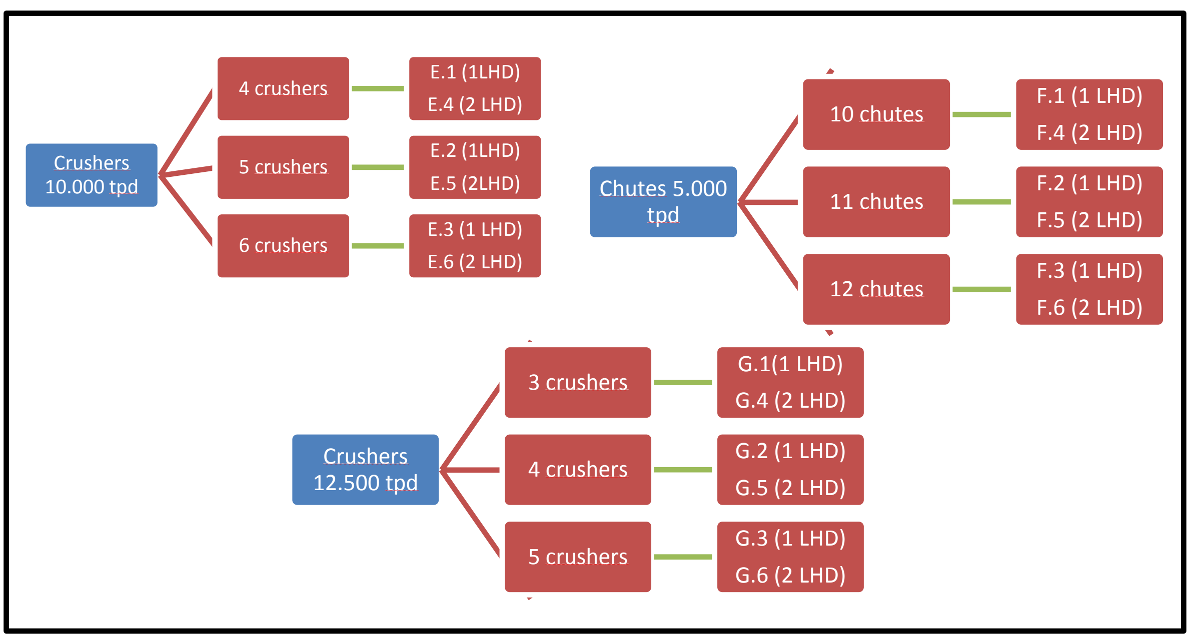

Figure 43. Mining system considering production capacity components changes.

Finally the capacity design was changed from 30,000 tpd to 50,000 tpd, and consequently the capacity components were changed. The idea is to generate the less “bottle neck”. The net for material handling and the associations are the same. The generated cases are shown in Figure 44.

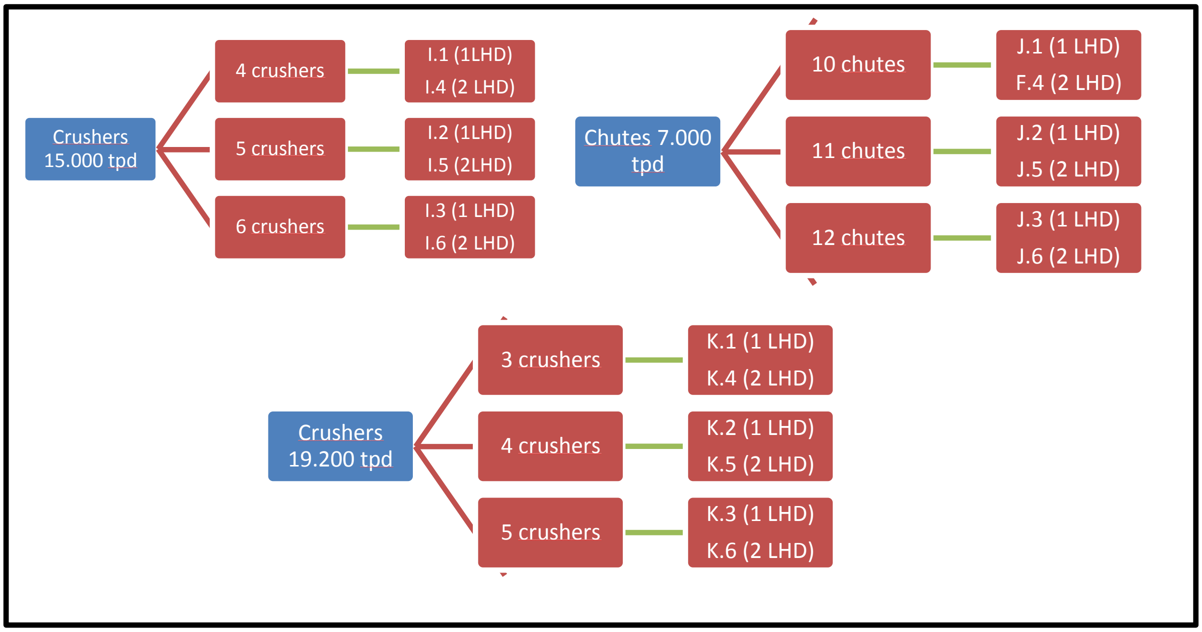

Figure 44. Mining system considering production capacity run out mine changes.

4.3 Model inputs

The model has been tested using a 332 draw points, distributed into 20 cross-cuts production. Each drawpoint was numbered, from north to south and each crosscut and from east to west. The parameters that remained invariant are shown in the following Table (Table 10):

Table 10. Principal static parameters used in the model.

	Value	unit
Production run out mine	30	Ktpd
Planning horizon	13	periods
Discount rate NPV	10	%
Maximum advance	5	Dpt/period
Minimum neighbors	6	dpt
Periods to mine the minimum neighbors	2	periods
Periods to mine a drawpoint.	3	periods
Minimum exploitation per column	30	%
Capacity per drawpoint	80	Ktpy
Capacity per crosscut	3,000	tpd

4.4 Results

4.4.1 Systems A, B, C and D

4.4.1.1 Objective function results.

The tests were made for each material handling system and a different sequence for each one was used, considering the maximization of NPV, and the constraints

In Table 11 are shown the results for NPV for the first case A, that involves the variation in the number of crushers and the variation for LHD per cross-cut production. The best case was with 6 crushers (capacity 7.500 tpd) for both cases, with one and two LHD per cross-cut. The results indicate that for each number of crushers, the case with one LHD per cross-cut production is better than the case with two LHD per cross-cut production. The order of the results is the same, if the group are classified by number of LHD per cross-cut. The case with one LHD per cross-cut production presents a variation similar than the case with two LHD per cross-cut production. This variation is quantified in 7%.

Table 11.NPV for case A group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
4 crushers [MUS$]	1,025	1,015
5 crushers [MUS$]	1,068	1,061
6 crushers [MUS$]	1,105	1,089
Max NPV [MUS$]	1,105	1,089
Min NPV [MUS$]	1,025	1,015
Difference [MUS$]	80	74
Percent. Diff. [%]	7.2	6.8

Table 12 shows the results for the second configurations called B. The results indicate that the best case considering 1 LHD per cross-cut production was the case with 12 chutes. In the case with two LHD per cross-cut the best case was with 11 chutes. This value is similar to the same case, but considering one LHD per cross-cut and also case is similar to the case with 12 chutes with 2 LHD per cross-cut. The order for the case with one LHD is not exactly the same as the case with two LHD. Although this system in general presents worse results than the last system, the variation between best cases is lower than for case A, the variation between best and worst case is approximated to 1.7%.

Table 12. NPV for case B group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
10 chutes [MUS$]	986	979
11 chutes [MUS$]	995	987
12 chutes [MUS$]	1,004	995
Max NPV [MUS$]	1,004	995
Min NPV [MUS$]	986	979
Difference [MUS$]	18	16
Percent. Diff. [%]	1.7	1.6

Table 13 shows the results for systems in case C. For the case with one LHD per cross-cut production the best case was with five crushers, and for the case with 2 LHD per cross-cut production the best result was for the case with five crushers. The variation between best and worst case is similar to case A, being lower for the case with two LHD per cross-cut. These tables do not include the investment.

Table 13. NPV for case C group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
3 crushers [MUS$]	1,037	1,025
4 crushers [MUS$]	1,088	1,074
5 crushers [MUS$]	1,117	1,096
Max NPV [MUS$]	1,037	1,096
Min NPV [MUS$]	1,010	1,025
Difference [MUS$]	78	71
Percent. Diff. [%]	7.2	6.5

In Table 14, the NPV value is shown for case D. A global statistic is shown in Table 15.

Table 14. NPV result for case D.

Case	NPV
Case D [MU$]	1,093

Table 15. NPV: Best and worst cases for cases A, B C and D.

	1 LHD per crosscut	2 LHD per crosscut
Max NPV [MUS$]	1,105	1,096
Min NPV [MUS$]	986	979
Difference [MUS$]	119	117
Percent. Diff. [%]	10.8	10.7

4.4.1.2 Production plan.

The following Figures show the best results for each set of cases A, B, C and D, considering the last tables. In the annexes, one can find the most important graphics and tables that show how the production in all considered cases is. Case B presents a slow performance, comparing with the others systems. System D doesn´t present much difference with the other systems, comparing with systems with one LHD per cross-cut (Figure 45). The next graphic shows the production (Figure 46) varying the number of crushers, considering 2 LHD per production cross-cuts. In this graph system B is system with the slowest performance again. System D and the others have a similar performance. Differences between moved material with one LHD and two LHD reflect the difference in NPV (low NPV, low tonnage per year).

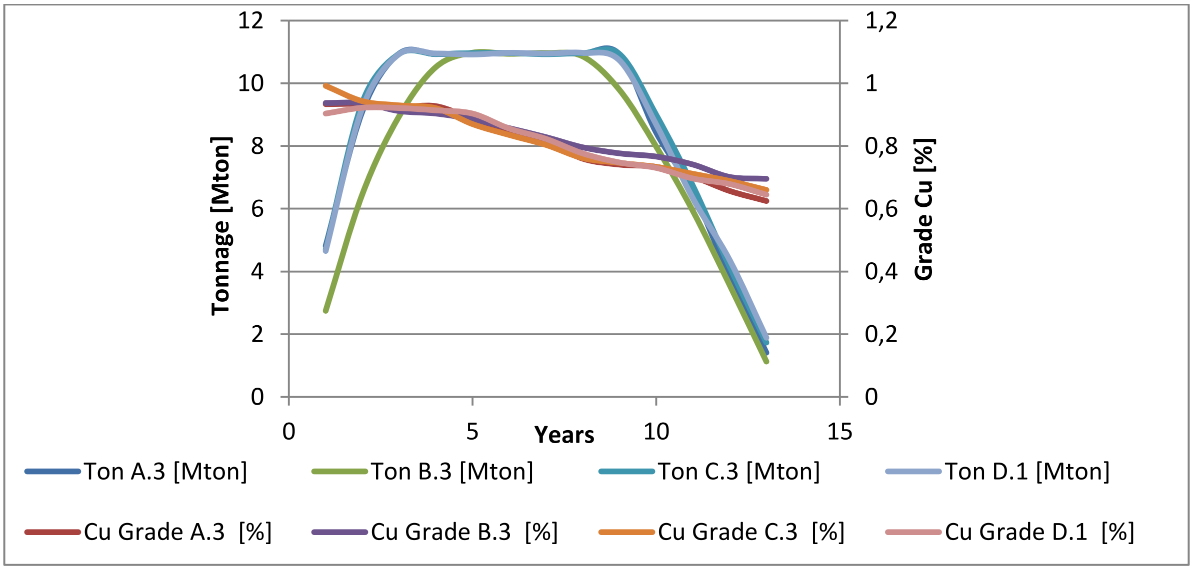

Figure 45. Best production plans with one LHD per cross-cut.

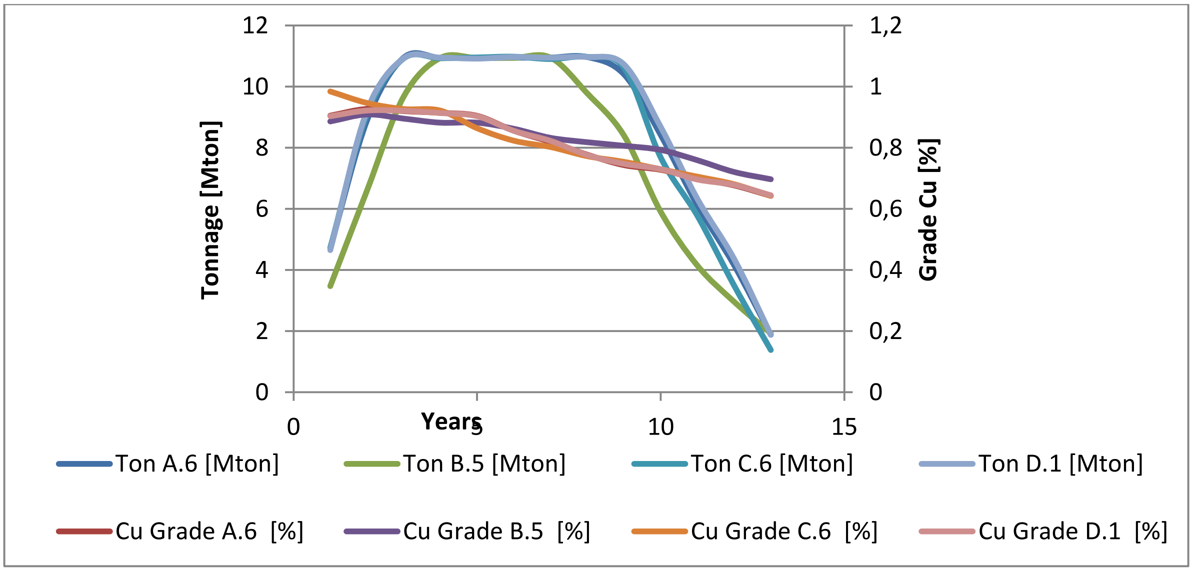

Figure 46. Best production plans with two LHD per cross-cut.

4.4.1.3 Drawpoints opening sequence.

In systems A, B and C, considering one LHD per cross-cut production, the opening sequence tends to start in the north-east sector of the layout. Each line symbolizes a cross-cut and each square is a drawpoint (Figures 47, 48 and 49) and each cross-cut is numerated (from right to left) from one to twenty. In case C the drawpoints open in year one are located from cross-cut four to the left, while in the other two cases the open drawpoints in year one are located from cross-cut production number five to the left. If the drawpoints open in year two are reviewed, in case C the drawpoints are open from cross-cut production number one to the left, while in the other two cases this opening occurs from cross-cut production number three to the left. This spatial displacement in the drawpoints opening during year one responds to the location of the starting drawpoint (It is marked with yellow in all cases). In system B the drawpoints in the left are open sooner than in the other cases (drawpoints farthest from the starting drawpoints). This is because this system has chutes units with less capacity (comparing with crushers in the other cases) and in the less possible time the complete system should reach the designed production (30,000 tpd). In the other cases, the farthest drawpoints from the starting point are open in later periods than in case B. This occurs because the crusher units are more capacity than the chutes in case B, so fewer units are required to reach the designed production. (The material extraction in columns has more preference than to advance to mine the neighbors drawpoints)

The three cases tend to form concentric shapes in the first years (three first years), but in the following years a change in shape happens. Not continuous Shapes (not continuous panels) can occur in the mining plan for advanced years, because the perimeter that contains the last open drawpoints (in previous periods) is too big, so the drawpoints selected during the optimization are the drawpoints that maximizes the objective function (more value in this case). Case B has a discontinuity in advance front that is marked in Figure 48 in circle, like an island. In Figure 49 the same situation occurs. The effect is explained by the column value, because it is a low value, so in the optimization these drawpoints are postponed in their mining or opening, satisfying all the geometric constraints in the optimization. In the first case A, the exposed situation cannot be seen clearly, but the front advance in direction northwest until year 6 and in year seven cannot be seen a clearly front advance direction. In the next year the front advance is from north to south in layout western sector, so these drawpoints again are delayed, because of the low column values.

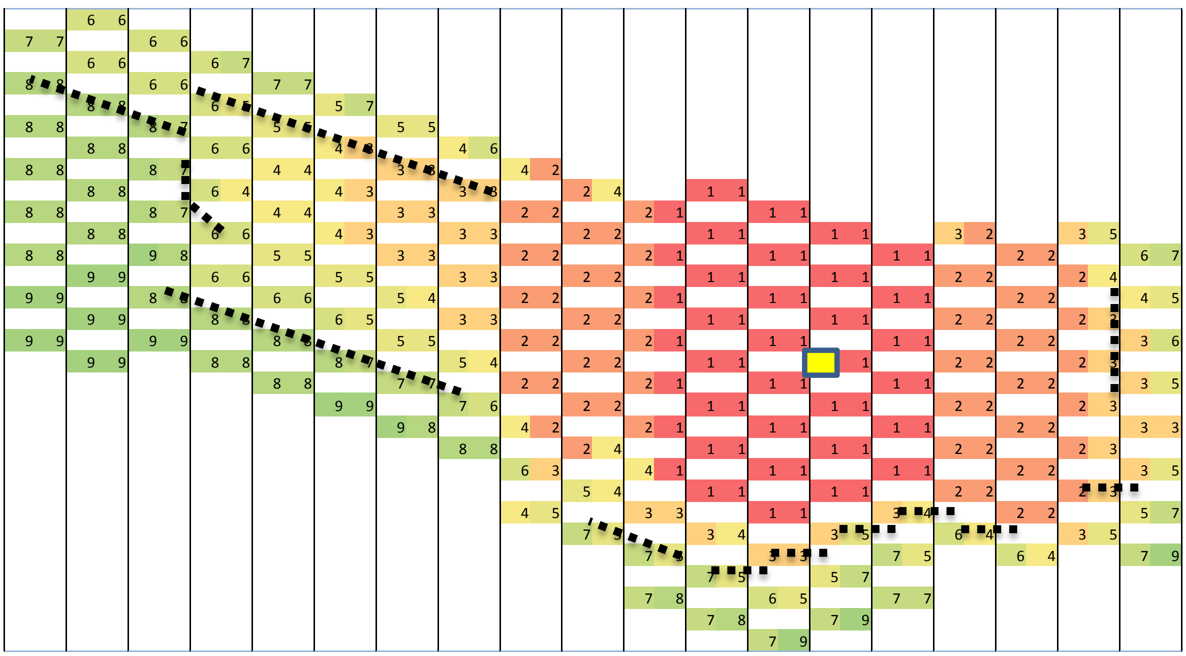

Figure 47. Drawpoints opening sequence for case A.3 with one LHD per cross-cut.

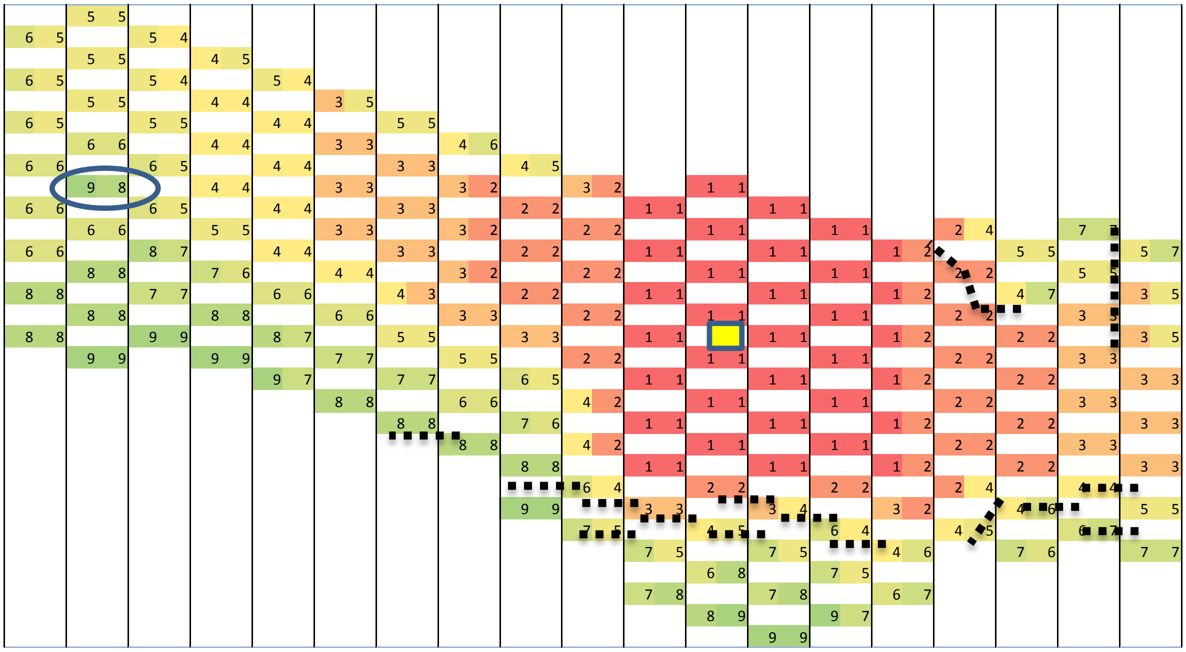

Figure 48. Drawpoints opening sequence for case B.3 with two LHD per cross-cut.

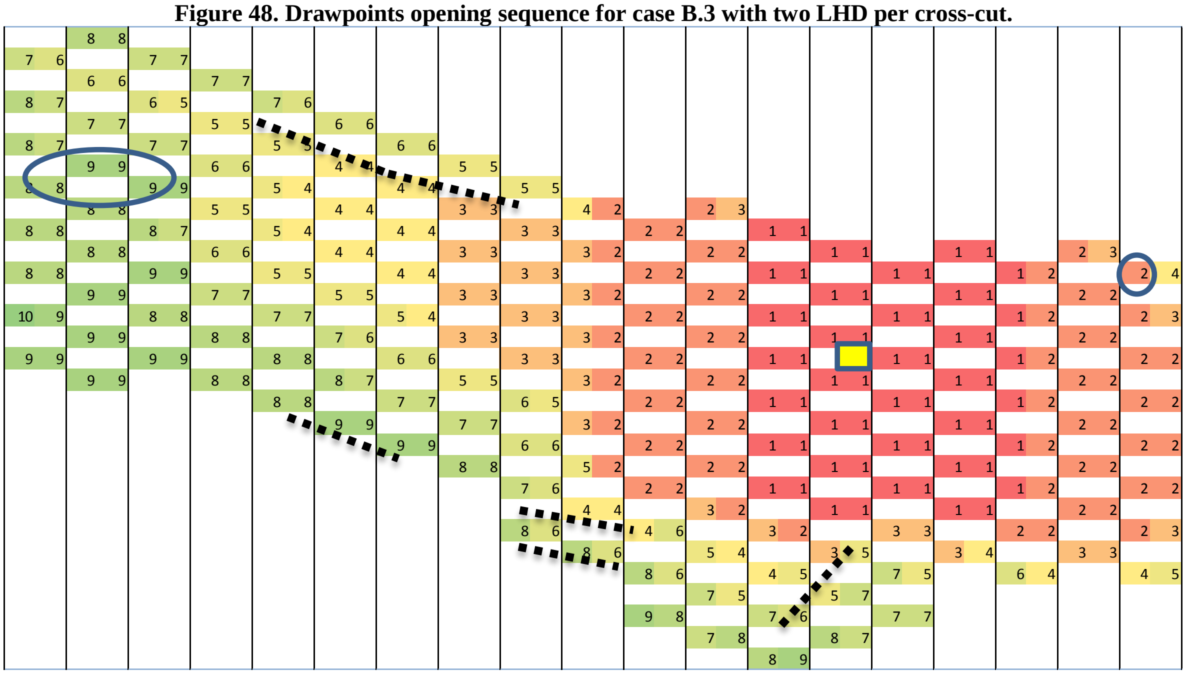

Figure 49. Drawpoints opening sequence for case C.3 with one LHD per cross-cut.

Figures 50 and 51 show the front cave line advance for years 1 and five, respectively. In year one case C is more displaced to the left than the other two cases, because this system has less crushers, so system is less constrained and tends to mine the best value drawpoints. Figure 51 shows that the polygon for case C has the biggest area, and the sequences present some differences, between them. This case is less constrained, so that it permits to advance more.

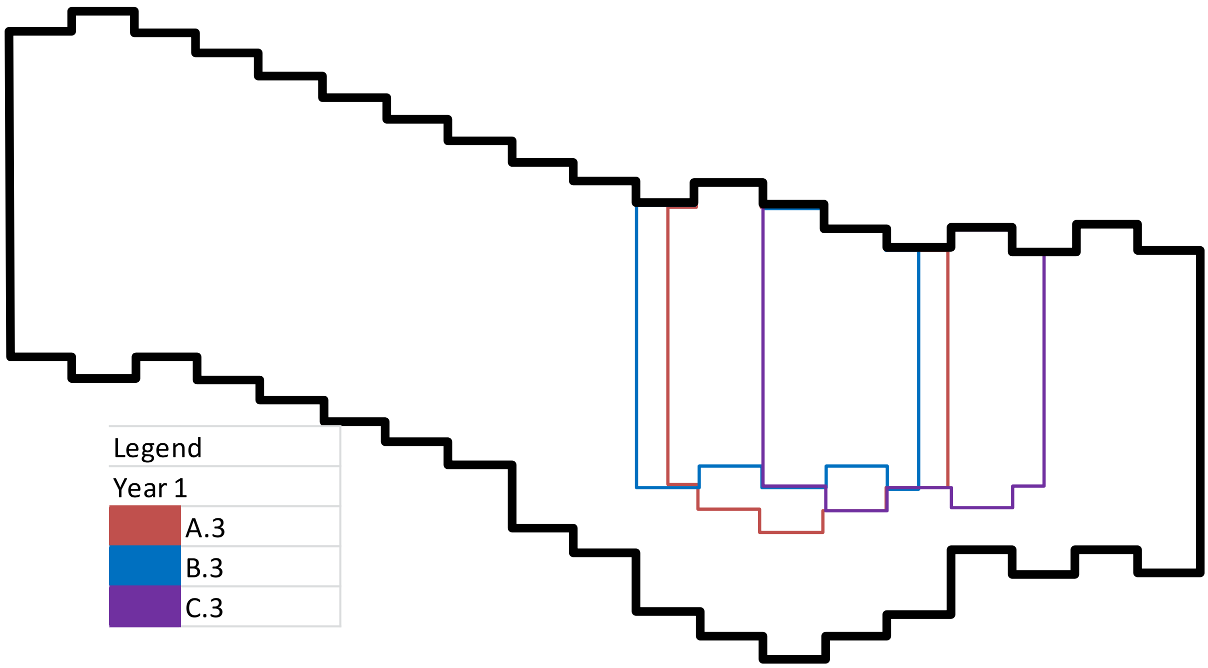

Figure 50. Comparing front cave lines for year one in cases A.3, B.3, and C.3.

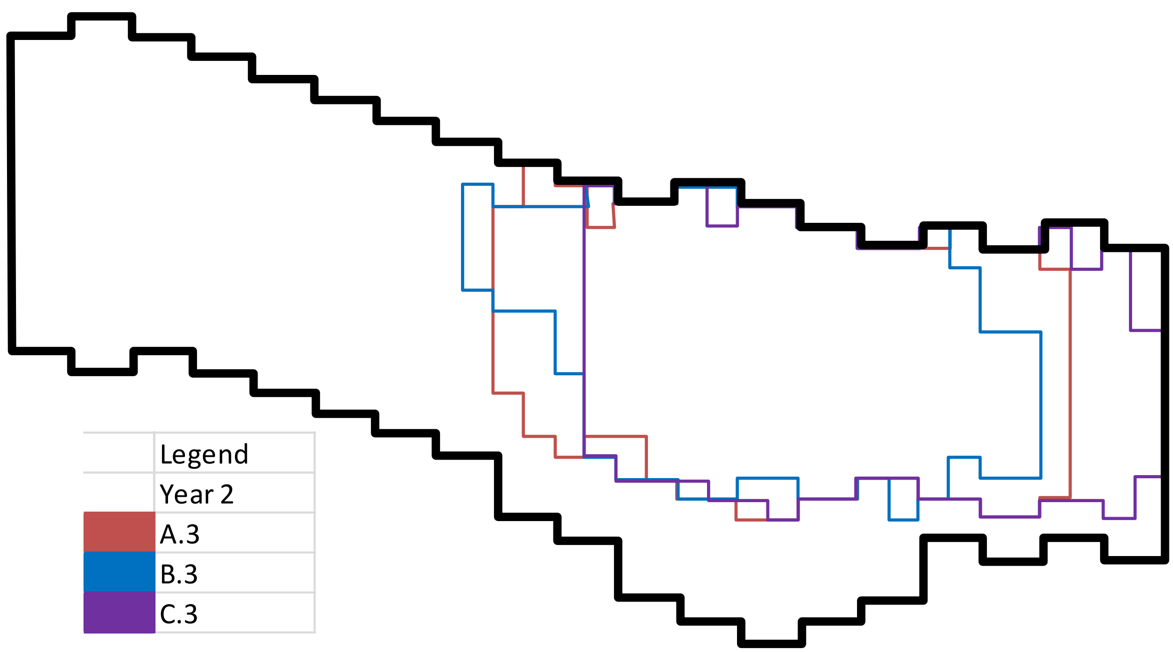

Figure 51.Comparing front cave lines for year two in cases A.3, B.3, and C.3.

Figures 52, 53, 54 and 55 correspond to the four cases with two LHD per cross-cut and the LHD deposits the material in the center of cross-cut production (each LHD charges material from the half of the cross-cut production). Not in all these four cases, the drawpoints those are open in year one have the same location, because in case C the drawpoints are located more to the north than in the other cases and also more to the east. Continuing with the same enumeration for cross-cuts than in the previous analysis, the open drawpoints appear from cross-cut production six to the west in case A, from seven in case B, from four in case C, and from six in case D. In this sense, cases A, B and D are similar, but the difference is made by case C. The starting drawpoint (yellow marked) in case C is located more to the east than in the other cases. In cases A, B and D, the starting drawpoint is located in similar positions. Because case C has the drawpoints open in period one oriented more to the east than the other cases, in period two all the crosscuts to the east of the last open have open drawpoints in important quantity. The first periods are important, because it defines roughly the orientation (advance front) to the opening drawpoints for the next periods. In the advanced periods the advance front presents discontinuities because the geometry produced in the previous periods (open drawpoints) is too big, to cover completely the perimeter. Also this depends on the objective function, and on how to select which drawpoint should be open.

In the last periods are open the drawpoints located at the west of the layout (first the north and after the south). In the last group of Figures some "islands" can be seen and these are marked with a circle in the referenced Figures. This situation is produced principally by the column value and the optimization that responds to the constraints and objective function exposed previously. Also, in some periods, some fronts don´t advance in some directions, and in the next or subsequent period drawpoints are open in these directions. In the final result, this situation can be seen as a temporal discontinuity, because it occurs that a drawpoint has its opening period and some neighbors has a later period, but not the next. Some examples of this are marked with dotted line in the referenced Figures. In reality, this situation means that in some directions, the advancing front will be stopped in some periods.

Case B again has the earliest drawpoints opening, because the last drawpoints open are open in an earlier period than the other cases that open drawpoints in period ten. This situation cannot be seen in case B (Figure 53). This is because, the units of this system (chutes) have a lower capacity than in the other systems (crushers) and, as in cases with one LHD, system requires to be functioning a large number of chutes to reach the 30.000 tpd run of mine.

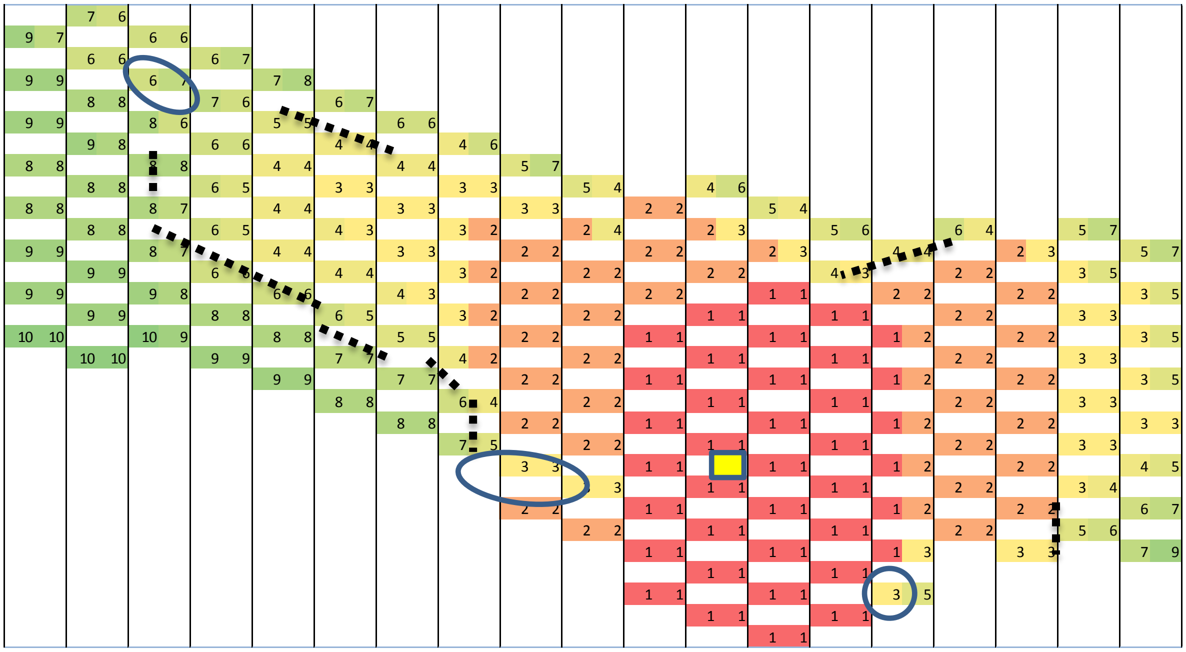

Figure 52. Drawpoints opening sequence for case A.6 with two LHD per cross-cut.

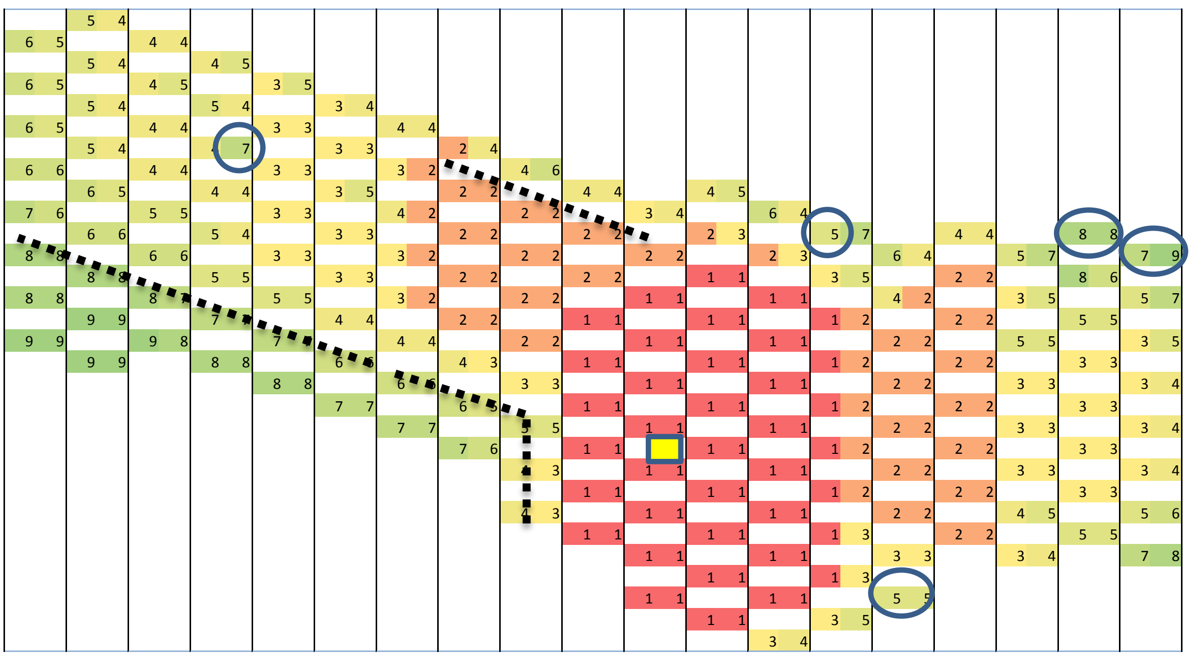

Figure 53. Drawpoints opening sequence for case B.6 with two LHD per cross-cut.

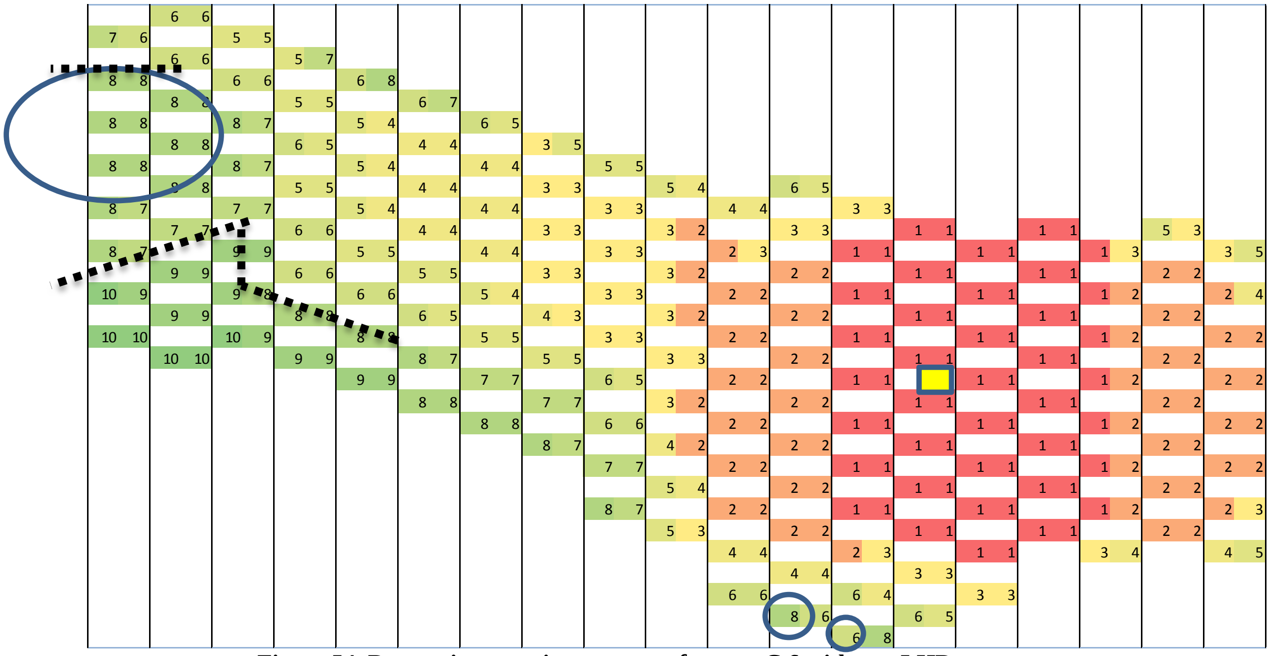

Figure 54. Drawpoints opening sequence for case C.6 with two LHD per cross-cut.

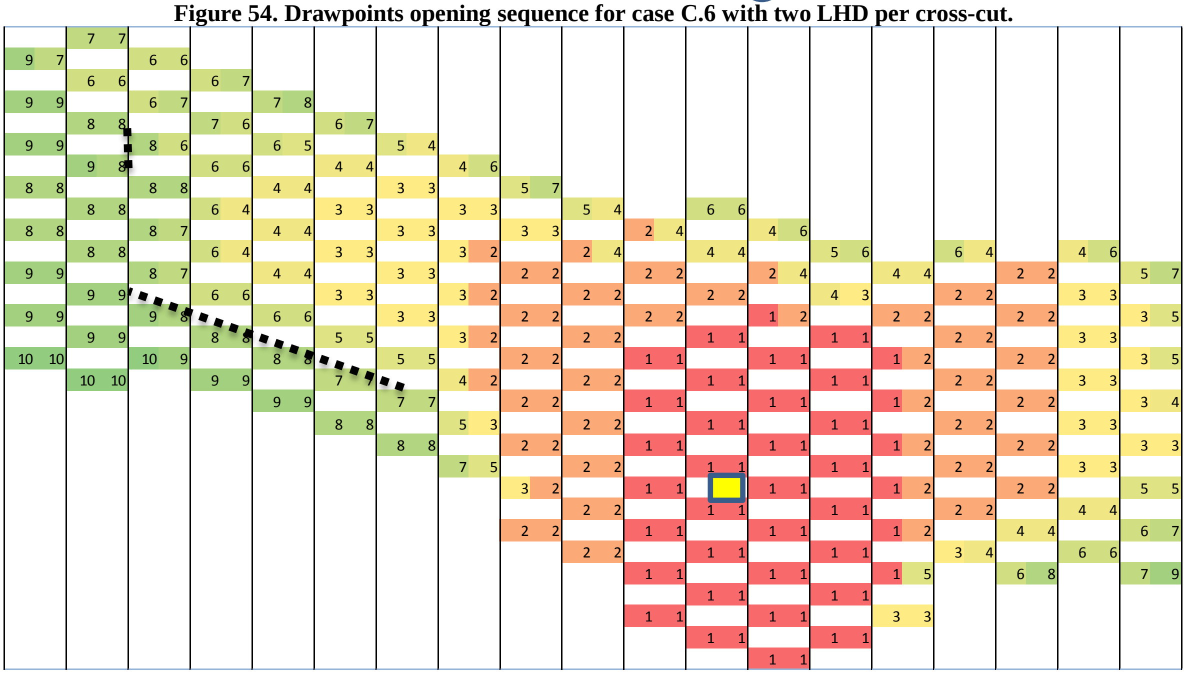

Figure 55. Drawpoints opening sequence for case D.1 with one LHD per cross-cut.

Figures 56 and 57 show the font cave lines in years one and five. In year one, case C shows a different location in the direction north-south (the center of the polygon is more oriented to the north than the other cases). Case A is more oriented to the west than the other cases. In year two again case C shows the biggest area. The other areas present some differences.

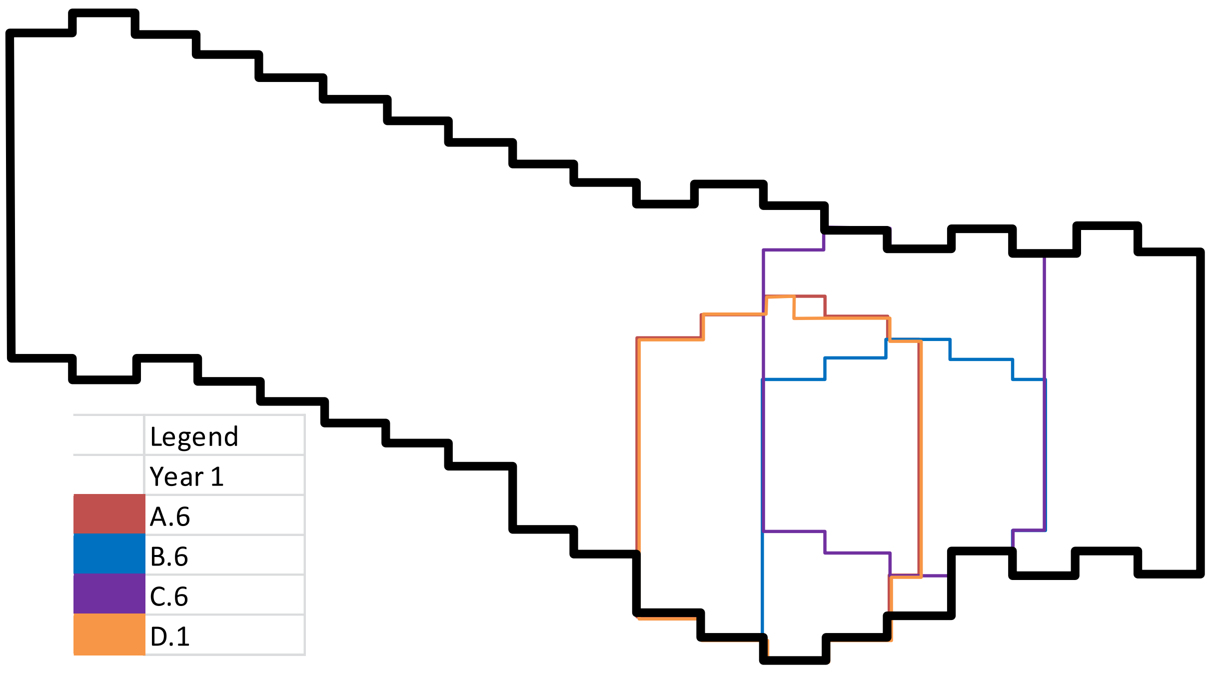

Figure 56.Comparing front cave lines for year one in cases A.6, B.6, C.6 and D.1.

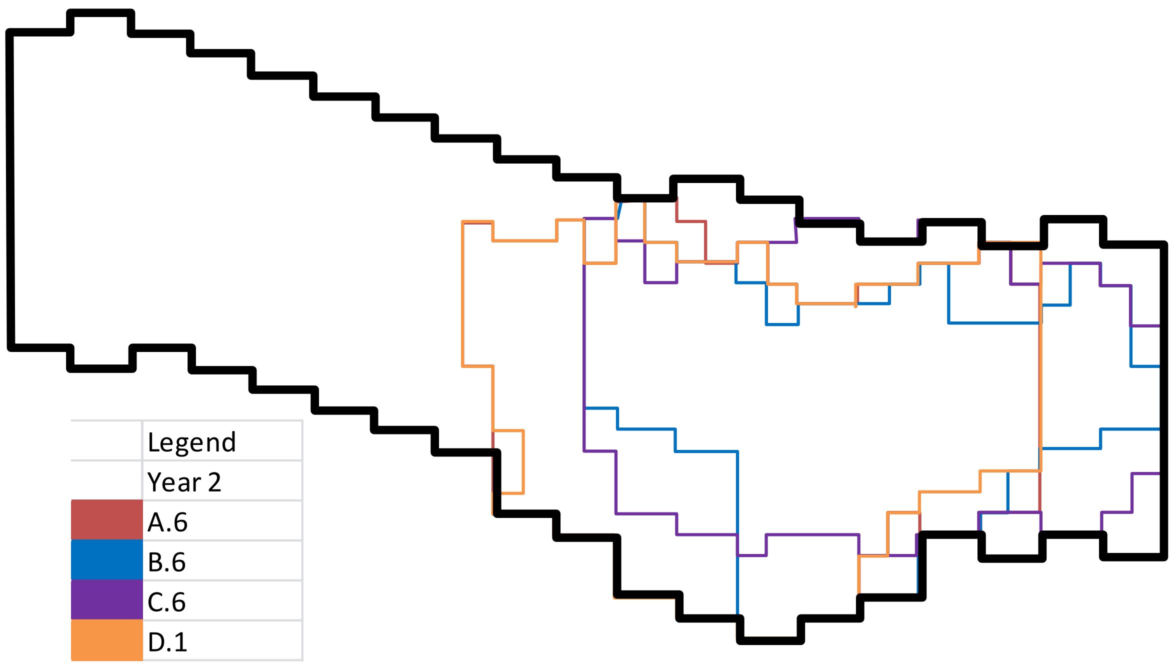

Figure 57. Comparing front cave lines for year two in cases A.6, B.6, C.6 and D.1.

4.4.1.4 Drawpoint opening, closing and activity analysis.

Figure 58 shows the closing drawpoint curve. The performance is similar for all systems until year six, and significant differences can be seen in the next years. From year six, all systems tend to lower the closing rate from 50-70 drawpoints per year to 20-40 drawpoints per year, except in case B where the rate lows to 40-50 drawpoints per year. The difference in the tendency (case B) is because the units in system (chutes) have a low capacity and system requires having active the major quantity of drawpoints to reach the design production. (30,000 tpd) In the last periods some oscillations can be seen in the drawpoints closing annual rate.

Figure 59 shows the opening drawpoints graph. In most of cases, the curve starts in a peak between 60 and 75 drawpoints per year, and after that lows abruptly in the four first years. Since year five, the rate maintains around a level. In the graph, the exception to the rule is case B, which presents a slower decay than the other systems, because this system requires to maintain the highest quantity of chutes functioning (so the highest quantity of active drawpoints) to reach the design production rate (30,000 tpd).

Case D presents an opening drawpoint rate amounting to 25 drawpoints per year, until period 10. After that the rate decreases in one year and it reaches zero opening drawpoint rate in year 13 (planning horizon proposed). Cases A and C have a similar behavior, showing an upturn just before the opening drawpoint rate decreases definitely (before year 10), that corresponds to an open drawpoints reposition to reach the design production.

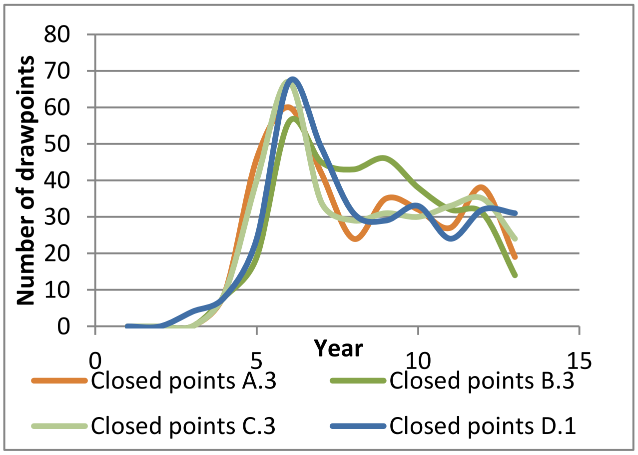

Figure 58. Closed Drawpoints per year for the best cases, 1 LHD per cross-cut.

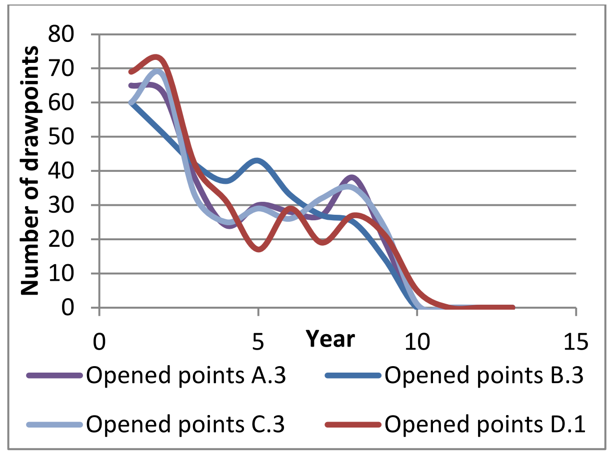

Figure 59. Open Drawpoints per year for the best cases, 1 LHD per cross-cut.

Figure 60 shows the active drawpoints per year and the curve peak is located near year five for cases A and C and the rate in the peak is almost 200 drawpoints per year, for cases exposed with one LHD per production crosscut. This is because the crushers have a high capacity in the two cases. This situation reflects that the layout is not open completely in a year and that is the panel cave mining method. In both cases, after year five the active drawpoints per year rate lows abrupt below 150 drawpoints active per year, but in period ten this rate is reached. The abruptly fall in the rate is because, during the activity of the drawpoints, the mining is intensive, so the drawpoints have to be closed because they do not have more material to mine. In case D, the rate grows at the beginning, but the peak is reached one year later than in the other systems and the fall after this peak is more gradual. This is expected because system mines the material massively and with fewer constraints than in the other cases. In case B, the rate until year five is growing, but the rates period to period are lower than the rates at the same time range in the others systems. This is due to the low chutes capacity. The peak is reached in the same year as system D, and the decline rate is more gradually than cases A and C. This is explained by the need to have the highest chutes quantity functioning to reach the production. Finally in the three last years the rate declines ostensibly.

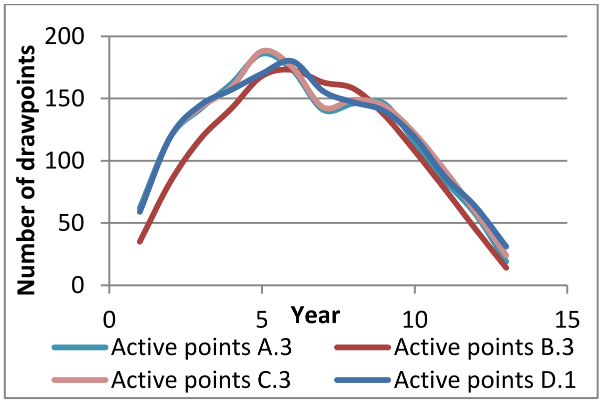

Figure 60. Active Drawpoints per year for the best cases, 1 LHD per cross-cut.

Figure 61 shows the drawpoints closing curve. This curve doesn´t begin immediately in year one and the beginning of the growth occurs in different periods for each system. In case D, the first drawpoints are closed in year three, while the remaining cases (A, B and C) present closing rates since year four. This ascent reaches a peak in year six for cases A, C and D and in year seven for case B. After the described peak, closing drawpoint rate declines and it is more abrupt for cases A, B and D, until year nine. After this year systems closing drawpoints rates range between 25 and 35 closed drawpoints per year. Case B presents a more gradual decay until year twelve, where the closing rate is sixteen drawpoints per year. After that, in year thirteen an upturn to 25 drawpoints per year can be seen. The gradual decline is explained by the need to have the major quantity of drawpoints open, because the chutes has a low capacity, so a high quantity of them is required to reach the design production run of mine.

In Figure 62 the opening drawpoint rate can be seen. As the last case, the drawpoint opening begins with high rates for all rates and then the rates begin to decrease and in this part systems are differenced. Systems A and D tends to be similar, so the rate decreases for both cases until year five and then the behavior of these systems tends to be oscillating around 25 drawpoints per year. In case B, despite system starts with the same 70 drawpoints per year, system has a gradual decrease in the opening drawpoint rate. Finally, case C presents oscillations, as cases A and D, but these are more pronounced than in the last cases. From year nine onwards a decrease in the opening drawpoint rate (final decrease) from 25 drawpoints per year to zero in some cases. Again the low capacity of chutes and the high capacity of crusher of panzer are noted and these explain the behavior in the decreasing of opening drawpoint rates.

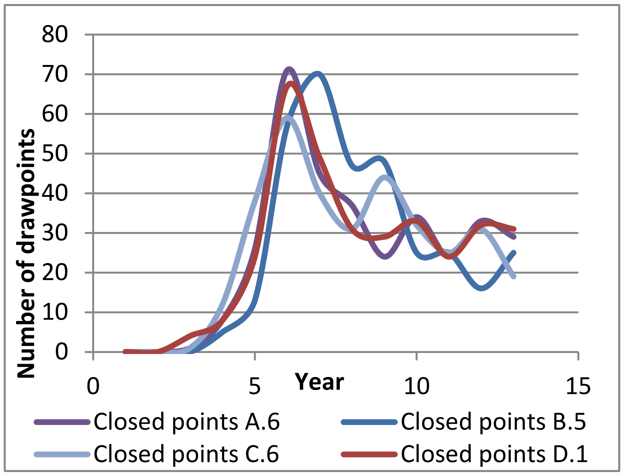

Figure 61. Closed Drawpoints per year for the best cases, 2 LHD per cross-cut.

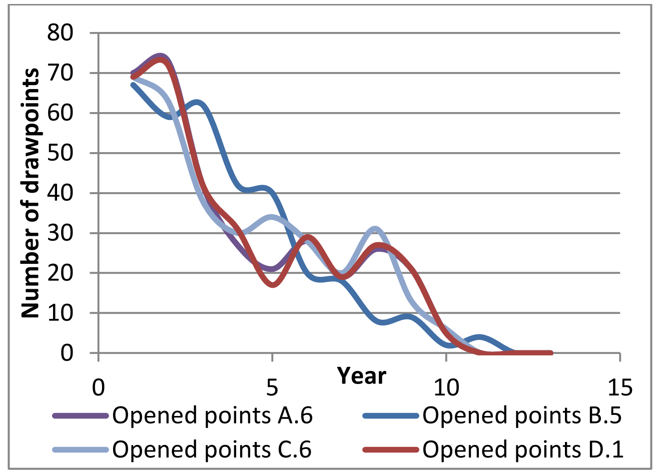

Figure 62. Open Drawpoints per year for the best cases, 2 LHD per cross-cut.

In Figure 63 the active drawpoints per year can be seen. The rate tends to increase first, after the rate reaches a maximum and after the rate decreases. The maximum rate is reached in year six and the major value is reached by system B with 191 drawpoints per year and system D with 180 drawpoints per year. In the growing part of the curve, case B presents the lowest drawpoint activity rate period to period. System B rate decreasing is gradual, but in the other systems the decreasing is more abrupt with a pronounced slope. The behavior in system B is newly explained by the chutes capacity constraints, because the chutes have a low capacity, unlike the crushers.

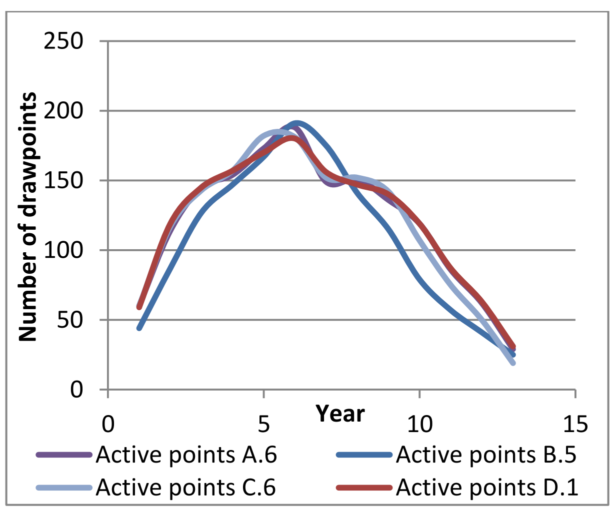

Figure 63. Active Drawpoints per year for the best cases, 2 LHD per cross-cut.

4.4.1.5 Production plan per crusher analysis.

Figures 64 to 67 show how the crushers rate production is distributed to reach the run of mine production, considering one LHD per cross-cut production. In the four Figures, only the best cases are shown for each set of cases A, B, C and D.

In case A (Figure 64), system is composed by six crushers, starting with two of them in year one. Four crushers have the highest rates and the rest has a lower rates and it operates in the following years. This case reaches a sustained production that corresponds to the production capacity design. Although all crushers produce in some years, not all crushers produce at the same rate, so a strong group contributes importantly to the global production rate.

In case B (Figure 65), each chute has a little production part and over years the production is sustained to intend to reach the production capacity design, and it was possible, but the duration of this production rate is shorter than the last reported case A (four years from year four to year eight). This case presents a lot of open area, because all chutes are in production simultaneously in an important number of years, and these chutes are located covering completely the layout (physically). This generates an operational problem, because the drawpoints should be active during important time. The last chute contributes with a very little production part (marginal).

In case C (Figure 66), there are crushers with higher capacity than in case A. Although the graphs are very similar, the principal difference is that system uses the first three crushers near the open drawpoints, and after that uses the next two crushers to complete the production with a lower rate than the other three. This situation happens in case A also, where the last drawpoint to be mined has the worst grade and the worst value and they are punished by NPV, so normally the columns are small and the reserves are low for these drawpoints and the mining is not complete or simply it does not happen. These drawpoints are located in the west of the layout.

Finally case D (Figure 67) is the more massive system in production, because it has two converging conveyor belts. The two crushers reach their capacity, and they operate during complete horizon. In the first years the first crusher has the most of production, but from year five the production is sustained by crusher number two.

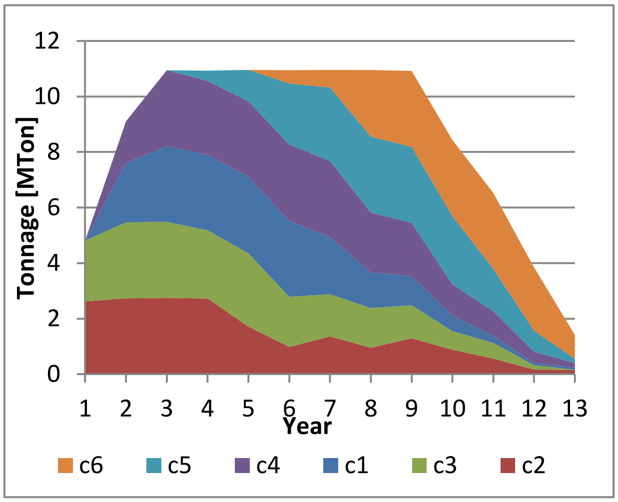

Figure 64. Production plan per crusher for case B.3.

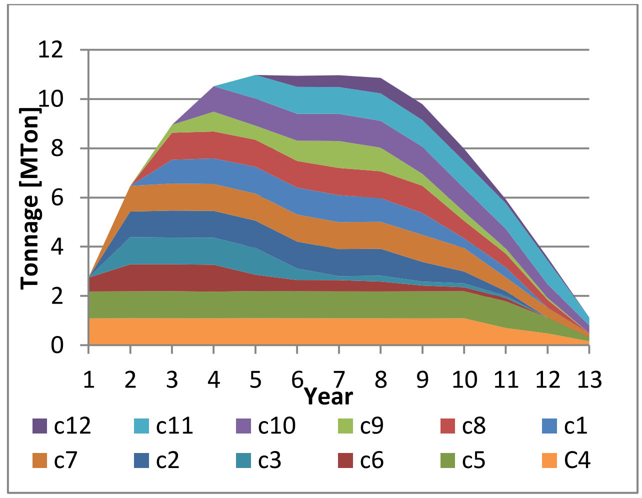

Figure 65. Production plan per crusher for case A.3.

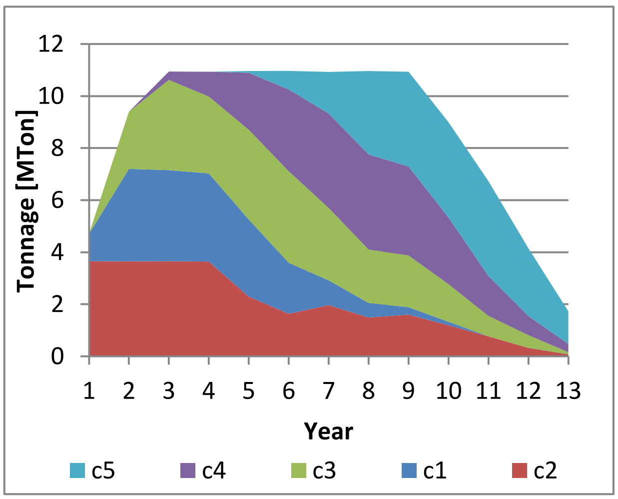

Figure 66. Production plan per crusher for case C.3.

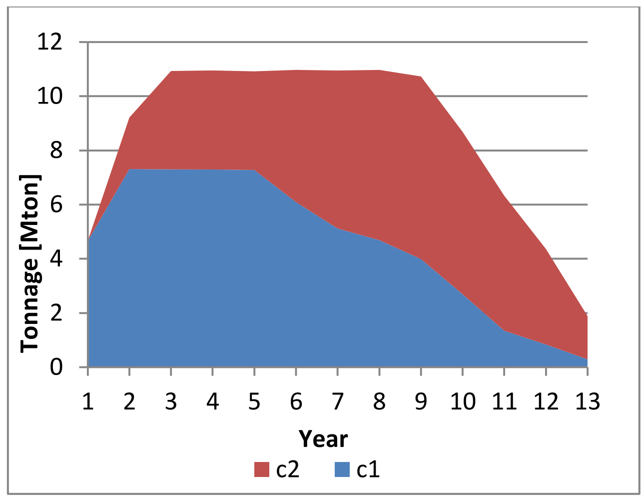

Figure 67. Production plan per crusher for case D.

Figures 68 to 70 contain the results for systems with two LHD per cross-cut production. Each cross-cut production has a one ore pass to leave the material by the two LHD. In Cases A and C, the plateau is similar to cases with one LHD per cross-cut, but in this case it is not so regular. This is because the cross-cuts drawpoints do not have the reserves distributed equally, so in the case with one LHD, the LHD takes the material according to the convenience, but in this case mining is more limited, because each LHD extracts material only for the half of drawpoints and with the half production capacity compared to the case with one LHD. The last idea demonstrates that when the LHD charges the material of the half of drawpoints, each LHD does not charge the same reserve and the same quality of material, so it is possible that one LHD does not charge all the reserve and the other charges all, but it left with idle time.

In case A (Figure 68) there isn´t clear plateau in the first operating crusher, as the case with one LHD per cross-cut production. This is because the two halves of cross-cuts have the same production capacity, and one half is saturated and the other is not, in consequence the 3,000 tpd per cross-cut are not distributed equally among the two halves of cross-cut. Now, other idea to understand the difference between the two LHD rates is the ore pass location. Probably, if the drawpoints were considered from north to south year to year until complete production of one LHD, probably the orepass not necessarily is located in the cross-cut center. In summary, to improve the results of this case, the LHD´s should have a different production rates and the ore pass should be located at the center of cross-cut production or the LHDs should have the same production rates, and the location of discharge ore pass should not be in the center of cross-cut necessarily. In spite of high capacity crushers, five of six of them operate an important part of the planning horizon, due to the imbalance that the location of discharge ore pass generates. In consequence, a higher quantity of crushers should be in operation to reach the global production rate. (The objective function brings with it the production maximization per year).

In case B (Figure 69), the chutes operate during most of the planning horizon period and the graph is similar to case B with one LHD per cross-cut production. This system requires having most of the chutes operating over the planning horizon, which results in having many drawpoints active, to reach the global design production run of mine. The production does not reach a plateau and this involves an important quantity of periods and the maximum production is slightly lower than in case B with one LHD per cross-cut production. Some chutes contribute with less production than others, inclusive the last chute in operation contributes marginally to the production.

Case C (Figure 70) is very similar to case C with one LHD per cross-cut, but the plateau shows slight irregularities.

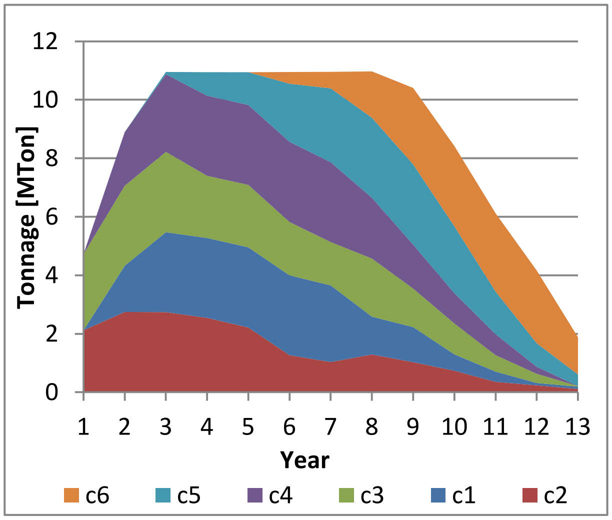

Figure 68. Production plan per crusher for case A.6.

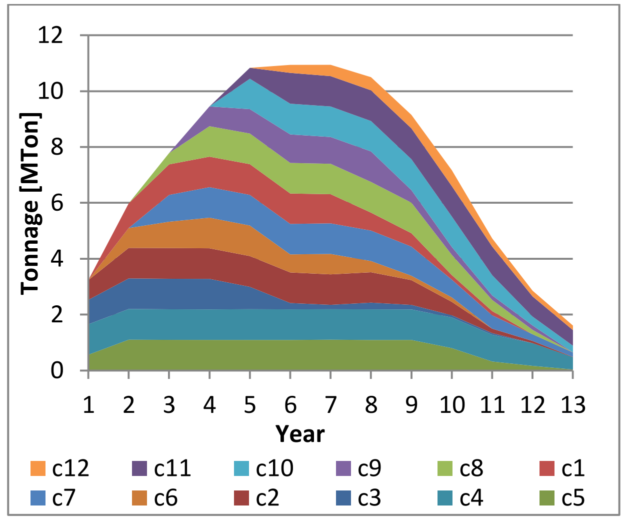

Figure 69. Production plan per crusher for case B.6.

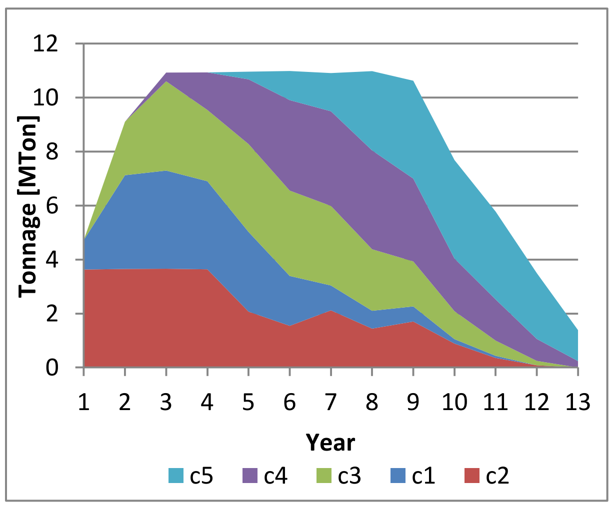

Figure 70. Production plan per crusher for case C.6.

Figures 71, 72 and 73 show the productivity per crusher/chute for the best cases, considering for each set of cases the best case with one LHD per cross-cut and the best case with two LHD per cross-cut. Case A reaches the crusher production for all crushers. The best case has six crushers (maximum quantity in the set of cases). In case B (Figure 72) the capacity is reached in the most of the crushers, except the last one that has less reserves and bad quality of ore. Case C (Figure 73) presents a low performance in crusher three, and this is accentuated in the case with two LHD due to the loss of the flexibility. Generally the crushers reach their respective capacities.

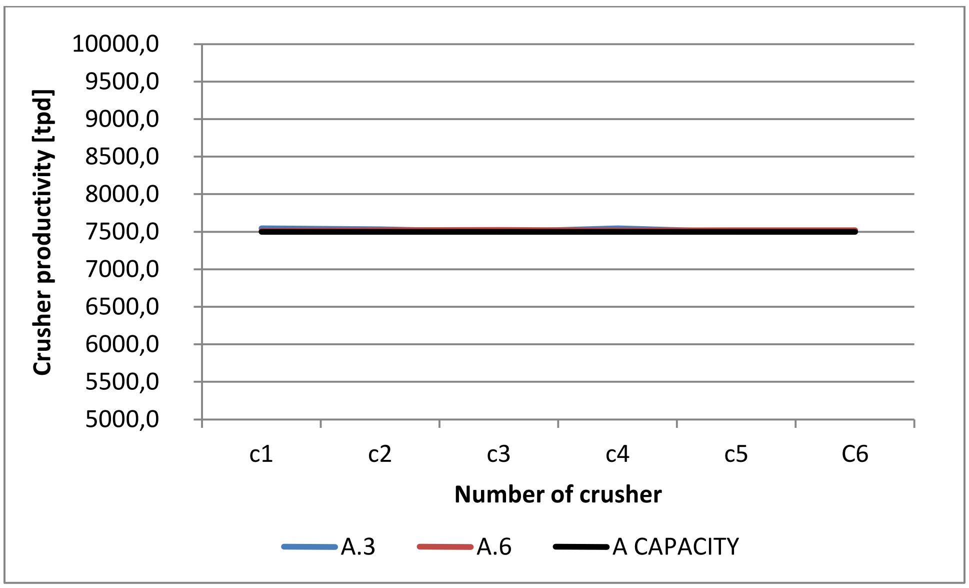

Figure 71. Production capacity crushers for case A.

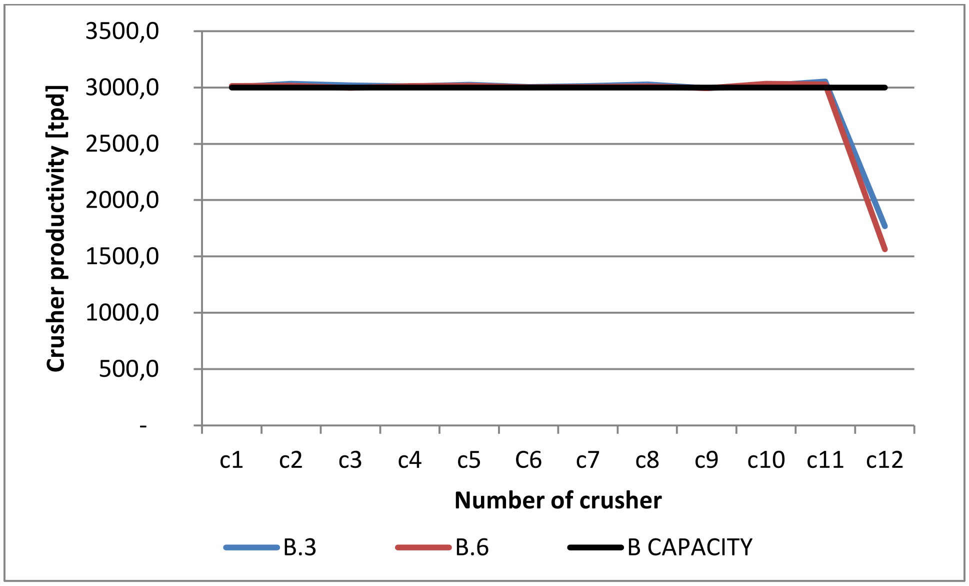

Figure 72. Production capacity chutes for case B.

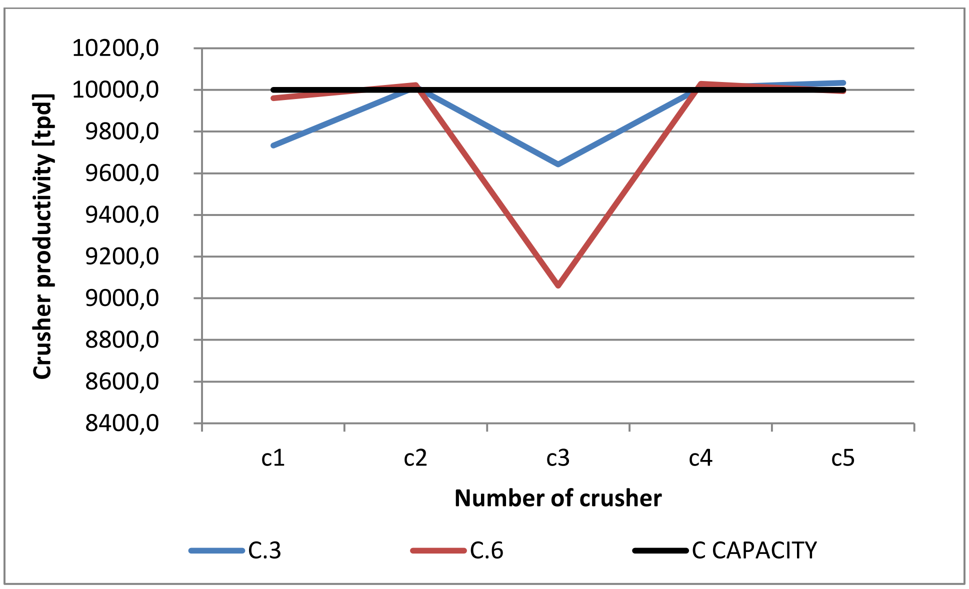

Figure 73. Production capacity crushers for case C.

4.4.1.6 Production plan per cross-cut analysis.

Reviewing in detail Figures 74 and 76, cases A and C tend to reach the saturation rate for cross-cuts production (3,000 tpd), but this situation is not sustained in time, but occurs sporadically. The tendency to reach this saturation rate is less dominant in cases A and C with two LHD per cross-cut than in cases with one LHD per cross-cut. Given that the drawpoints assignation to charge material is more limited, it not necessarily adjusts to obtain the maximum productivity as the case with one LHD. Case D reaches the saturation production for each cross-cut production better than cases A and C with two LHD, because this case has fewer constraints. Finally, case B does not reach the maximum production for each cross-cut steadily, but by peaks. This situation means that the bottle neck exists in the chutes, because this system operates with a small units to handling material, so these units need to operate simultaneously to reach the production, and the panel caving is a method that needs an advance in some direction and this implies that the mining system should operates according to the closeness to the active drawpoints. The majority of the cases presents a low quantity of periods in regime state (10%-20% of the horizon), but with some exceptions. Case B has the an important quantity of cross-cuts in regime state an important quantity of periods.

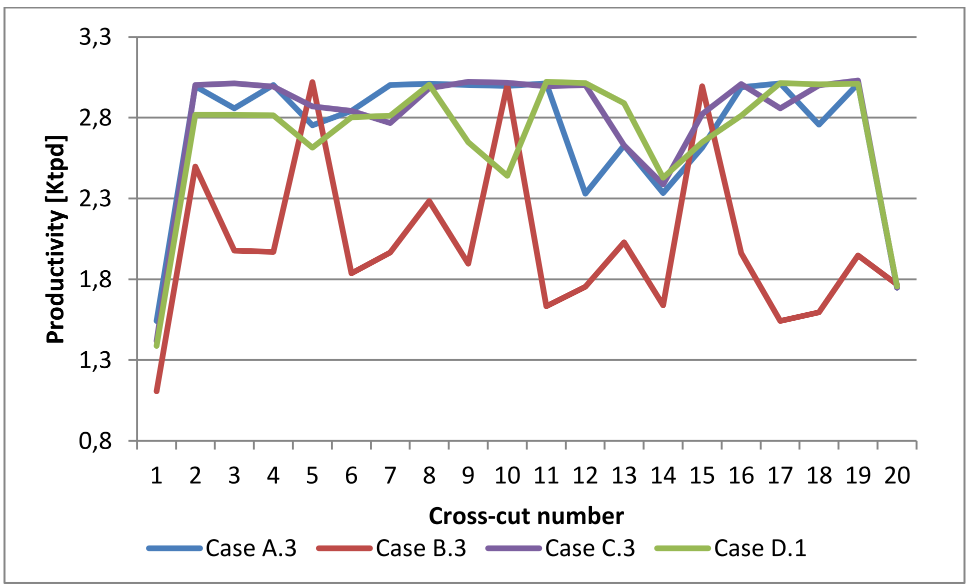

Figure 74. Productivity per cross-cut best cases, 1 LHD per cross-cut.

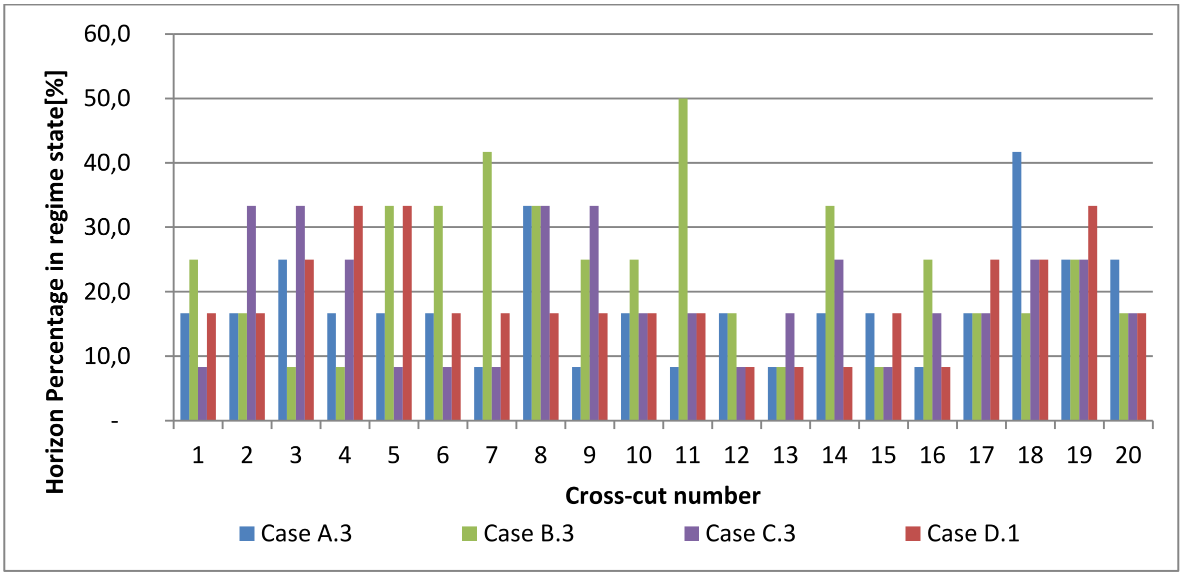

Figure 75. Horizon percentage in regime state best cases, 1 LHD per cross-cut.

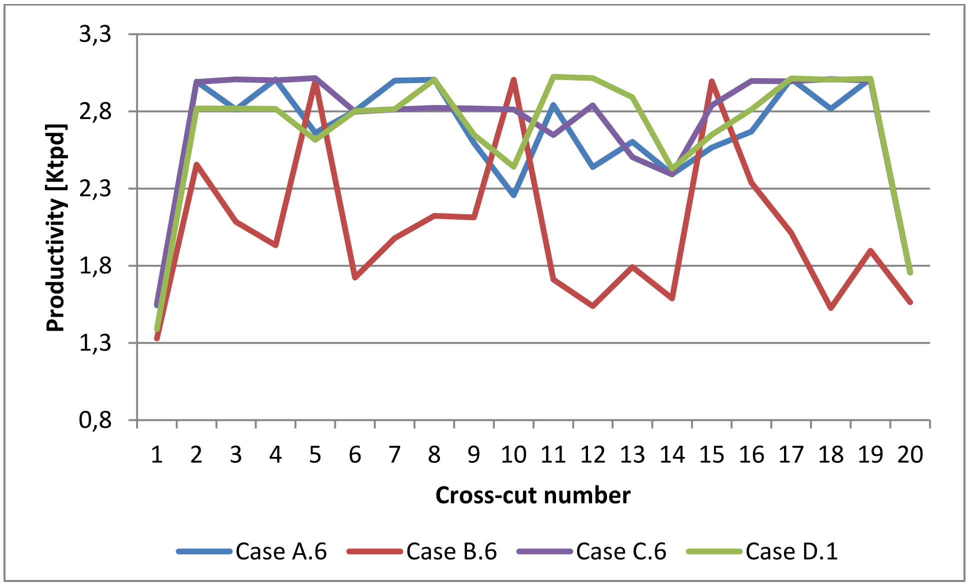

Figure 76. Productivity per cross-cut best cases, 2 LHD per cross-cut.

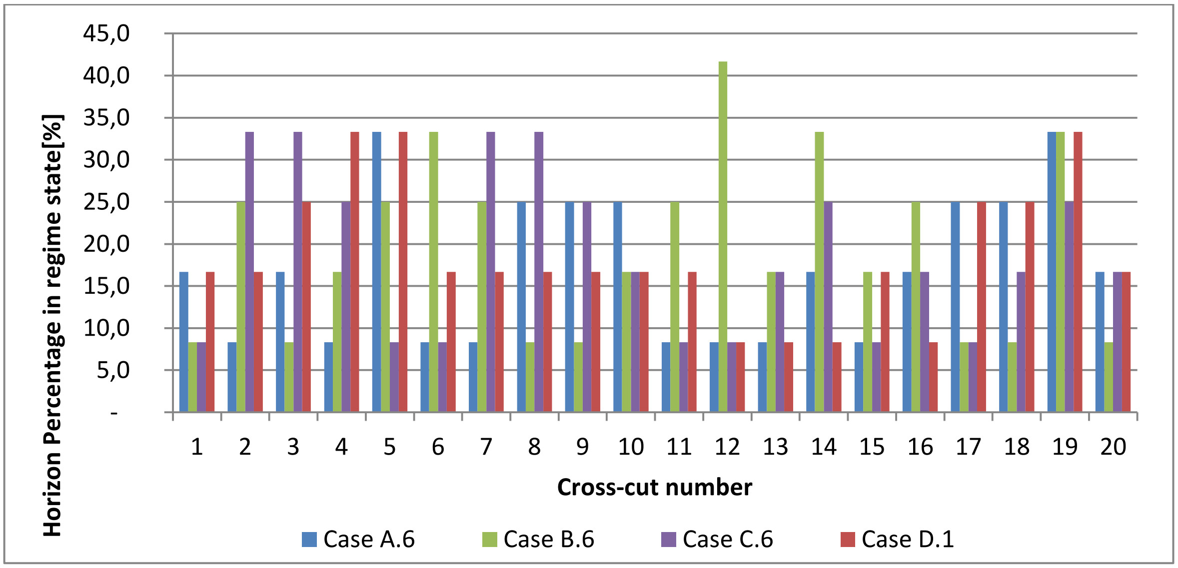

Figure 77. Horizon percentage in regime state best cases, 2 LHD per cross-cut.

4.4.2 Systems E, F and G

4.4.2.1 Objective function results.

In the following tables (Tables 16, 17 and 18) the best result for each system is presented, considering each drawpoint as a possible mining start. The difference with systems A, B and C is the crushers capacity, but maintaining the run out mine capacity.

Table 16 has to be compared to Table 11 (Case A). In all cases the objective function tends to increase the value. The increasing average is 39 MU$. The difference between the worst and the best case is reduced. This means that the worst scenarios increase the value. The tendency to have high values is on systems with more number of crushers, because they have more capacity (this doesn´t mean that the production distribution is equal for each system component with the same hierarchy).

Table 16.NPV for case E group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
4 crushers [MUS$]	1,088	1,074
5 crushers [MUS$]	1,117	1,096
6 crushers [MUS$]	1,123	1,100
Max NPV [MUS$]	1,123	1,100
Min NPV [MUS$]	1,088	1,074
Difference [MUS$]	35	26
Percent. Diff. [%]	3.1	2.4

In Table 17, the results for case F are shown. If these results are compared with the corresponding case: (B), an important increasing NPV value is produced, and it averages 108 MU$, a value more important than cases A and E. The tests are similar between those, so the difference is really little and is around 0.5%. This situation indicates more sturdiness faced to change in the number of crushers or chutes, considering always the best starting point for each system.

Table 17. NPV for case F group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
10 chutes [MUS$]	1,110	1,091
11 chutes [MUS$]	1,105	1,086
12 chutes [MUS$]	1,110	1,091
Max NPV [MUS$]	1,110	1,091
Min NPV [MUS$]	1,105	1,086
Difference [MUS$]	5	5
Percent. Diff. [%]	0.5	0.5

Finally Table 18 shows an important difference between cases C and G and the difference average is 20 MU$. The percent difference with respect to case C averages 50%. In the last cases (E, F and G), the maximum and minimum increase. The NPV increases with the number of crushers.

Table 18. NPV for case G group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
3 crushers [MUS$]	1,088	1,079
4 crushers [MUS$]	1,117	1,101
5 crushers [MUS$]	1,124	1,101
Max NPV [MUS$]	1,124	1,101
Min NPV [MUS$]	1,088	1,079
Difference [MUS$]	36	22
Percent. Diff. [%]	3.2	2

Table 19 shows the best and worst cases, and cases with two LHD per cross-cut present slower values than in cases with one LHD per cross-cut. The range between the best and worst case is lower than cases A, B and C.

The best result is shown for sets E, F and G, to conceptually compare systems.

Table 19. Best and worst cases for cases E, F and G.

	1 LHD per crosscut	2 LHD per crosscut
Max NPV [MUS$]	1,124	1,101
Min NPV [MUS$]	1,088	1,074
Difference [MUS$]	36	27
Percent. Diff. [%]	3.2	2.5

4.4.2.2 Production plan.

In Figure 78 the best cases with one LHD per cross-cut production are shown. The plans are similar between them unlike cases A, B and C where higher differences were presented. While higher differences don't exist about the best plan between cases A, B and C, the plateau is obtained in all cases, so the plan can be selected choosing the most rentable infrastructure, without thinking in production lost. But the last idea does not mean that the three cases have the same objective function value. The plans are similar and they reach the run out mine capacity, because the capacity increases for chutes and crushers.

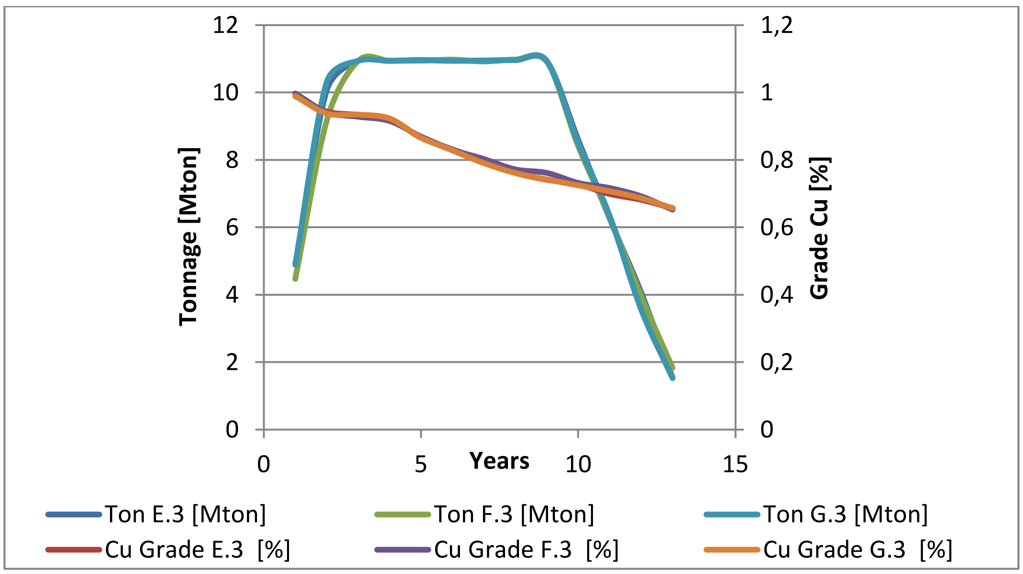

Figure 78. Best production plans with one LHD per cross-cut.

In Figure 79 the best production plans for two LHD per cross-cut are shown. Again cases are similar between them, because the capacity increases for crushers and chutes that permits having much more combination to distribute the production, obtaining the same result. As in cases A, B and C, the plateau with 2 LHD per cross-cut is worse with respect to cases with one LHD per cross-cut production. This is because, as it was already mentioned, the ore pass isn´t located in a cross-cut production part such that the productions are similar. The run out mine production is reached, and system has an acceptable performance, considering the large plateau.

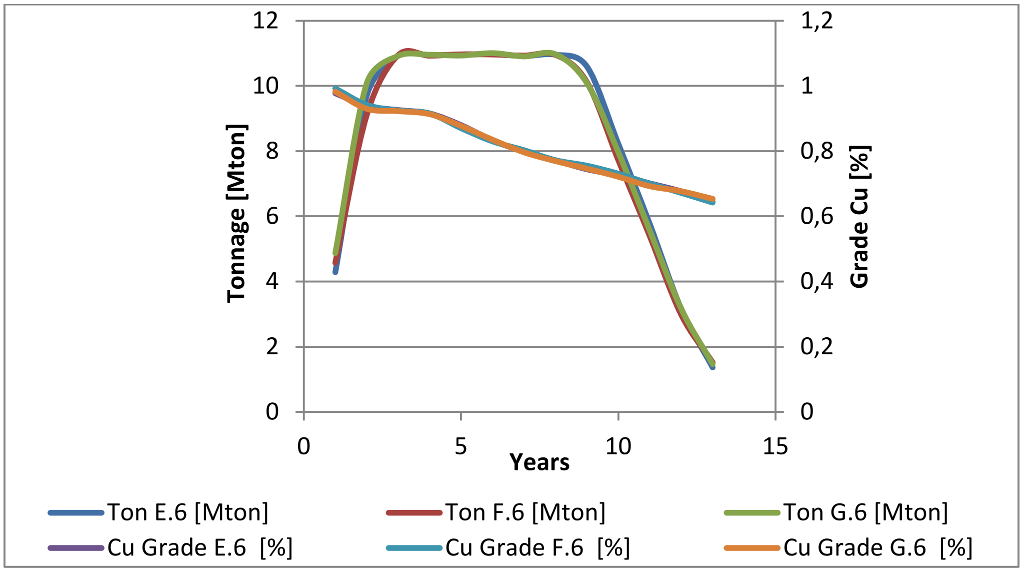

Figure 79. Best production plans with two LHD per cross-cut.

4.4.2.3 Drawpoints opening sequence.

The analyses of the sequences in the three cases with one LHD (Figures 80, 81 and 82), indicate that the open drawpoints in year one are located at north-east, because the starting point has this location and it is the same for the three cases. At the last years changes in sequences can be seen and some "islands" and temporal discontinuity appear (as in cases A, B and C), because the low value of the material associated with drawpoints. These discontinuities and "islands" (marked with circle) respect the constraints, and if the requirements are that these don´t exist, so the neighbors and advance constraints should be modified. In this group of cases it is less evident the change in sequence of case F, than in cases A, B and C, where case B was different, because it was limited by the capacity and the horizon time was longer than in cases A and C. In addition, the capacity run of mine is reached, and it is not necessary to have opened all drawpoints to reach this production. The geometries are regular in the first years, but starting year three the opening starts to advance to the west part of layout. In the next years the concentric shape is lost, and in the last years it is from north to south, and this sequence responds to the layout shape.

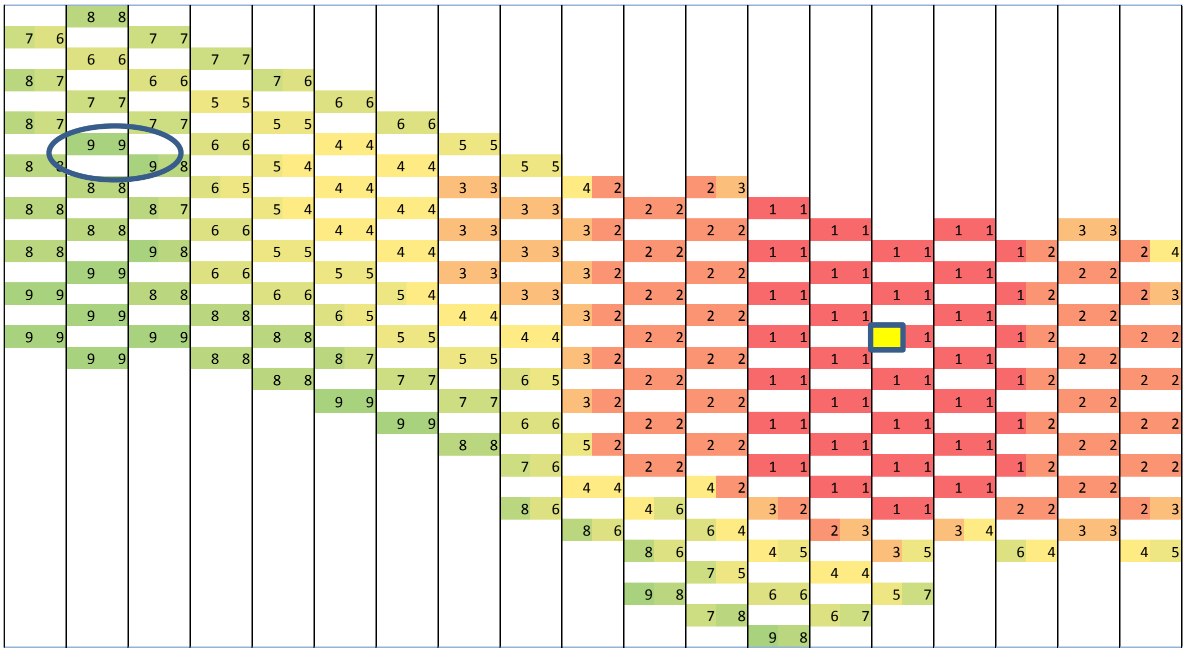

Figure 80. Drawpoints opening sequence for case E.3 with one LHD per cross-cut.

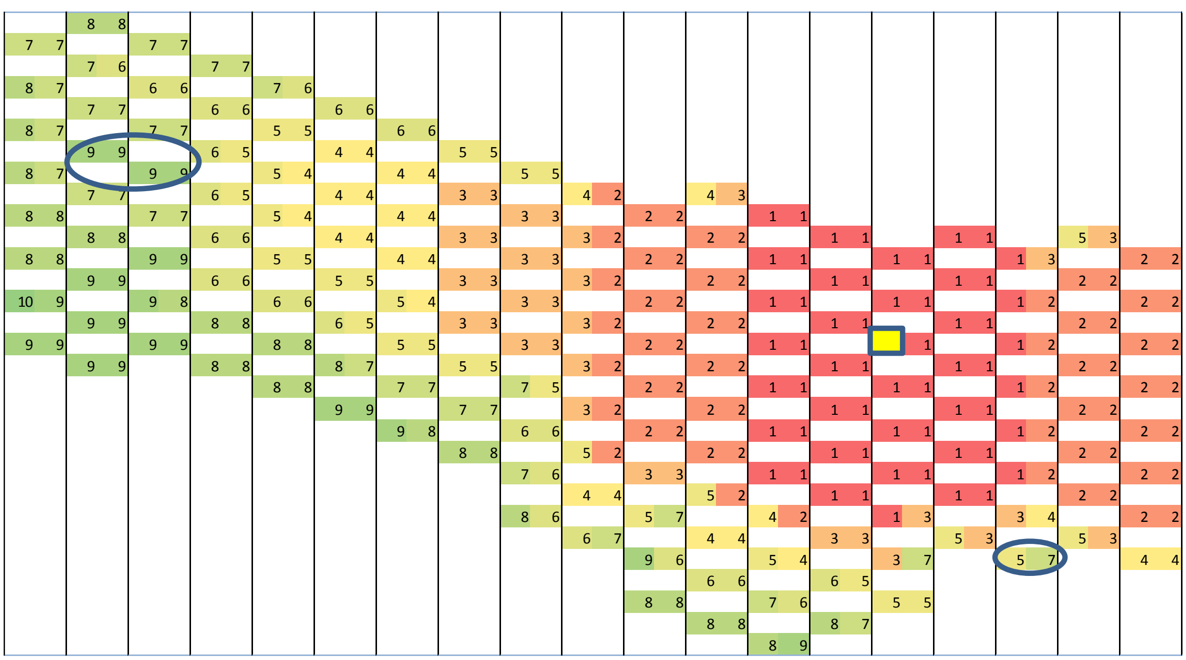

Figure 81. Drawpoints opening sequence for case F.3 with one LHD per cross-cut.

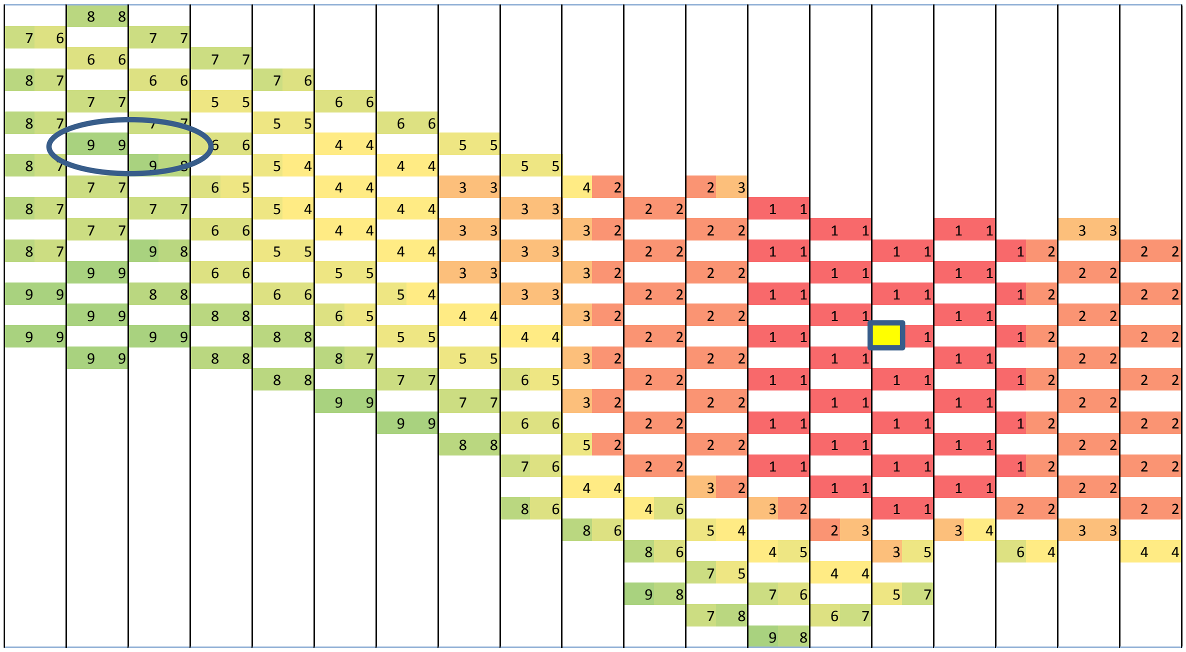

Figure 82. Drawpoints opening sequence for case G.3 with one LHD per cross-cut.

Figures 83 and 84 shows the front cave line for years one and two. In the two cases the cave lines are very similar, so the behavior sequences is scenically the same.

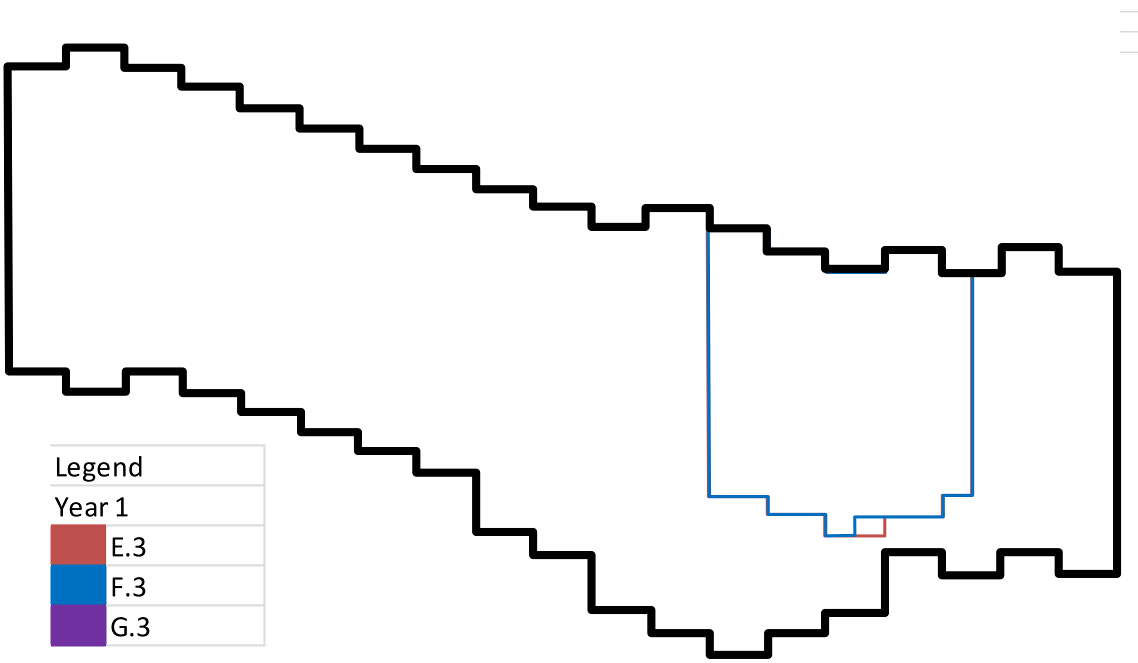

Figure 83. Comparing front cave lines for year one in cases E.3, F.3, and G.3.

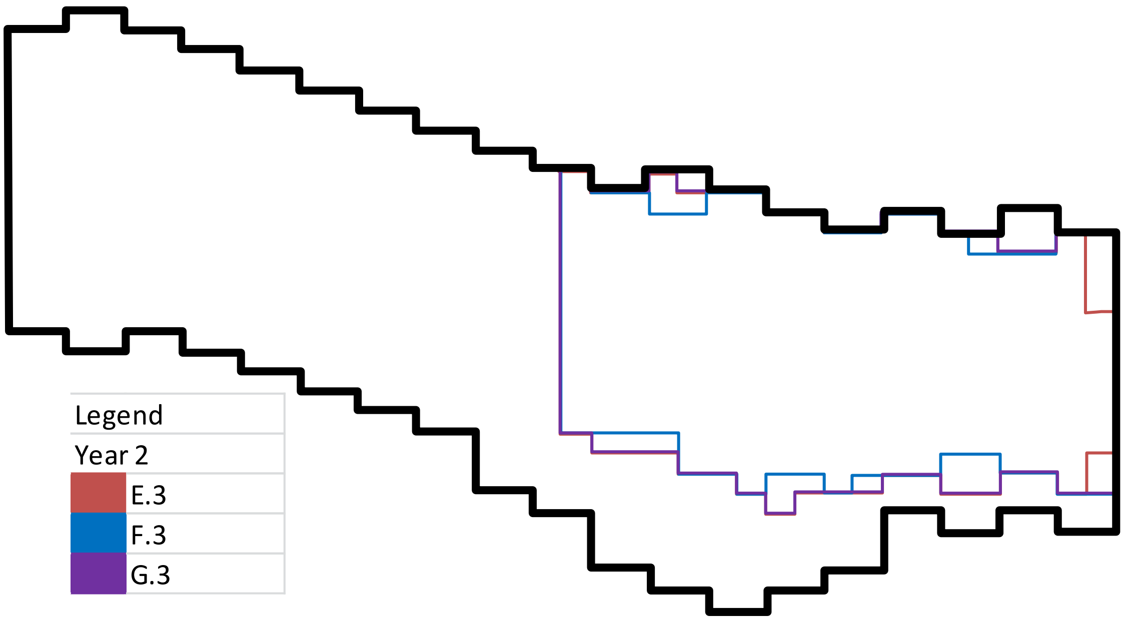

Figure 84. Comparing front cave lines for year two in cases E.3, F.3, and G.3.

In this group of cases (Figures 85, 86 and 87) there exist some differences with respect to the sequences with one LHD. Important differences between the sequences with two LHD can be seen, especially in the first years (year one), where case F has this drawpoint group more to the north than the other two cases. This difference is produced because the infrastructure location should be reconciled with the objective function year to year. In case G (Figure 87) some irregularities can be seen from year three onwards. In this sequence it appears drawpoints that are opened in year ten, unlike the sequence with one LHD, where the drawpoints are open a little earlier. The west sector mine presents the same discontinuity (marked with circle), as in cases A, B and C. In cases E and G, after year one, there exist some drawpoints that don't open immediately, because of the economic evaluation for the objective functions. In year three the advance direction is for the west, because in year two the west sector is completed. In the last opening years, the drawpoints opening starts to be from north to south. With the sequence review it is possible to detect the low value drawpoints.

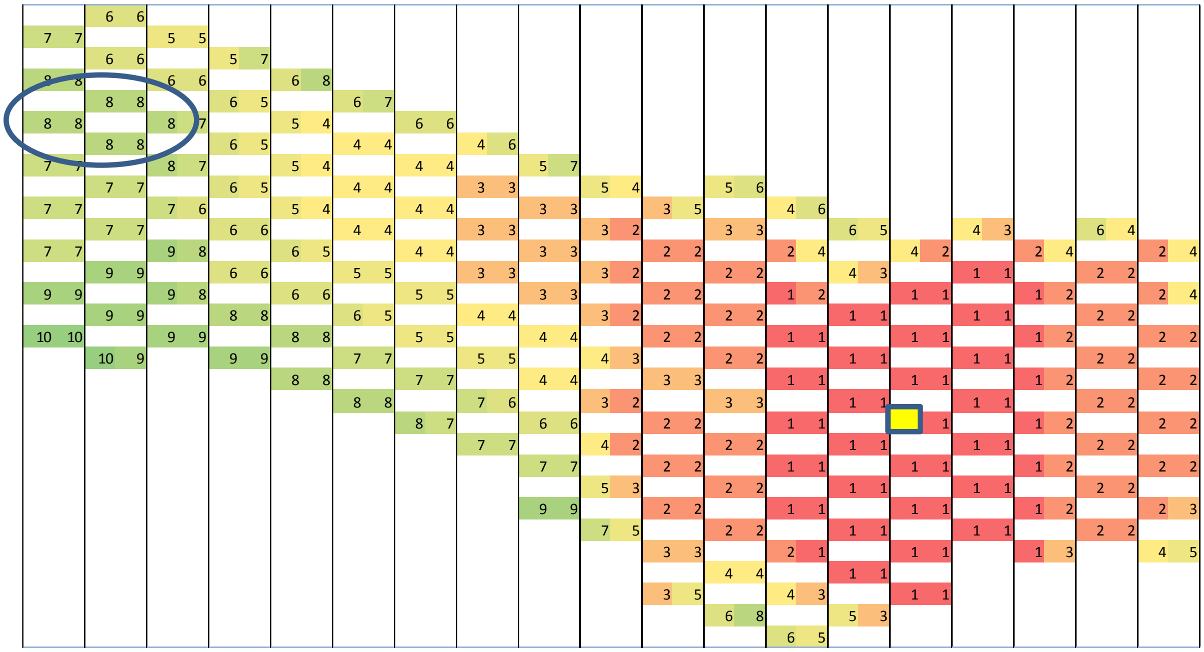

Figure 85. Drawpoints opening sequence for case E.6 with two LHD per cross-cut.

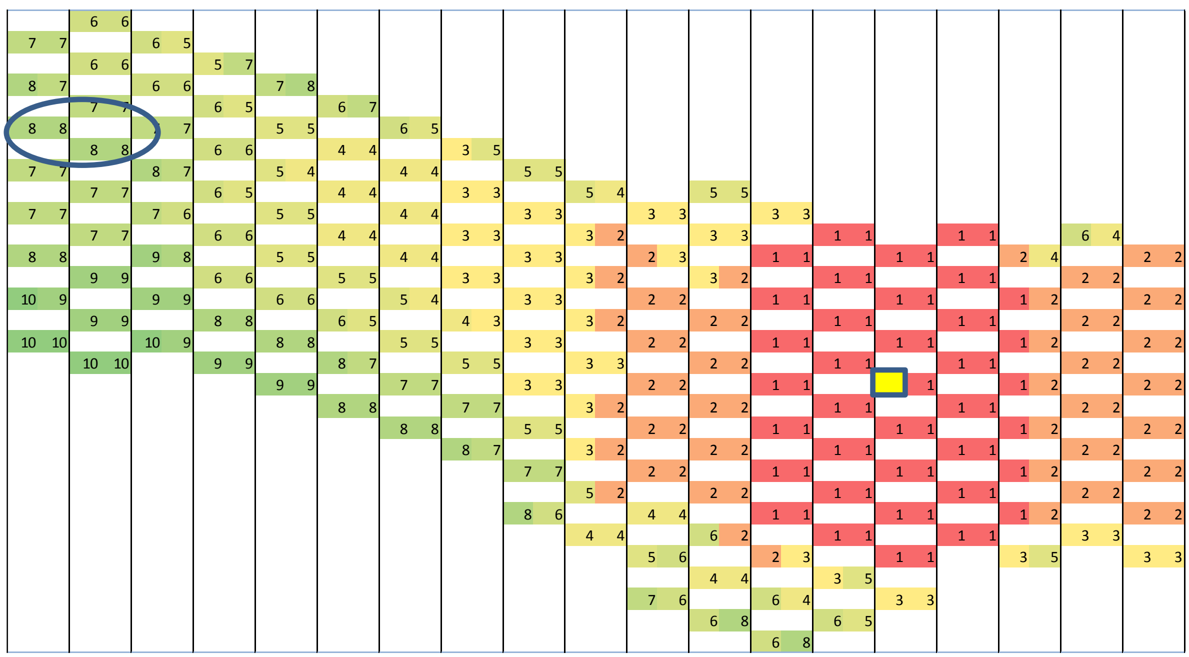

Figure 86. Drawpoints opening sequence for case F.6 with two LHD per cross-cut.

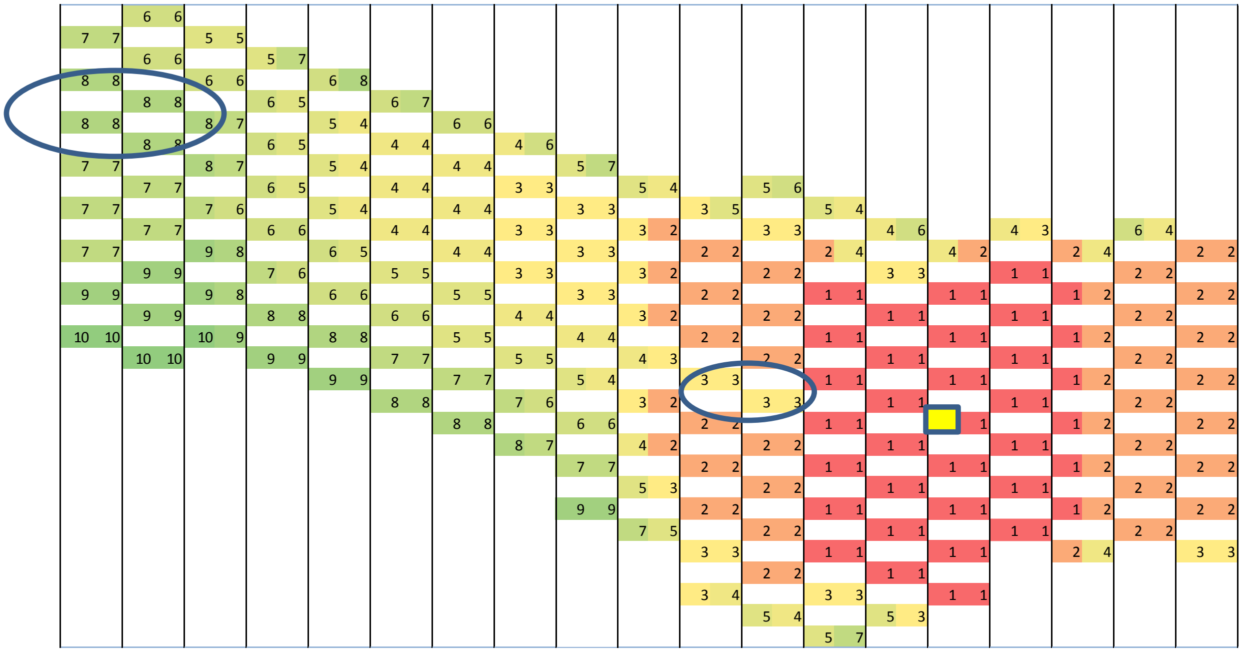

Figure 87. Drawpoints opening sequence for case G.6 with two LHD per cross-cut.

Figures 88 and 89 show the front cave lines in year one and two. The polygons show that differences aren´t important, but the sequences are different.

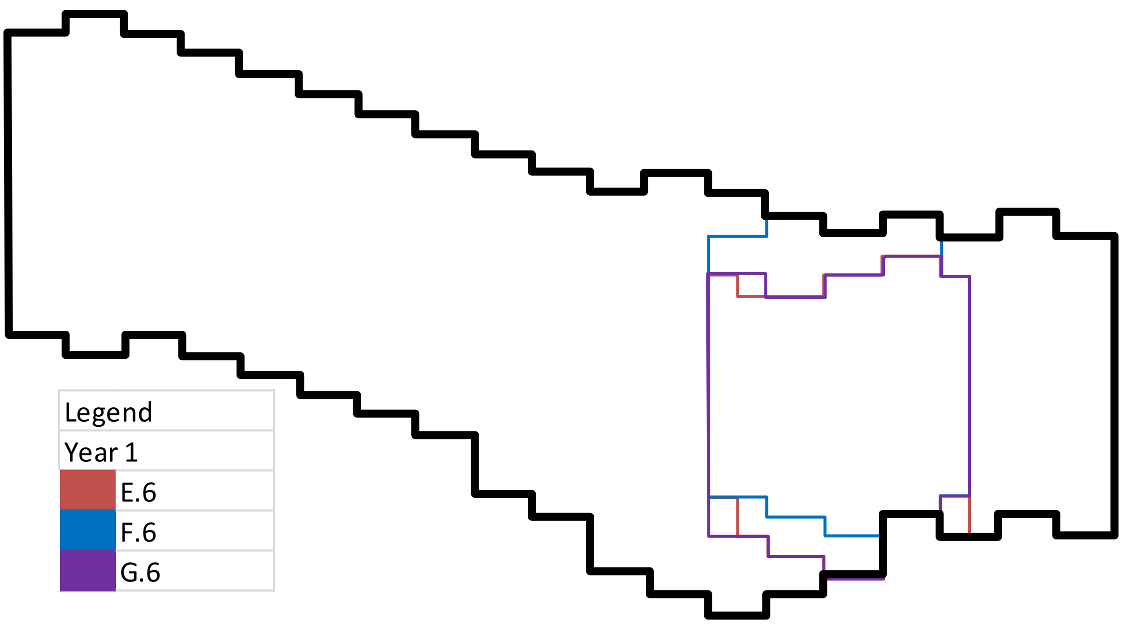

Figure 88. Comparing front cave lines for year one in cases E.6, F.6, and G.6.

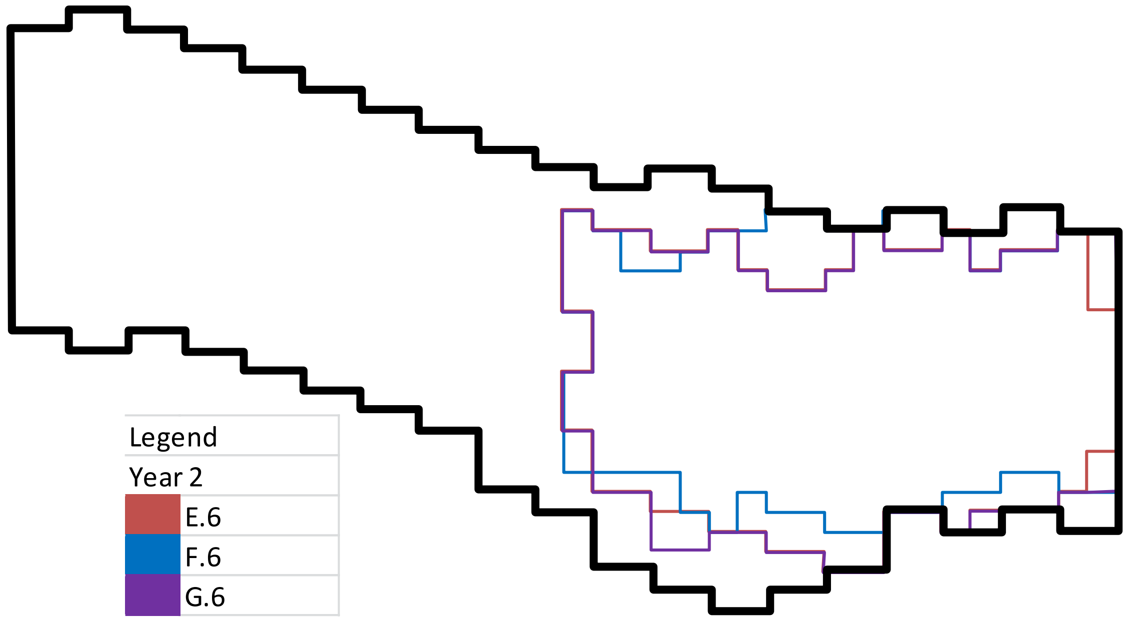

Figure 89. Comparing front cave lines for year two in cases E.6, F.6, and G.6.

4.4.2.4 Drawpoint opening, closing and activity analysis.

Figure 90 shows the opening drawpoints rate. The maximum rate happens in year two (70), but in the next years it decreases to 30 until period eight. In the last horizon part the rate decreases to zero in period ten. Between years two and eight the graph presents some fluctuations. The important thing is that in the first periods (year two) system opens too much drawpoints and finally with 30 is enough to maintain system in operation. In the first years system generates more area than in the other periods. In the closing case graph (Figure 91), the graph shows an initial increasing the closing rate and the maximum is reached in year five (70 drawpoints per year). In the next years this value decreases to 30 drawpoints per year and presents fluctuations until the end. The difference in rates for closing is because in the first years too much drawpoints are open, and it is required to close to the extent that they deplete. After that the rate is the same than the opening rate (30).

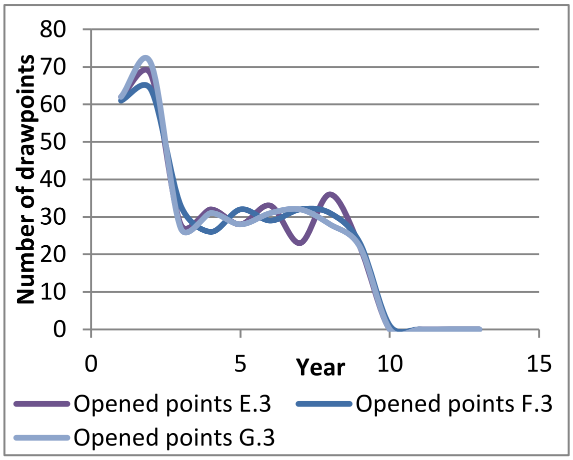

Figure 90. Open Drawpoints per year for the best cases, 1 LHD per cross-cut.

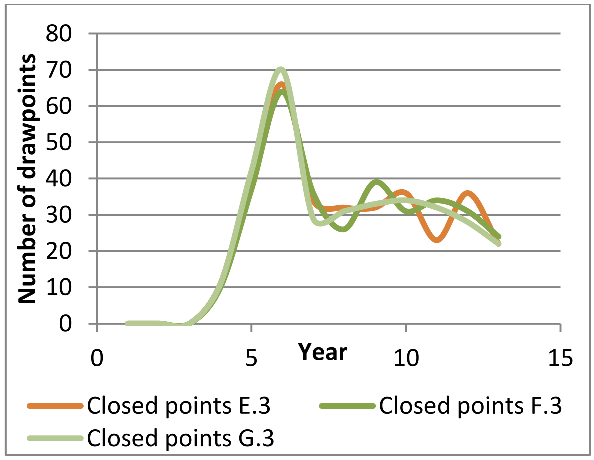

Figure 91. Closed Drawpoints per year for the best cases, 1 LHD per cross-cut.

Figure 92 displays the graph with the drawpoint activity per year. The maximum is on year five: 180 drawpoints, but in the next years the value is 140 drawpoints per year and is maintained until year nine. Finally, in the three cases the rate decreases. The three cases present similar curves with a maximum with a short duration. The maximum production is found between years three and six, and if the plan production graph is considered, in year three the maximum production has been reached, so with a little more than 140 drawpoints is the minimum number to sustain the production and higher opening drawpoints rates, indicates the existence of idle drawpoints, as in year five.

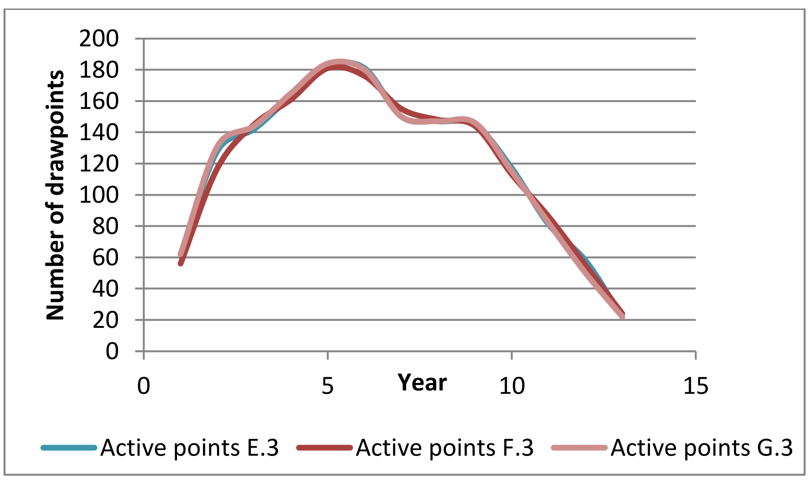

Figure 92. Active Drawpoints per year for the best cases, 1 LHD per cross-cut.

Figure 93 shows the drawpoint opening rate considering the case without LHD. In the first and second year the opening is intensive in the three cases. From year three a decrease in the rate can be seen until year four, where the value is 30, and this rate remains in this value until year seven, for the three cases and then the rate decreases. Similar to the previous case, the strategy was to open a lot of drawpoints in the beginning and then the rate needs to equilibrate. This system is likely to have idle drawpoints, but this permits to have more flexibility in the drawpoint selection for mining, for example, in case of mining system component failure. In case of closing (Figure 94), a peak appears in year five, as in case of opening, but obviously in another year. This situation can be explained by the excessive drawpoint opening in the first years. Each drawpoint doesn´t have the same reserves and this is an important factor that determines the drawpoints life extraction. After the peak, a decreasing in the closing drawpoint rate is produced, but in year seven the rates begin to differentiate, because system F presents an important decreasing in this production rate, with in the other two cases doesn´t happen.

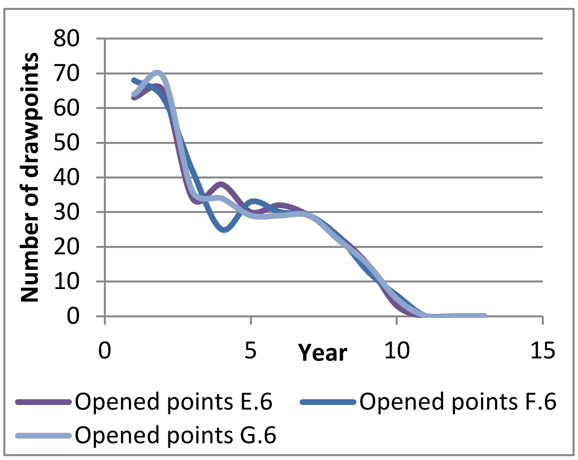

Figure 93. Open Drawpoints per year for the best cases, 2 LHD per cross-cut.

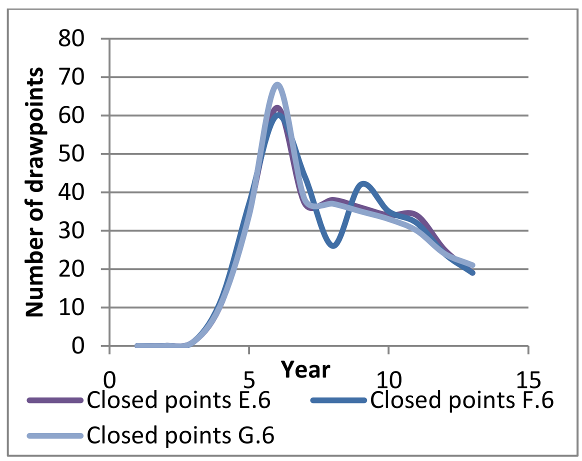

Figure 94. Closed Drawpoints per year for the best cases, 2 LHD per cross-cut.

Figure 95 shows the drawpoints activity rate per year. Production plan shows between years three and six, the highest production is reached and sustained. Between these years a maximum exists only in year five, but, clearly with the drawpoints active in year three it is possible to sustain the production rate and in later years some drawpoints are idle, because they are active, but they aren´t mined. So, a higher quantity of drawpoints than the minimal requirements was open and it was because a neighbor drawpoint has an attractive grade, so the advance tends to get to this drawpoint. Finally in year nine a decrease was produced. The three cases are similar and there don´t present high differences.

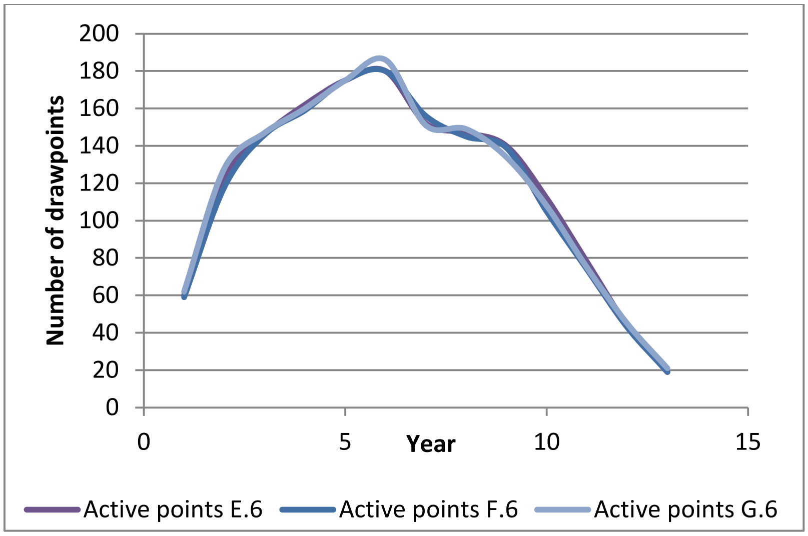

Figure 95. Active Drawpoints per year for the best cases, 2 LHD per cross-cut.

Some differences are noted between cases with one and two LHD, in the opening drawpoints graphs, where in the last years less drawpoints are opened in the case with two LHD than the case with one LHD. Finally in cases I, J and K the curves of drawpoints activity are equal.

4.4.2.5 Production plan per crusher analysis.

Figures 96, 97 and 98 show the crushers or chutes production behavior for each case. In case E with one LHD per cross-cut production (Figure 96), only with three crushers the designed production was reached in year two, in contrast to case A (with one LHD per cross-cut), where the production was reached in year three with four crushers operating. This situation is predictable, because a capacity increase for crushers was applied. From year six a gradual change in operation crushers is produced, because the other three crushers go into operation mostly, but crusher six contributes less than the others, because it is located where the reserves are low. In case F (Figure 83), the design production is reached (30,000 tpd). In addition, in this case the chutes are not operating with full production (as in case B), but until year six, the most production is concentrated in the first six chutes and after that, gradually, the production is sustained by the other six chutes. The plateau is from year three to year nine, and unlike the previous case E, the active units are more, but if the association for units were replaced by the units of case A, probably, the result would be similar.

In case G, the solution is with five crushers as in case C with one LHD per cross-cut, but it is slightly different, because while the first crusher to operate (C2) has a similar behavior to the previous test C. Crusher 1 (C1) makes the difference, reaching eight Mton per year, situation that in case C occurs with seven Mton per year. The others crushers show a similar activity than in case C. An important conclusion is that the solution is scenically the same, but with different distribution in the internal system. Probably the NPV could be a good factor to choose, but other results can be used, depending on the enterprise strategy.

In case of systems with two LHD per cross-cut, the results per crusher or chute are shown in Figures 99, 100 and 101. In case E (Figure 99) the three first crushers have a better performance than the crushers in case A. In case E the crushers reach 10 Mton per year and in case A the crushers reach 8 Mton per year. In addition the fourth crusher begins to operate from year two in case E gradually, unlike case A, where the same crusher begins to operate from the first year. The other crushers operate similarly to case A. In summary, the capacity increasing means that the crushers that they operate in the first years increase their production rate, because these crushers are associated with the best value drawpoints. The plateau is similar than in the case with one LHD per cross-cut.

In case F (Figure 100), there are lots of chutes and the two principal differences with case B are: on the one hand the productions rates are different per chute, unlike case B where all rates were similar, on the other hand the crushers do not operate simultaneously as case B, but in two groups (six and six). Case F reaches the design production steadily (two LHD per cross-cut), unlike homologous case B. In addition, the production for the case with one LHD is higher than the case with two LHD because the important number of constraints incorporated. Finally case G with two LHD per cross-cut shows a solution with five crushers as the homologous case C. The last two cases are similar with little differences; like that the crusher one has less production in the last years, unlike case C. The last crusher to go into operation contributes a little to the global production rate. The design production rate is reached. In summary case C and G are similar, which allows to infer that in case C doesn´t have exist an important “bottle necks” that could disappear with the capacity increasing. The other cases are different.

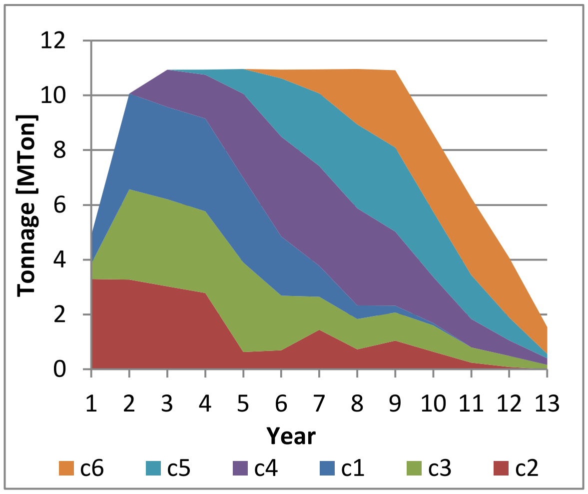

Figure 96. Production plan per crusher for case E.3.

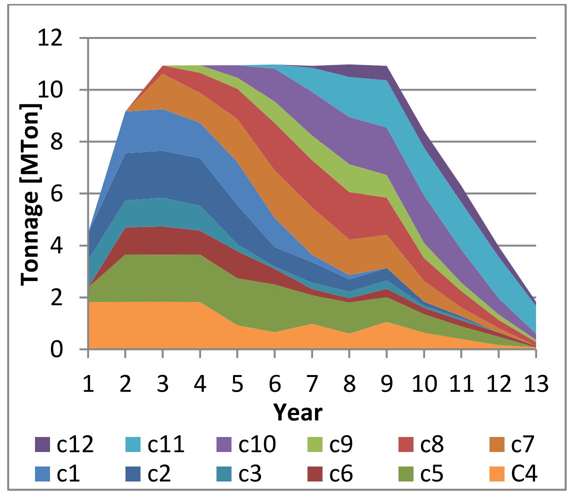

Figure 97. Production plan per crusher for case F.3.

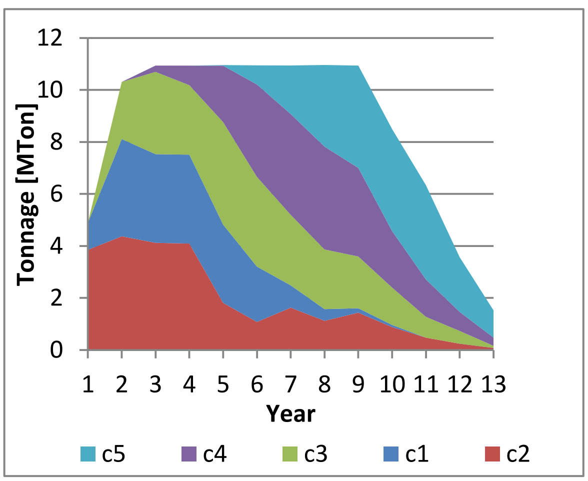

Figure 98. Production plan per crusher for case G.3.

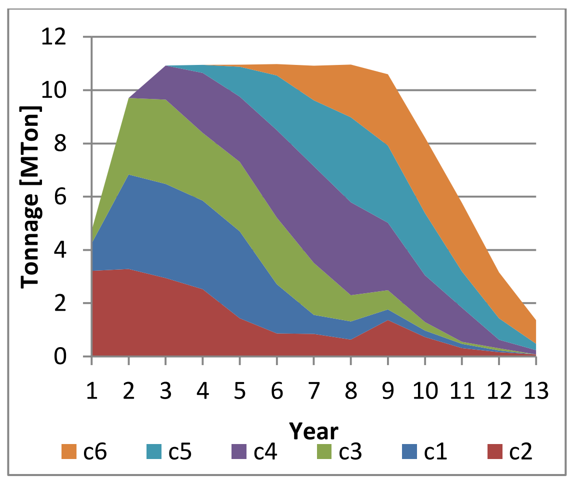

Figure 99. Production plan per crusher for case E.6.

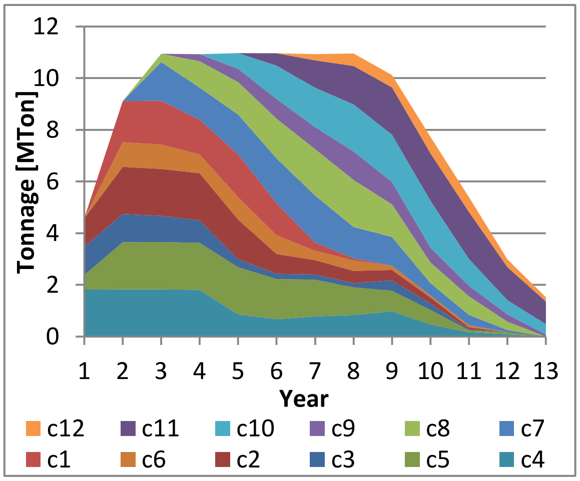

Figure 100. Production plan per crusher for case F.6.

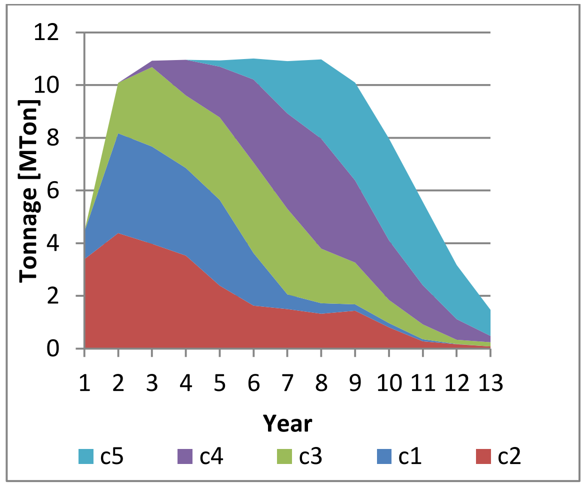

Figure 101. Production plan per crusher for case G.6.

Figures 102, 103 and 104 show the maximum productivity for each crusher/chute. In the three systems the crushers/chutes are not saturated except in case F, where some crushers are saturated. Always the last crusher has less production in these results. This result confirms that the crushers are not the bottleneck for this case. In cases A, B and C, the crushers are more saturated.

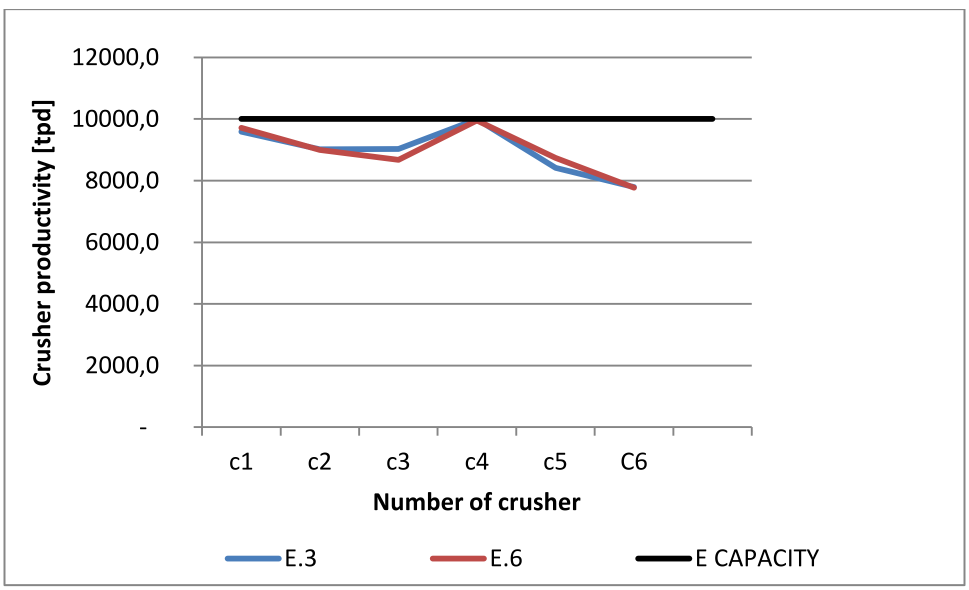

Figure 102. Production capacity crushers for case E.

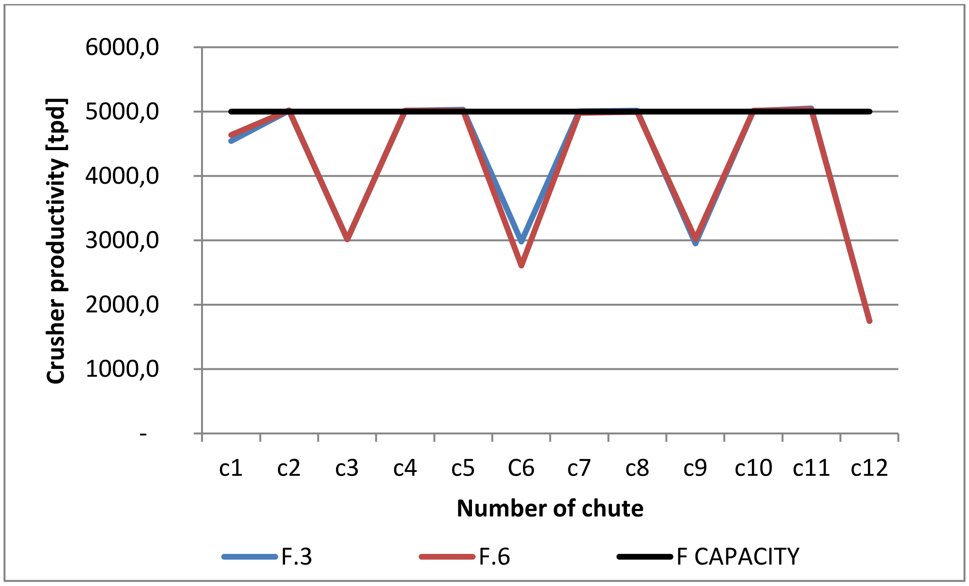

Figure 103. Production capacity chutes for case F.

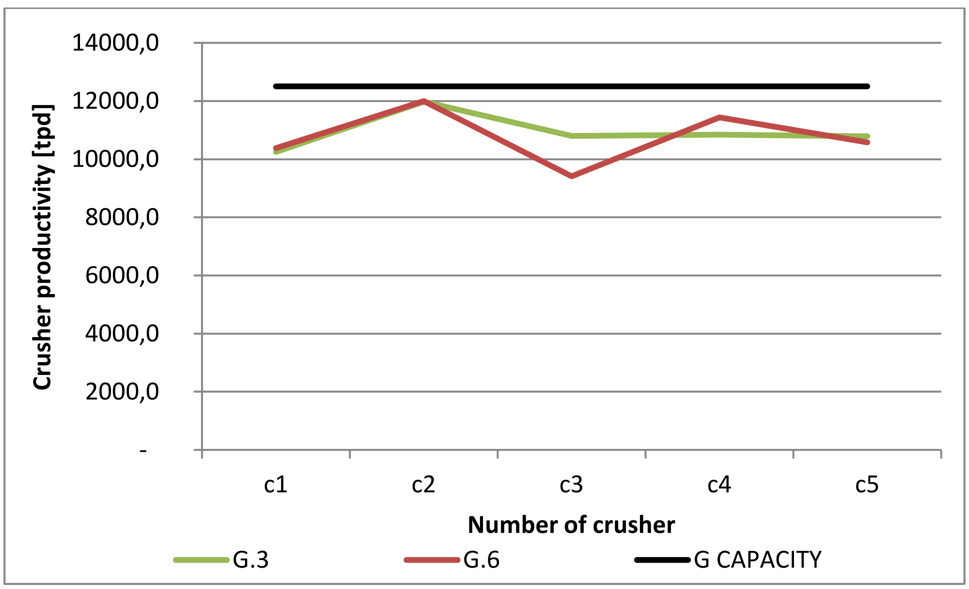

Figure 104. Production capacity crushers for case G.

4.4.2.6 Production plan per cross-cut analysis.

In case of cross-cuts rates production (Figures 105 and 106), the design capacity is reached in the most cross-cuts, with some differences between cases with one LHD per cross-cut. Case F has lower rates per cross-cut than the two other cases. Case where the cross-cuts are more saturated is case G. However, the productivity shown in Figure 86 is the maximum annual average rate per day. In Figure 106 the part of production horizon in which the cross-cut production is on regime, the production is the design capacity with a 10% tolerance. The maximum proportion reaches 35% with respect to the design capacity and the minimum proportion is about 5%. In case F only two cross-cuts of twenty reach the maximum time proportion in regime state. In case G four cross-cuts satisfy this criterion. The cross-cuts with shortest regime state cross-cut life (under 17%) can be founded in case E: 8 cross-cuts satisfy this criterion, in case F: 10 cross-cuts and in case G: 9 cross-cuts. In summary all systems present the half of cross-cuts in regime state and it corresponds to 17% of horizon production. A few cross-cuts present large quantity of periods for regime state.

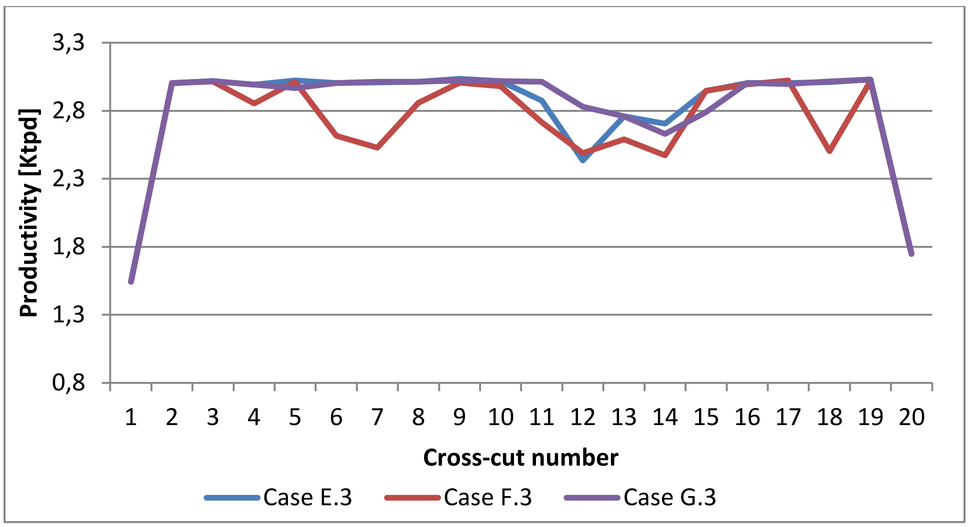

Figure 105. Productivity per cross-cut best cases, 1 LHD per cross-cut.

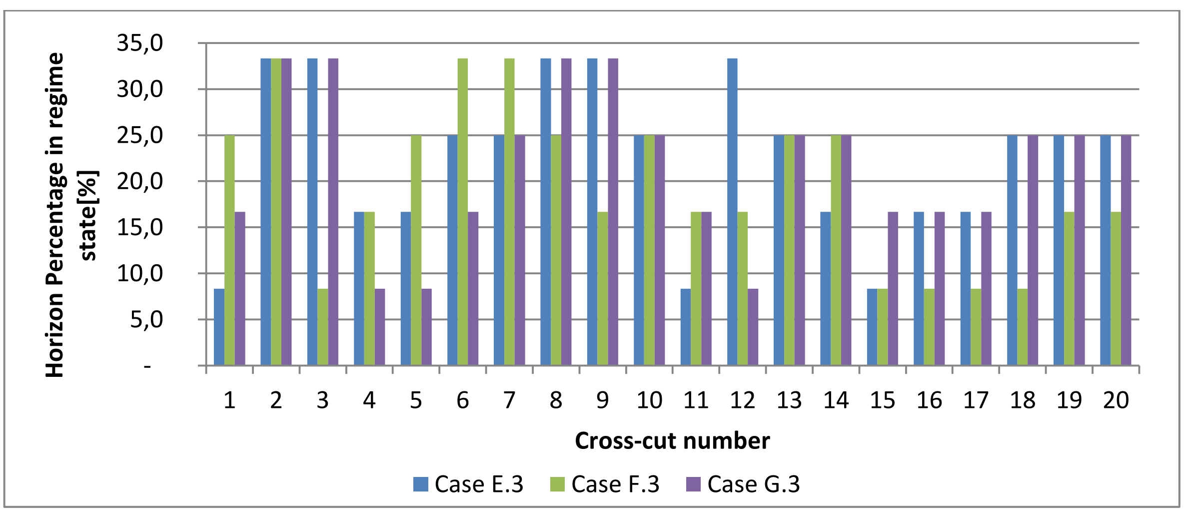

Figure 106. Horizon percentage in regime state best cases, 1 LHD per cross-cut.

In case of the following graph (Figure 107) more crushers than in cases with one LHD per cross-cuts don´t reach their capacity, but in general the cross-cuts tend to reach the capacity. However, case F presents a lower performance than the other two cases. If this case is compared with the case with one LHD per cross-cut, the latter has better performance per cross-cuts, because it has fewer constraints, unlike the case with two LHD. The three results are similar. The number of cross-cut with 30% or more of the horizon production time are: case E has 1 cross-cuts, case F has 4 cross-cuts and case G has 3 cross-cuts. The worst rates, where the cross-cuts operate up to 17% of horizon in regime state are: case E has eleven cross-cuts, case F has 8 cross-cuts and case G has 11 cross-cuts. Again it is possible to conclude that an important number of cross-cuts operate in regime state in the 17% of the horizon production or less. A few cross-cuts operate in a regime state from the 30% of the horizon production (Figure 108).

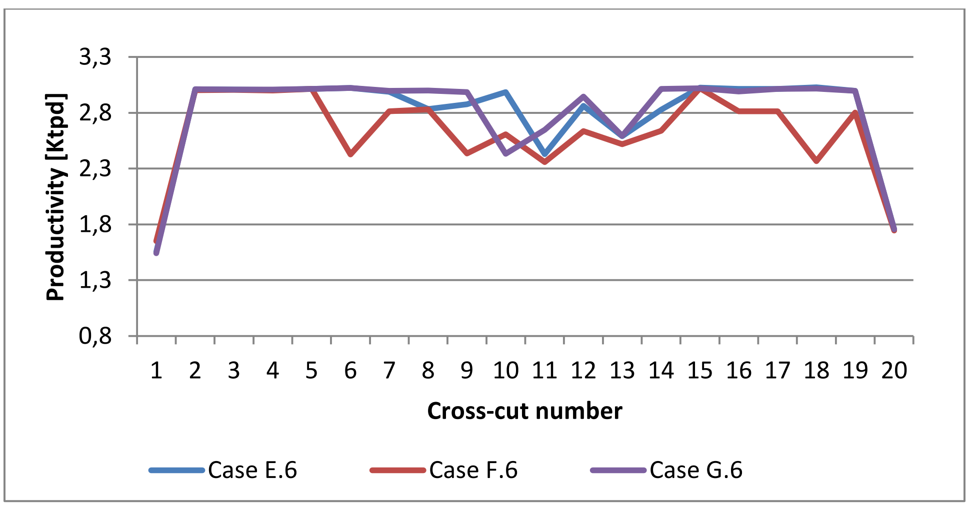

Figure 107. Productivity per cross-cut best cases, 2 LHD per cross-cut.

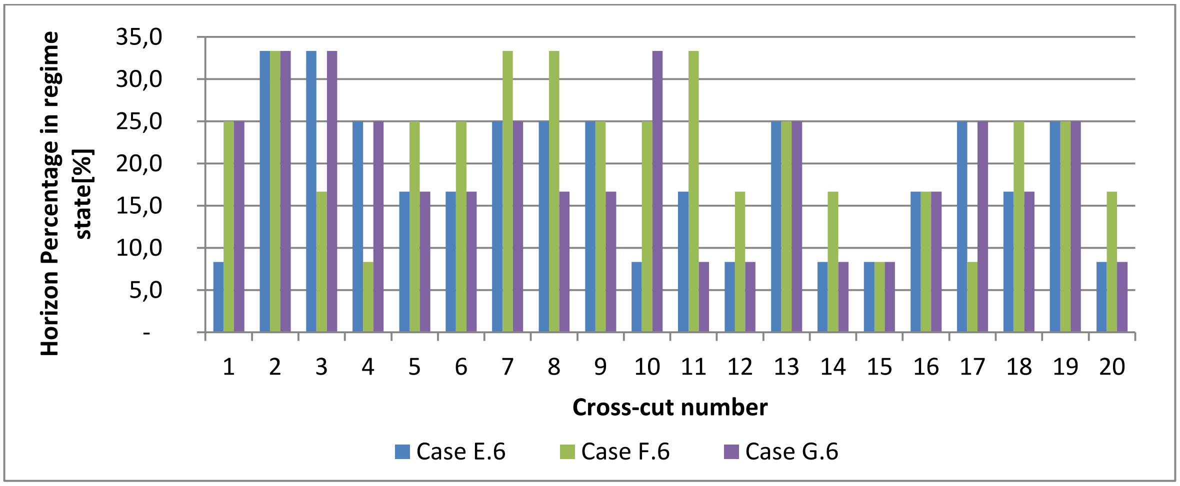

Figure 108. Productivity per cross-cut best cases, 1 LHD per cross-cut.

4.4.3 Systems I, J and K.

4.4.3.1 Objective function results.

These new three systems are generated considering a change in the run out mine rate. In this case the rate was considered as 50,000 tpd, and the capacity of chutes and crushers was changed consequently, and system net was the same as in the other cases. Also the cross-cut capacity was not changed because it didn´t saturate in the previous case. The new capacities are: Case I has crushers of 15,000 tpd, system J has chutes of 7,000 tpd and in system K has 19,200 tpd crushers.

In Tables 20, 21 and 22 the results of the objective function calculated for these cases are shown. They indicate a convergence in the results because in each one kind of test (with one and two LHD per cross-cut), the maximum and minimum value are very similar (about 1,200 MUS$ and 1,181 MUS$). This similarity makes the deviation little for each case. The obtained values are higher than the values got in the previous cases with the same net to material handling (only the components were changed). The last ideas permit to conclude that in most of the cases the capacity run out mine constraints is not to the limit, because other constraints are limiting the production and these are common for the three cases, but system tries to produce as much as possible. In table 23 the summary of the results is presented.

Table 20.NPV for case I group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
4 crushers [MUS$]	1,201	1,181
5 crushers [MUS$]	1,200	1,181
6 crushers [MUS$]	1,200	1,181
Max NPV [MUS$]	1,201	1,181
Min NPV [MUS$]	1,200	1,181
Difference [MUS$]	1	0
Percent. Diff. [%]	0.08	0

Table 21. NPV for case J group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
10 chutes [MUS$]	1,200	1,181
11 chutes [MUS$]	1,199	1,179
12 chutes [MUS$]	1,200	1,181
Max NPV [MUS$]	1,200	1,181
Min NPV [MUS$]	1,199	1,179
Difference [MUS$]	1	2
Percent. Diff. [%]	0.08	0.2

Table 22. NPV for case K group.

Case	1 LHD per cross-cut	2 LHD per cross-cut
3 crushers [MUS$]	1,196	1,179
4 crushers [MUS$]	1,200	1,181
5 crushers [MUS$]	1,201	1,181
Max NPV [MUS$]	1,201	1,181
Min NPV [MUS$]	1,196	1,179
Difference [MUS$]	5	3
Percent. Diff. [%]	0.4	0.3

Table 23. Best and worst cases for cases I, J and K.

	1 LHD per crosscut	2 LHD per crosscut
Max NPV [MUS$]	1,201	1,181
Min NPV [MUS$]	1,196	1,179
Difference [MUS$]	5	2
Percent. Diff. [%]	0.4	0.2

4.4.3.2 Production plan.

The production plans are similar (Figures 109 and 110) in the case with 1 LHD per cross-cut production and in the case with 2 LHD per cross-cut production. In none of the two graphics the design capacity production is reached. This situation confirms the previous conclusion, because system is forced to reach the production but due to other constraints it is not reached.

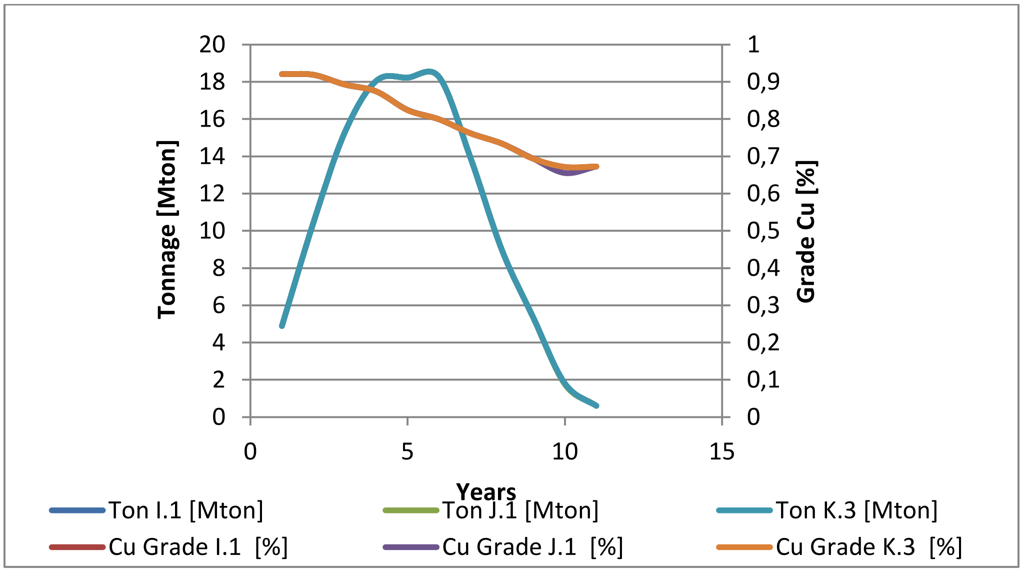

Figure 109. Best production plans with one LHD per cross-cut.

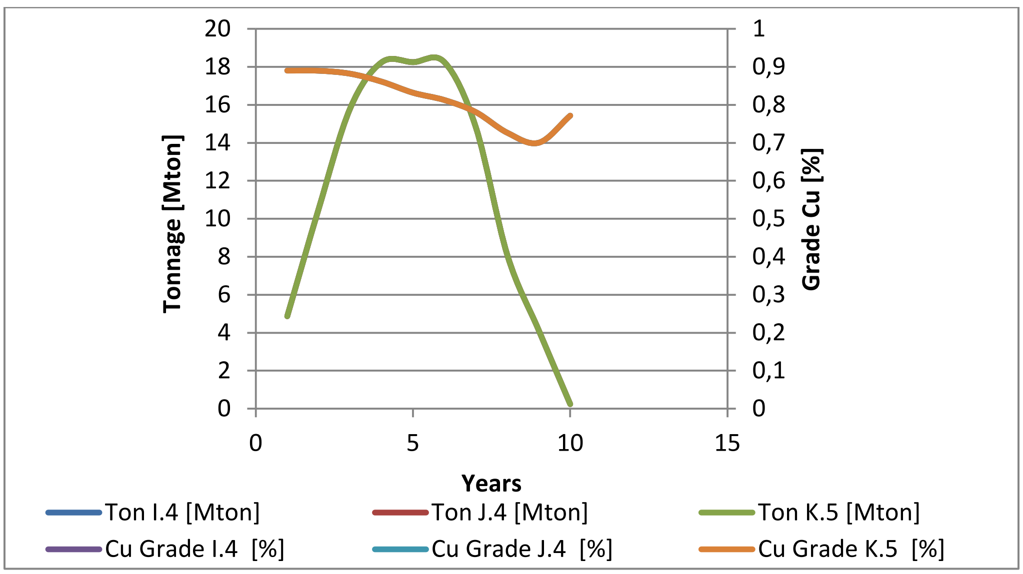

Figure 110. Best production plans with two LHD per cross-cut.

4.4.3.3 Drawpoints opening sequence.

In Figures 111, 112 and 113 the sequences for cases with two LHD per cross-cut production are shown. The first point that is obvious is the early that the opening drawpoints layout is finished, that despite the last period in Figure is 7, the opening practically finishes in period five. The three sequences are very similar and start in the same drawpoint noted with a yellow square. The difference between the three sequences is only two drawpoints, that permits to conclude that cases have practically the same solution, so the components are not limiting system production, but the design production is not reached. The last idea means that the common constraints are limiting system. In this case the capacity per cross-cut perfectly could be reached.

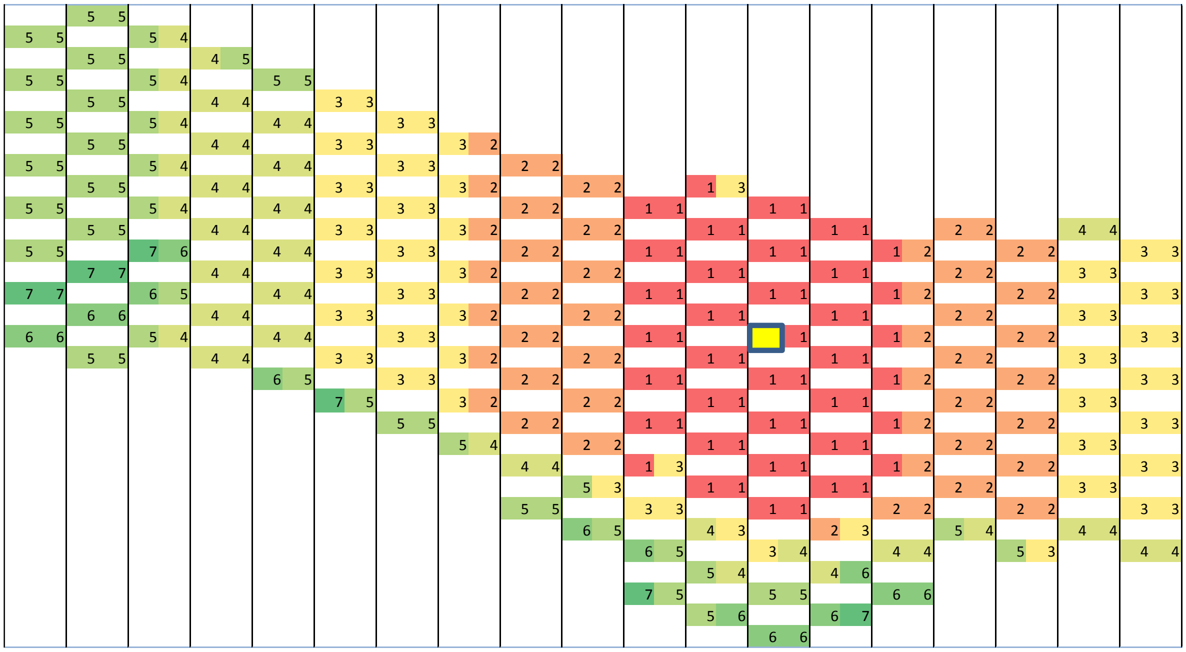

Figure 111. Drawpoints opening sequence for case I.1 with one LHD per cross-cut.

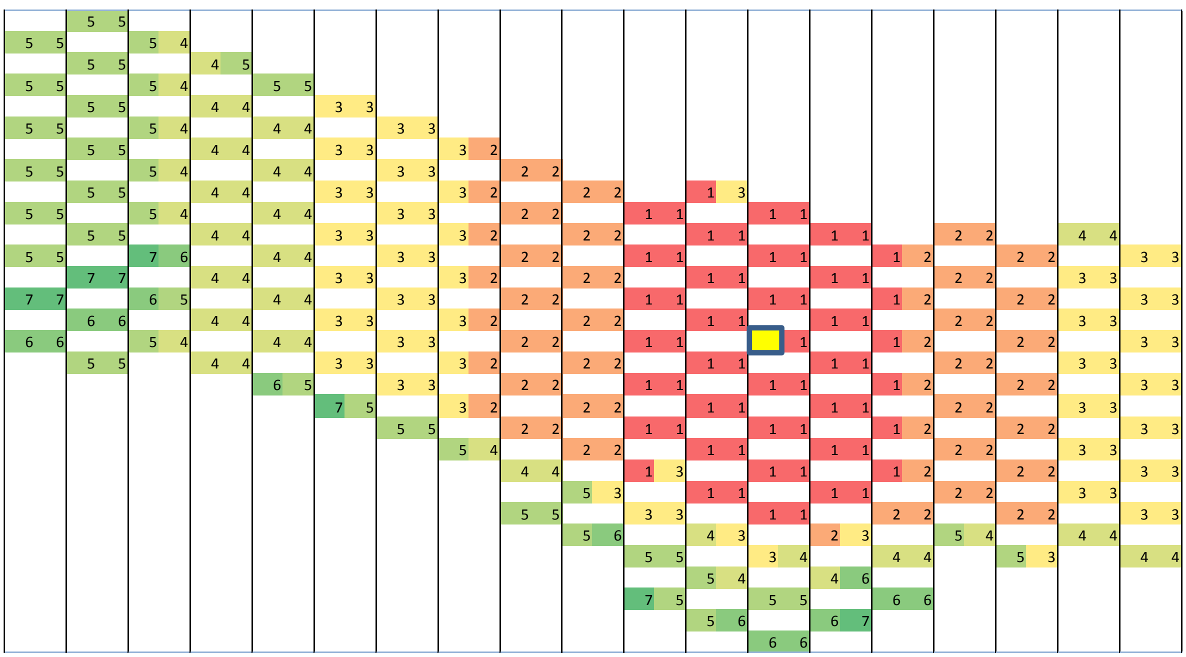

Figure 112.Drawpoints opening sequence for case J.1 with one LHD per cross-cut.

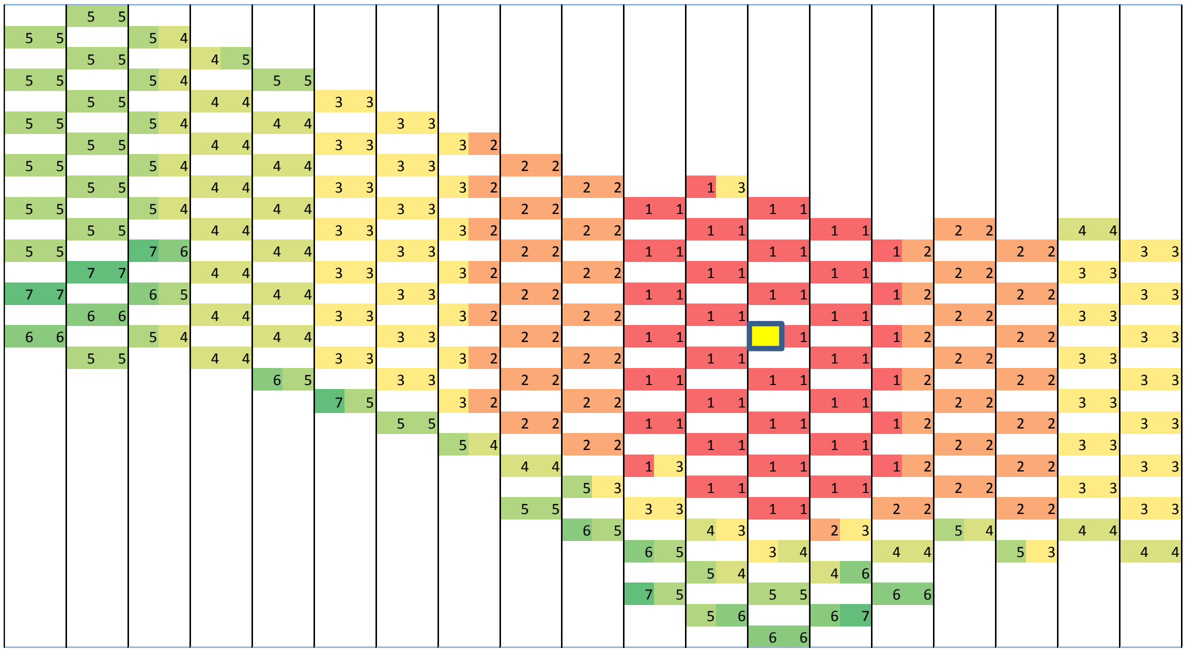

Figure 113. Drawpoints opening sequence for case K.3 with one LHD per cross-cut.

Figures 114 and 115 show the front cave line for years one and two. For the three cases the obtained line is the same, so the sequences are not different between them.

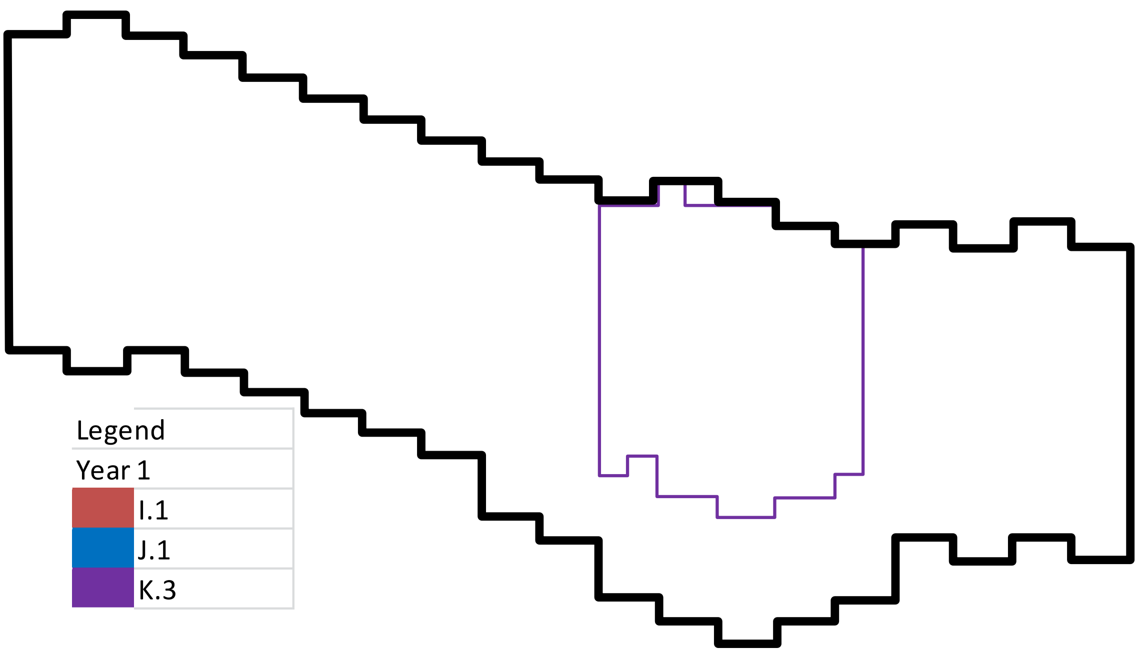

Figure 114. Comparing front cave lines for year one in cases I.1, J.1, and K.3.

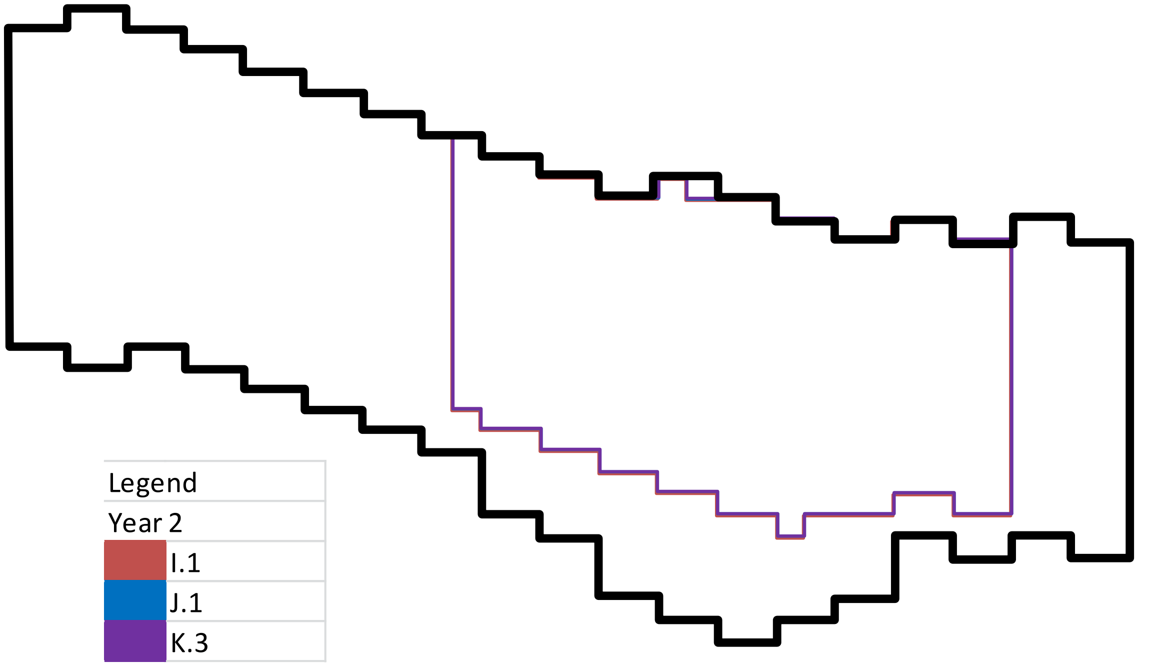

Figure 115. Comparing front cave lines for year two in cases I.1, J.1, and K.3.

In the case with two LHD per cross-cut production (Figures 116, 117 and 118), the sequences are exactly equal, so three different mining systems have the same solution. Again, the mining system components are not limiting the production, but the design production is not reached, but the solution is different to the case with one LHD per cross-cut. This is because the orepass is located in the middle of the cross-cut, and each LHD has the half capacity, but not necessarily the material is located with the supposed location (grades), and one LHD is saturated and the other isn´t, so the production per cross-cut is not the same as in three cases with one LHD per cross-cut. Finally in the three cases no drawpoint is open in period seven as in cases with one LHD per cross-cut.

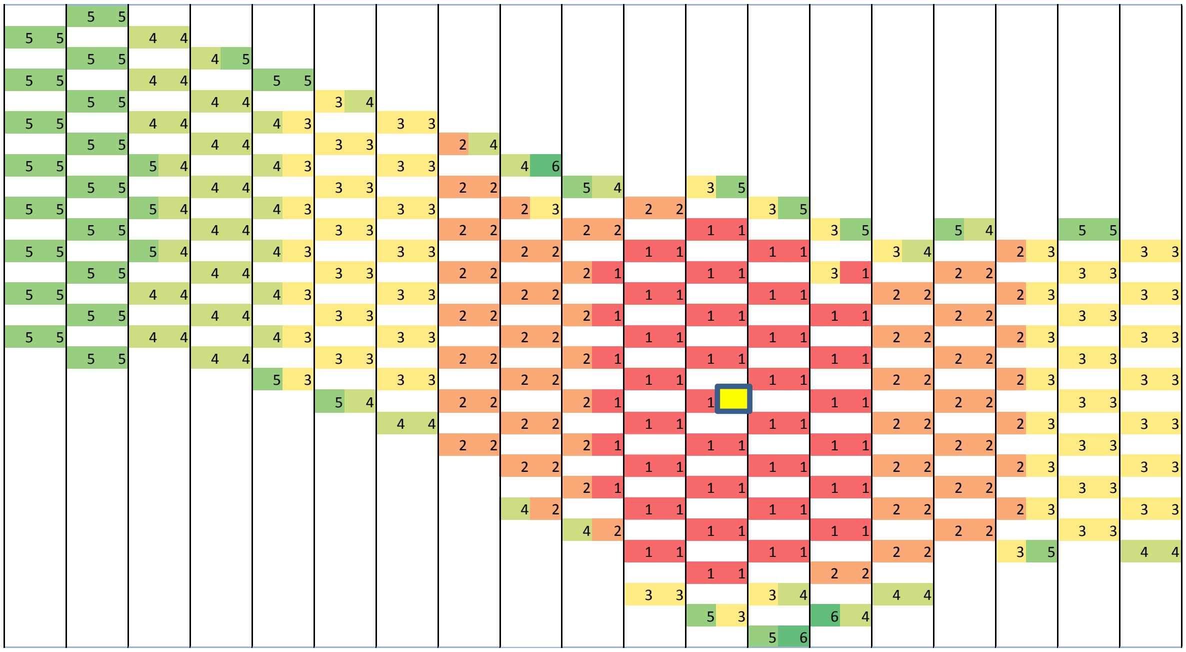

Figure 116. Drawpoints opening sequence for case I.4 with two LHD per cross-cut.

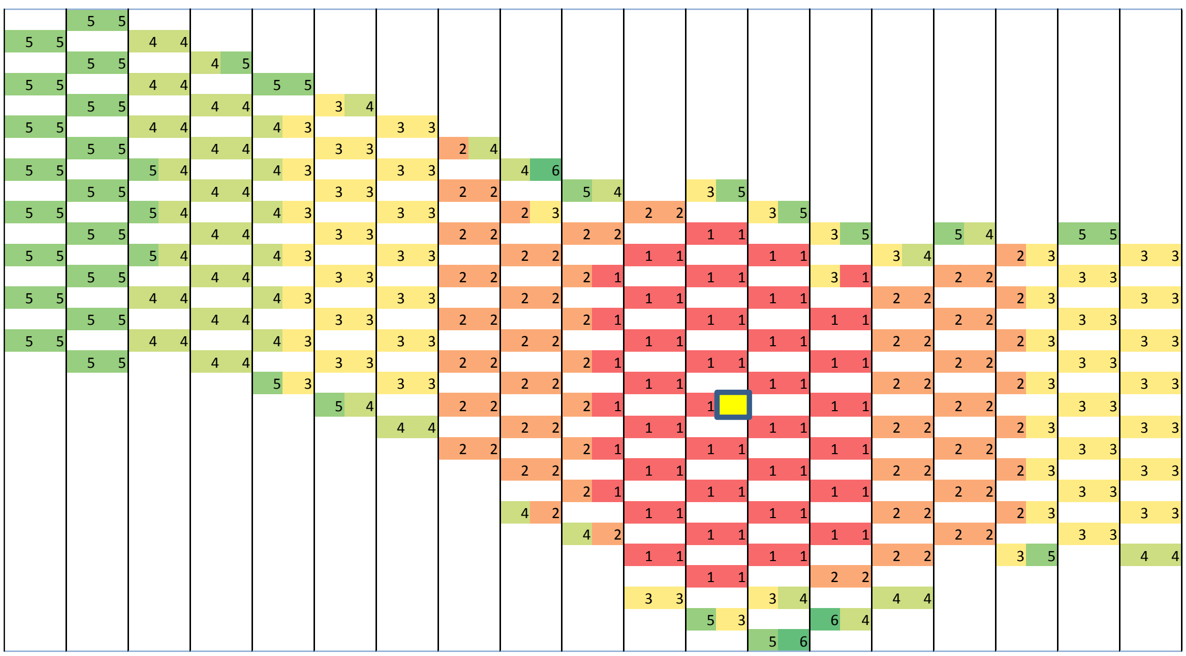

Figure 117.Drawpoints opening sequence for case J.4 with two LHD per cross-cut.

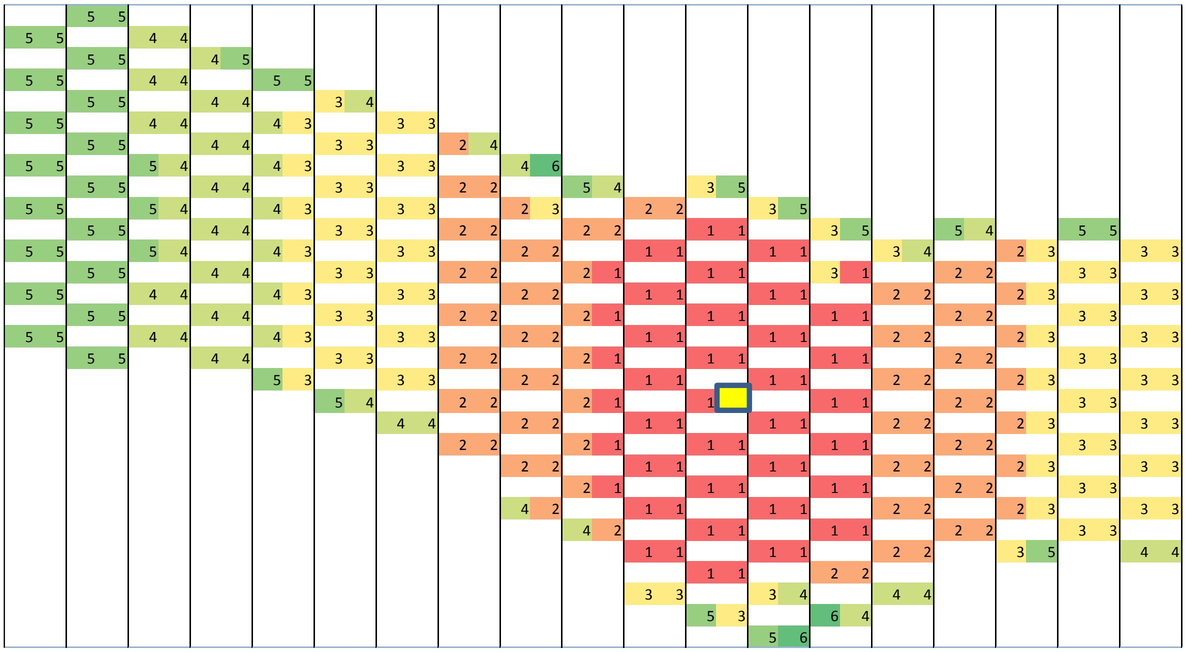

Figure 118.Drawpoints opening sequence for case K.5 with two LHD per cross-cut.

In Figures 119 and 120 the cave lines for years one and two probe to be the same for the three cases and in year five almost the drawpoints are open.

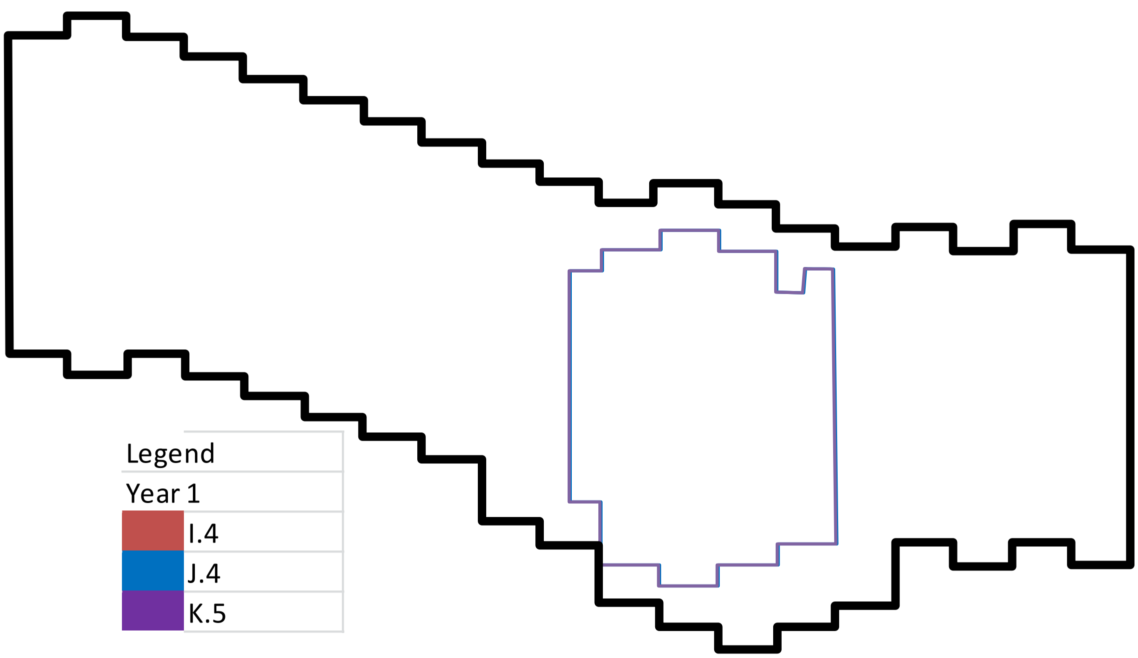

Figure 119. Comparing front cave lines for year one in cases I.4, J.4, and K.5.

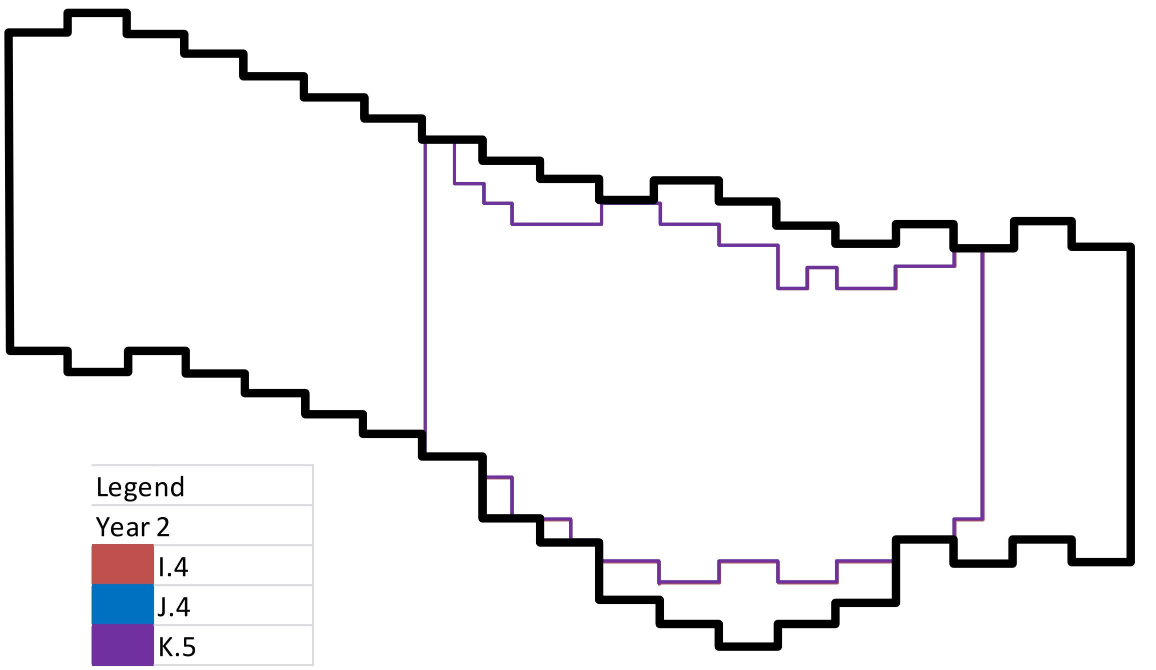

Figure 120. Comparing front cave lines for year two in cases I.4, J.4, and K.5.

4.4.3.4 Drawpoint opening, closing and activity analysis.

Figure 121 shows the drawpoints opening tendency per year, where the maximum is on year two around 70 drawpoints per year. Then a decrease in the rate can be seen, that extends until year eight and the final rate is zero (six years for opening decreasing). This tendency does not happen in the 30,000 tpd cases, because in these cases the final of curve (last years) has a rate around 30 drawpoints per year, and after that decreases to zero. In the closing drawpoints graph, the curve has a hill shape, where the maximum is around 80 drawpoints per year on year five and the decrease is gradual. These cases are different from the homologous cases of 30,000 tpd, because in the last years the rate is around 30 drawpoints per year until the end. The shape of the closing graph is explained by the opening graph, because all drawpoints should be closed (Figure 122). The closing curve doesn´t start with high values, but the high values are reached after year five. This situation is logic, because the opening curve shows high values between years one and two, and these rates should reflect in the future. Finally, Figure 123 shows the active drawpoints and the maximum rate reaches 300 drawpoints per year. These cases are different from the homologous cases of 30,000 tpd, because the last ones reach the maximum at most 200 drawpoints per year, so the capacity increases run out mine (and the increase to capacity per component) is reflected in the results. The cross-cut capacity was maintained as the case with 30,000 tpd (3,000 tpd per cross-cut), because in the previous tests it was a little over estimated. The three evaluated cases are essentially equal, and this is because the capacity constraints for each system were not reached, and this is equivalent to run the problem without these constraints, but in these cases cross-cut capacity are equal and there reach the maximum (in the constraint), so it could be the bottle neck to reach (because it is the strongest) the 50,000 tpd, but this will be reviewed in the next part.

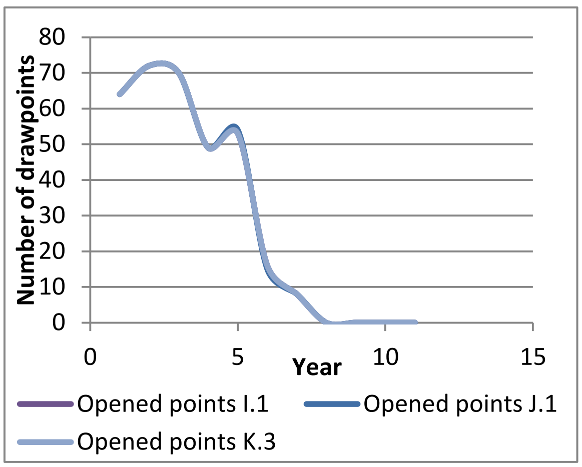

Figure 121.Open Drawpoints per year for the best cases, 1 LHD per cross-cut.

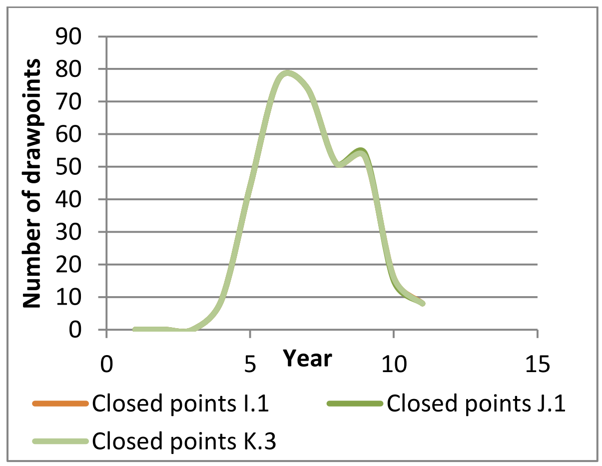

Figure 122. Closed Drawpoints per year for the best cases, 1 LHD per cross-cut.

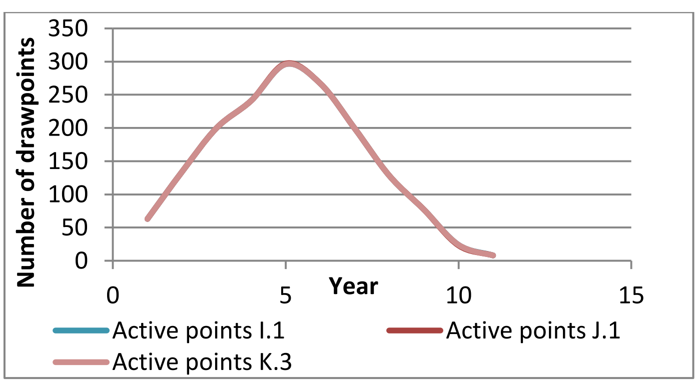

Figure 123.Active Drawpoints per year for the best cases, 1 LHD per cross-cut.

Figure 124 shows the opening drawpoints rate for the case with two LHD per cross-cut, and this one shows a tendency similar to the previous graph, but the maximum is reached around 80 drawpoints per year . The decrease is produced between year three (maximum) and year six. In case of closing drawpoint graph (Figure 125), newly a “hill” shape appears with a maximum on year 7 around 100 drawpoints per year and this rate is higher than the opening rate reached. This is because the activity times for drawpoints not necessarily are equal, because of the existing difference in column reserves (not necessarily the columns are mined completely) or the drawpoints that don´t have a continuous activity, because they are interrupt by others drawpoints (capacity is limited and the mining should be optimized). The activity graph is similar to the activity graph for cases with one LHD per cross-cut (Figure 126) and it is higher than cases with 30,000 tpd. The three cases have similar curves, and system is limited by the capacity per cross-cut and this will be reviewed in the respective graph. Obviously, the maximum advance and the minimum neighbors cannot be discarded as the cause to this not-fulfillment of the capacity.

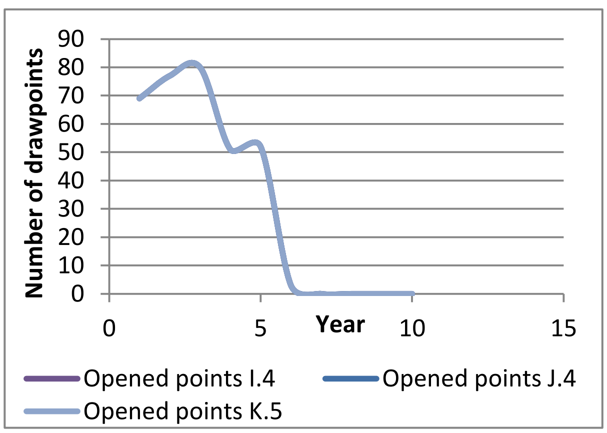

Figure 124. Open Drawpoints per year for the best cases, 2 LHD per cross-cut.

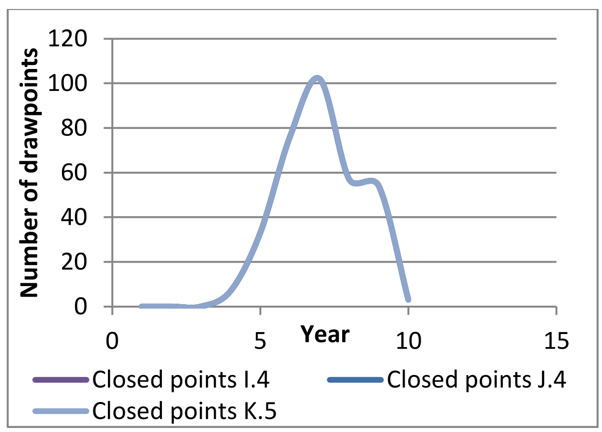

Figure 125. Open Drawpoints per year for the best cases, 2 LHD per cross-cut.

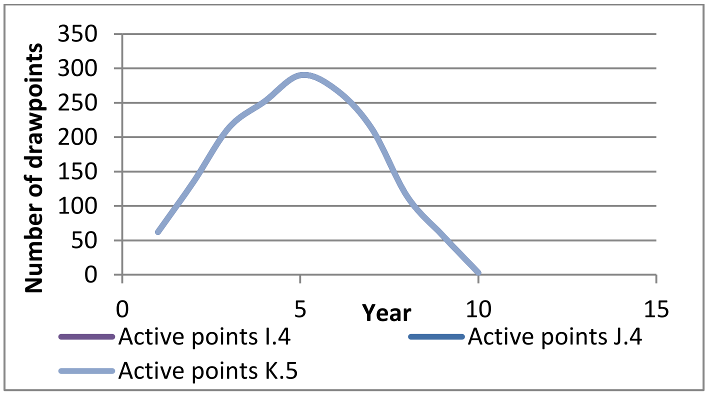

Figure 126. Active Drawpoints per year for the best cases, 2 LHD per cross-cut.

4.4.3.5 Production plan per crusher analysis.

In case of capacities per crusher, case I with one LHD per cross-cut (Figure 127) has the simultaneous operation of the three of four crushers in the first periods and in the last periods the last crusher is operated practically alone. The case with one LHD presents a similar to the case with two LHD per cross-cut (Figure 130). These cases present crushers operating simultaneously because system is forced to reach the maximum production, but by others constraints the production run out mine is reached by a few years and a small plateau appears on production. In the case with one LHD the case with the smallest number of crushers is the best value for the objective function, but in the case with two LHD, the three results of objective function were equal, so the criterion to choose the best case was to select the case with the lowest investment (this criterion applies for all cases in this part). In the two cases the crushers was near to the full capacity by a little time.

In case J, cases were considered with 10 chutes for the layout (Figures 128 and 131), but again the difference is a little value between all cases obtained to determine the maximum. The best case in case J with one LHD per cross-cut has five chutes operating until year two and in the next years eight chutes is operating. The last observation reflects the high quantity of chutes operating simultaneously to reach the design production. So, all chutes of the layout are operating and this implies to have a big quantity of open drawpoints to reach the production. As in cases of 30,000 tpd, the last chute is marginal. The capacity increase for each chute is reflected in the production of each one, because the productions per chutes are higher than in case of 30,000 tpd. In case of two LHD per cross-cut production is slightly higher than in the case with one LHD.

Finally case K (Figures 129 and 132) presents different numbers of crushers considering cases with one and two LHD per cross-cut. This is because in the case with two LHD per cross-cut, some cases are equal (objective function) and the criterion to select the best case was the NPV. The cases show a plateau, but the plateau for the case with two LHD per cross-cut is clearer than the plateau of the case with one LHD per cross-cut production. In the case with two LHD per cross-cut the production is more balanced between crushers than in the case with one LHD per cross-cut.

In general the capacity design is reached with difficulty. Per crusher the scenario is not different, because in the three cases the capacity per crusher (chute) is shyly reached. The last idea indicates that the bottle neck is not on the crushers, but possibly it is on the cross-cut, that will be reviewed in the next part.

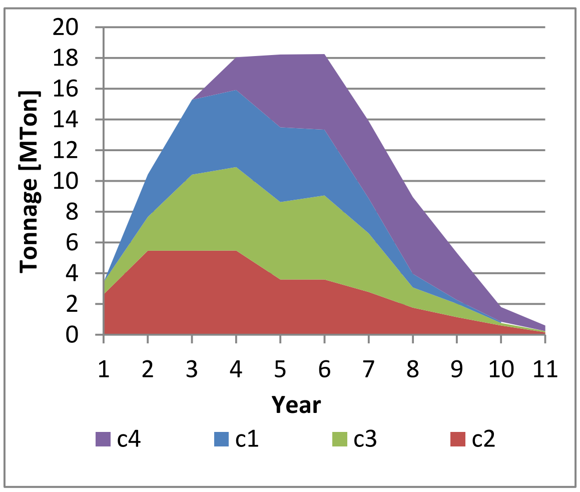

Figure 127.Production plan per crusher for case I.1.

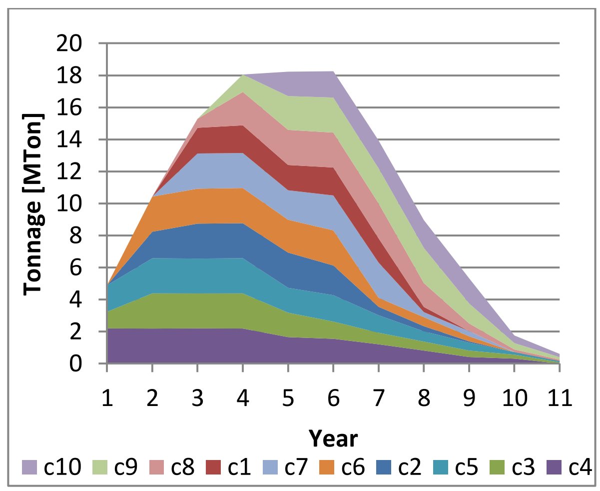

Figure 128. Production plan per crusher for case J.1.

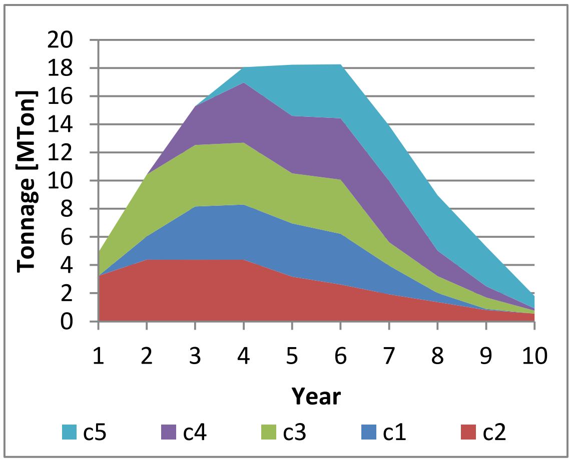

Figure 129. Production plan per crusher for case K.3.

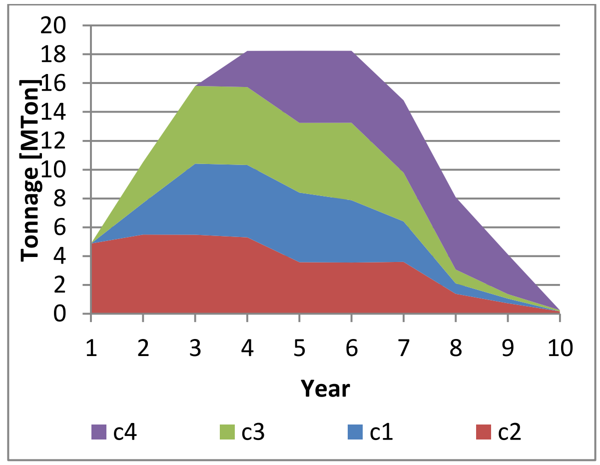

Figure 130. Production plan per crusher for case I.4.

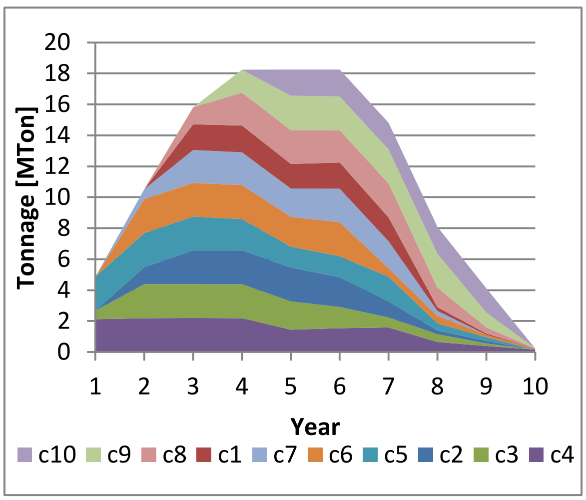

Figure 131. Production plan per crusher for case J.4.

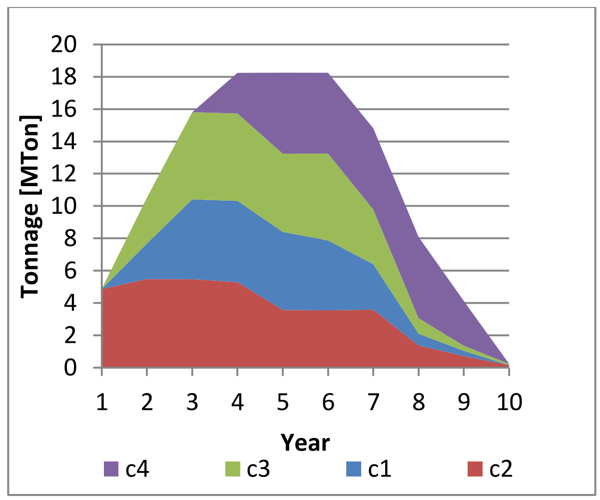

Figure 132. Production plan per crusher for case K.5.

In this case with 50,000 tpd the crushers/chutes do not reach the capacity, but some cases are closer to the capacity, specifically case I (Figures 133, 134, 135). In general the "bottle necks" does not exist in crushers, so other components induce the lack of production. The case with two LHD presents a lower production than cases with one LHD per crusher, except in case K. The graphs indicate the maximum production to determine with precision which the crusher or chute is more important.

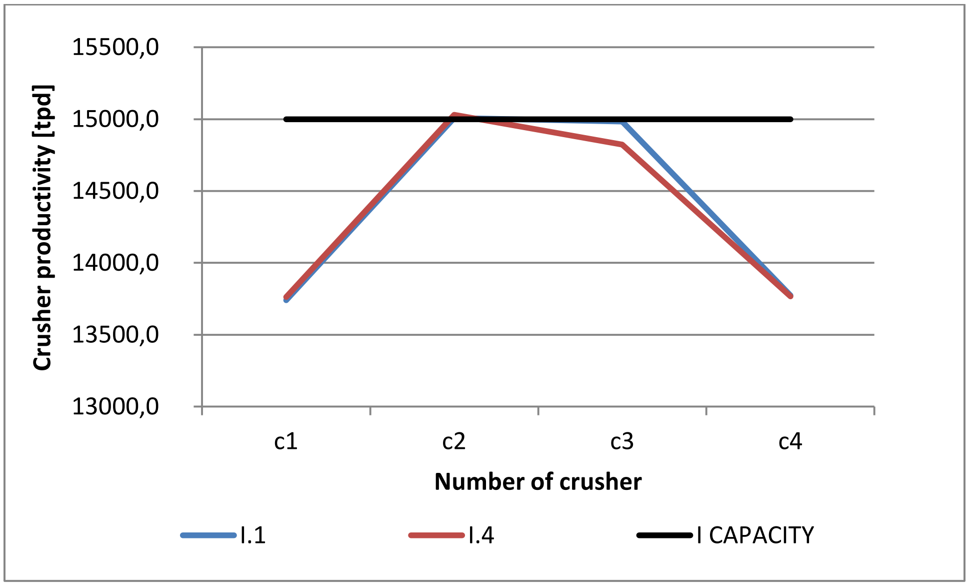

Figure 133. Production capacity crushers for case I.

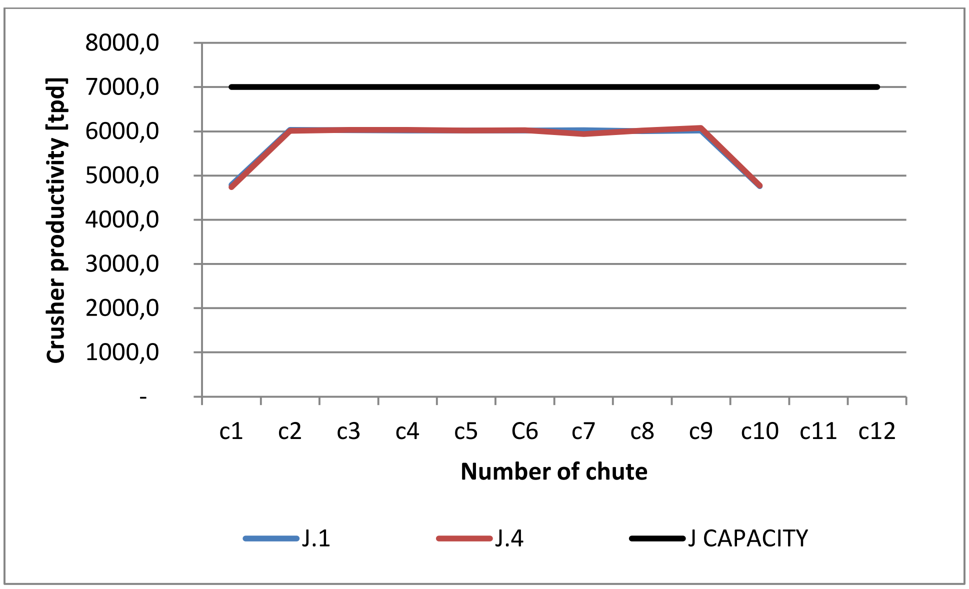

Figure 134. Production capacity crushers for case J.

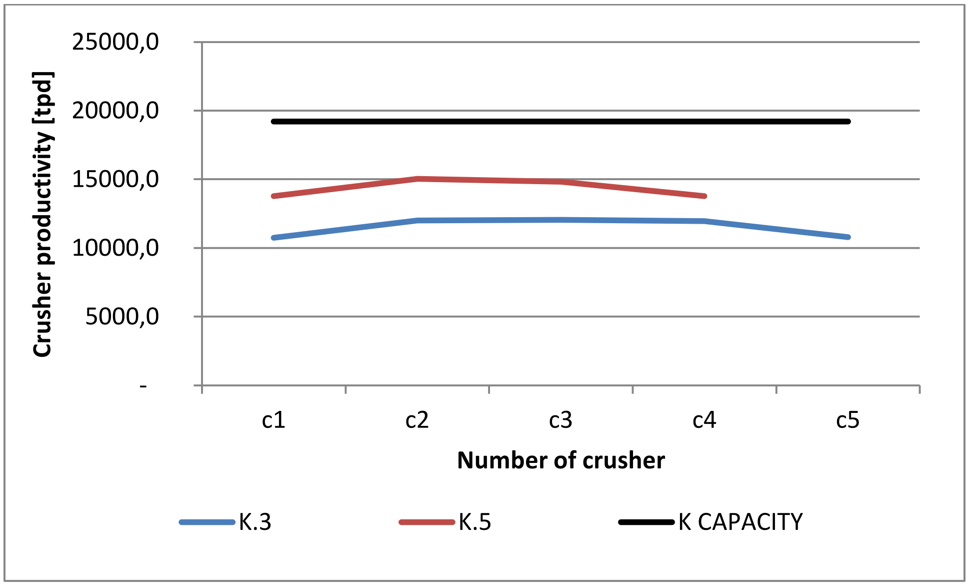

Figure 135. Production capacity crushers for case K.

4.4.3.6 Production plan per cross-cut analysis.

Figures 136 to 137 show the behavior per cross-cut for systems. In the case with one LHD, the cross-cuts are saturated mostly (Figure 118) and 17 of 20 cross-cuts have the regime production at less in 30% of the planning production horizon. In case of the two LHD per cross-cut the situation changes because the productivity in regime state is not the same for the all cross-cuts. In 19 of 20 cross-cuts the productivity in regime state lasts at least the 30% of the horizon planning. Finally, the cross-cuts are very saturated in cases with one LHD per cross-cut and in the case with two LHD per cross-cut. The difference is the rate in which the drawpoints are in regime state (Figure 120 and 121).

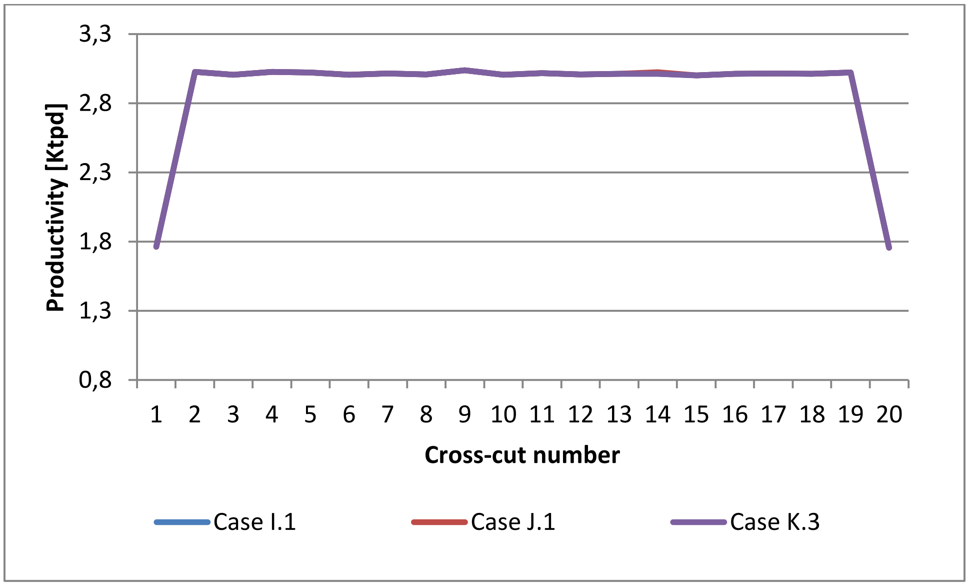

Figure 136. Productivity per cross-cut best cases, 1 LHD per cross-cut.

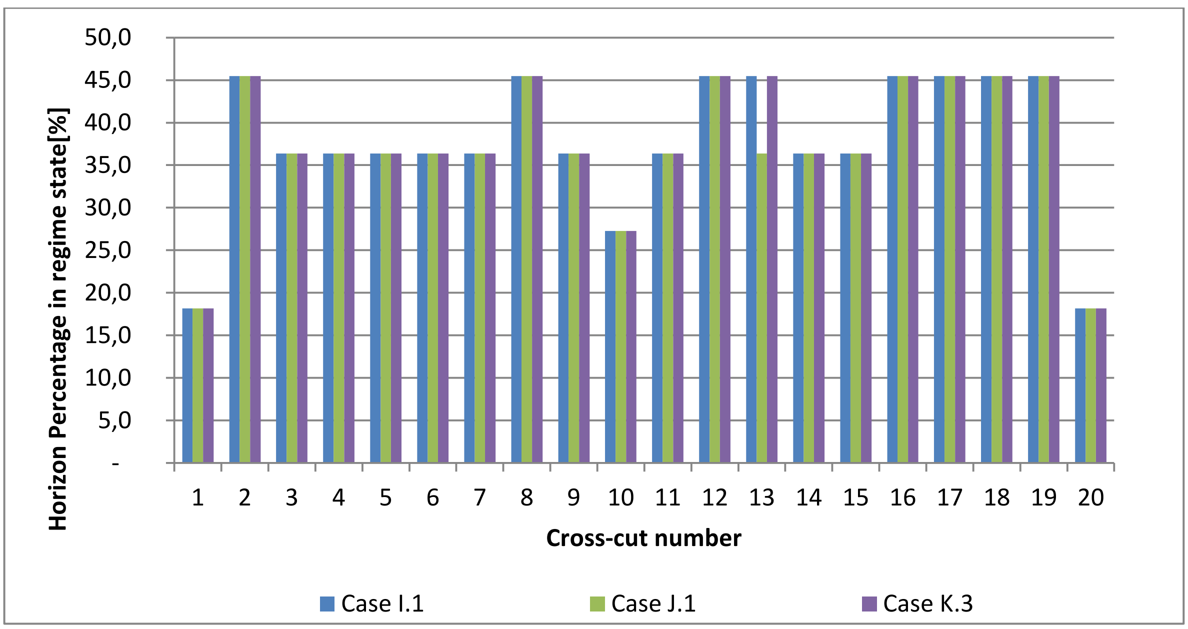

Figure 137. Horizon percentage in regime state best cases, 1 LHD per cross-cut.

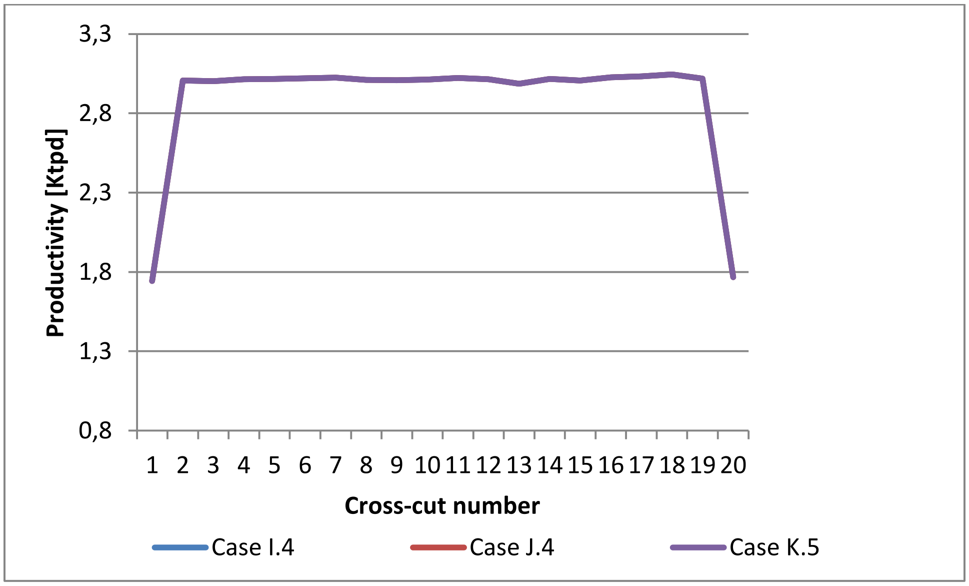

Figure 138. Productivity per cross-cut best cases, 2 LHD per cross-cut.

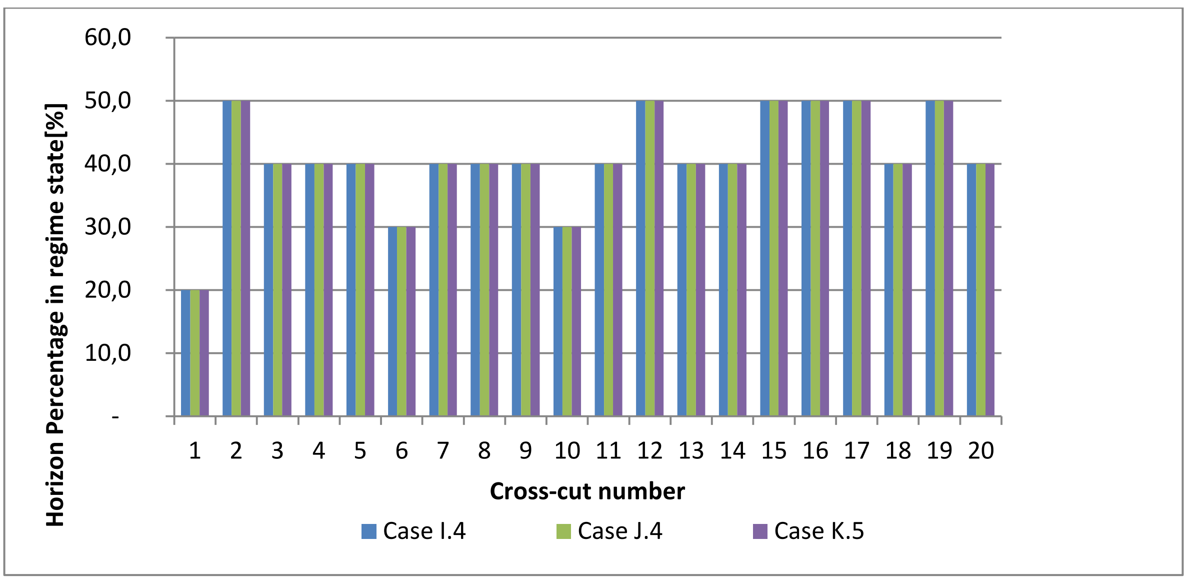

Figure 139. Horizon percentage in regime state best cases, 2 LHD per cross-cut.

4.4.4 Summary.

Finally a summary of results is (table 24):

Table 24. Statistics results for all cases studied.

	1 LHD per crosscut	2 LHD per crosscut	Global
Max NPV [MUS$]	1,201	1,181	1,201
Min NPV [MUS$]	986	979	979
Difference [MUS$]	215	202	222
Percent. Diff. [%]	17.9	17.1	18.4

In case A the best NPV value was with 6 crushers (capacity 7.500 tpd) for both cases, with one and two LHD per cross-cut. Always the case with one LHD per cross-cut production is better than the case with two LHD per cross-cut production. This variation is quantified in 7% for scenarios with one and two LHDs.

In case B the best case considering 1 LHD per cross-cut production was the case with 12 chutes and in the case with two LHD per cross-cut the best case was with 11 chutes. This system in general presents worse results than the last system, the variation between best cases is lower than for case A, the variation between best and worst case is approximated to 1.7%.

In case C, for the case with one LHD per cross-cut production the best case was with five crushers, and for the case with 2 LHD per cross-cut production the best result was for the case with five crushers. The variation between best and worst case is similar to case A, being lower for the case with two LHD per cross-cut. Case D presents an intermediate value :1,093 MUS$.

In Case E, in all cases the objective function tends to increase the value respect to case A. The increasing average is 39 MU$. The difference between the worst and the best case is reduced. This means that the worst scenarios increase the value. The tendency to have high values is on systems with more number of crushers, because they have more capacity.

In case F, an important increasing NPV value is produced respect the case B. and The NPV increasing averages 108 MU$, a more important value than cases A and E. The NPV results are similar between those, so the difference is really little and is around 0.5%.

In case G, the difference average is 20 MU$ respect the corresponding case C. The percent difference with respect to case C averages 50%. In the last cases (E, F and G), the maximum and minimum increased. The NPV increases with the number of crushers.

Cases I, J and K indicate a convergence in the results because in each one kind of test (with one and two LHD per cross-cut), the maximum and minimum value are very similar (about 1,200 MUS$ and 1,181 MUS$). This similarity makes the deviation little for each case. The obtained values are higher than the values got in the previous cases with the same net to material handling (only the components were changed). The last ideas permit to conclude that in most of the cases the capacity run out mine constraints is not to the limit, because other constraints are limiting the production. Obviously, the maximum advance and the minimum neighbors cannot be discarded as the cause to this not-fulfillment of the capacity.

In global production, systems A, B, C, D, E, and F present a clear plateau. In contrast, cases I, J and K presents a plateau more little. Case B presents the slower performance, comparing with its systems group. System D doesn´t present much difference with the others system in its group. Also, this situation is valid for two LHD per cross-cut. In the cases E, F and G the plans are similar between them unlike cases A, B and C. Cases I, J and K are forced to reach the production but due to other constraints it is not reached.

In the sequences of each cases the most important factor are: the location of the system components (crushers, chutes), especially in the first years that are the most important in the production. For cases with less capacity units (B, F and J) the advance is major to reach the production. For the high production cases the sequence obtained is the same, so the system is not relevant, but this production rate is excessive considering the reserves and the layout size. In all cases some “islands” can be seen, but they are a few drawpoints and these details can be solved with a smoothing (in time). This is because the constraints are not enough strict to anticipate this situation in the last years due to the objective function. In bigger areas these islands shouldn´t appear. The incorporation of this would be a future work. Other important situation is the front cave line temporal discontinuity in some directions. This is because in some periods the best values drawpoints are located in other direction, so the front cave line doesn´t advance in a group of periods. This situation happens in advanced periods. Probably in a future work this situation should be reviewed because the results are not necessarily feasible, so a smoothing is necessary.

For cases A, C and D the activity is similar and with less drawpoints than case B, because this case requires to have much drawpoints active. The main difference between the cases with one and two LHD per cross-cut is the decreasing in Cases E, F and G presents a similar behavior, because the capacity of the more constrained case (F) is increased, so after the opening the systems don´t present major differences. Some differences are noted between cases with one and two LHD, in the opening drawpoints graphs, where in the last years less drawpoints are open in the case with two LHD than the case with one LHD. Finally in cases I, J and K the curves of drawpoints activity are equal, but the difference between the case with one LHS per cross-cut and the case with two LHD per cross-cut is the major value for closing drawpoints.

In production per crusher, with one LHD per cross-cut, case B presents the most of the crushers as active showing the important number of drawpoint in regime to sustain the production. The cases A, C and D have the crushers in regime state in different periods, so periods of “transition” can be seen”. Case D is more massive. In the case with two LHD per cross-cut the plateau is not clear as in the cases with one LHD. This is because in the case with two LHD per crusher one of the LHD could be saturated and the other not. This means that the system with two LHDs is more constrained than the system with one LHD per cross-cut. A possible change to improve the system performance is to change the location of orepass and obtain the location that balances the reserves or to maintain the location of the orepass and to consider different production per LHD according to the reserves contained per drawpoints group (that feed each LHD). In case E the maximum production (regime state) is reached earlier than in the corresponding case A. Case F presents less simultaneous crushers than the case F. Case G is more similar to C, but this case presents a performance improvement. Again the best case results the case with one LHD per cross-cut and the case with two LHD per cross-cut reach the production unlike the homologous first three cases (A, B and C). For case I, the case with one LHD presents a similar to the case with two LHD per cross-cut. For cases E, F and G, in general, the capacity design is reached with difficult. As the system B, case J has operating all chutes of the layout. In case K, the plateau for the case with two LHD per cross-cut is clearer than the plateau of the case with one LHD per cross-cut production. Per crusher the scenario is not different, because in the three cases the capacity per crusher (chute) is shyly reached. The last idea indicates that the bottle neck is not on the crushers, but possibly it is on the cross-cut.

Production per cross-cut shows that the maximum production is reached for cases A and C, but in case B the maximum production per cross-cut is different between the cross-cuts. The majority of the cross-cuts presents a low quantity of periods in regime state (10%-20% of the horizon), but with some exceptions. Case B has an important quantity of cross-cuts in regime state an important quantity of periods. This applies for the cases with ones and two LHDs per cross-cut. For cases E, F and G all systems present the half of cross-cuts in regime state, but the design production is reached in the most of the cross-cuts. A few cross-cuts present large quantity of periods for regime state. Finally the cases I, J and K presents the major number of periods in regime state and the major quantity of cross-cuts with this condition and the design production is reached.

5. CONCLUSIONS AND RECOMMENDATIONS.

Different mining systems generate different sequences and therefore different objective function optimized values. The most important is balancing system so that a critical part of system was chosen and according to that to make the balance. For example, if crushers were chosen as a critical component, the cross-cut should be adapted to get the minimum production to satisfy the critical component.

Depending on the unitary capacity of each component and the distribution net for handling material system, the opening sequence will change. Ergo, if the components are too many and their capacity is low (as in case B), system will open a lot of drawpoints to reach the design production and the drawpoints maintain active for an important time. This system finishes the mining too late if the components don´t have the enough capacity.

In all cases studied, when they are tested with two LHD per cross-cut, the objective function values are lower than in the case with one LHD per cross-cut, because the LHD does not go to any drawpoint in the cross-cut as in the case with one LHD per cross-cut. This is because the cross-cut halves present different quality and quantity of material, so it is likely that one LHD (of two per cross-cut) mines more material than the other in a year, and it will be saturated in the capacity. If in a cross-cut, one LHD has more material to extract in a year than its capacity, the LHD will extract all material possible and the rest will be postponed to the next year, but the problem is that the other LHD will not reach the corresponding production, and it could perfectly extract the other drawpoints that the saturated LHD leaves. For this problem, two solutions are proposed: The first is considering that one LHD complete the production and the shaft ought to be put in the part of cross-cut such that the production is completed. The feasible solution will be one where the LHDs extract two separated and continue drawpoints groups. This is the reason because the solution for one LHD per cross-cut is not necessarily the same as the proposed. The other solution is maintaining the location of shaft and the production for the two LHD should be different to extract the material that the “saturated” LHD was not extract and maintain the lowest production for the other “non saturated” LHD.

The sensitivity of the number of crushers shows while the number of crushers increases, the global system productivity increases. However if this number increases indefinitely, the last crushers have marginal contribution to system, so the value that these crushers contributes to the NPV should be compared with the investment and the tonnage that they contribute to the production.

Capacity constraints for different mining system have up to 10% of difference in NPV but it is important that it only considers the capacity per crosscut and the capacity per drawpoint. It would be interesting to incorporate other components to complete the set of constraints.

By incorporating the capacity of each mining system component as a constraint to the proposed model, there are important NPV differences between different mining systems. However, it is very important to review the productivity obtained for the solution to reach the desired production rate mine.

The front cave line presents temporal discontinuities in some directions and the "islands" that appears in sequences can be a future work. The parameters for geometrical constraints are only an upper bound, to have more flexibility and select the best sequence in a big group. Probably with a lower bound some solutions could be discarded. Finding good values for these constraints is not enough, so one suggestion to improve this is to incorporate connectivity and convexity constraints (expensive). By the moment, a smoothing is recommended.

The values for the geometrical constraints parameters are proposed with a visual criterion, but these values require a complete geomechanical study to set up (Maximum advance and minimum neighbors). This could be a future work.

The main conclusion is that having a proper optimization engine to assist mine planner to compute the best sequence that suits the strategic objectives of a company is extremely necessary. This initial work has shown that different sequences can show significant differences depending on how the geometries are set up and how the mine design is laid out for a given ore body.

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APPENDIX A

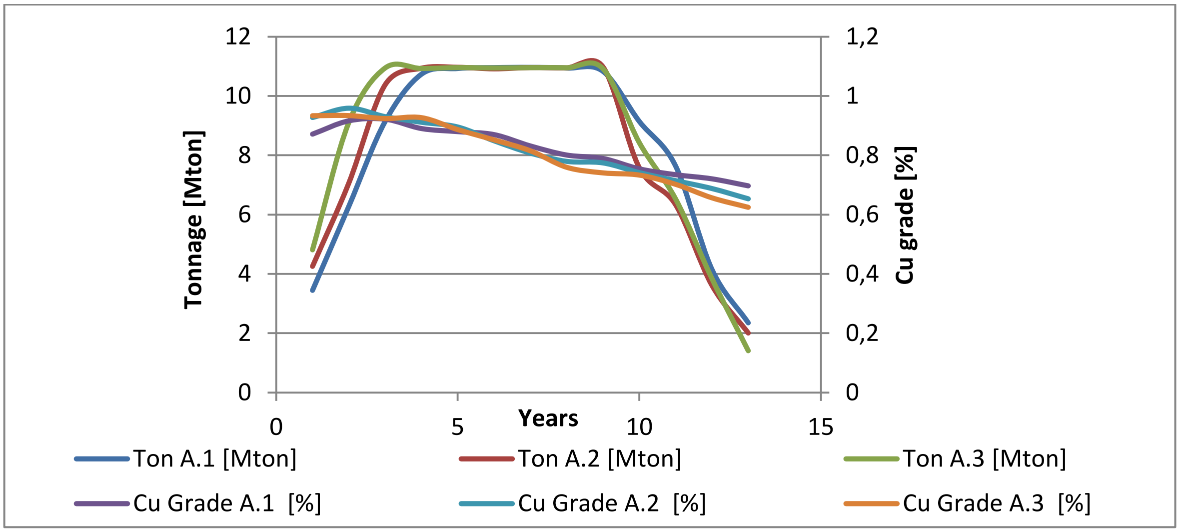

Figure 140. Production plans for case A with one LHD per cross-cut.

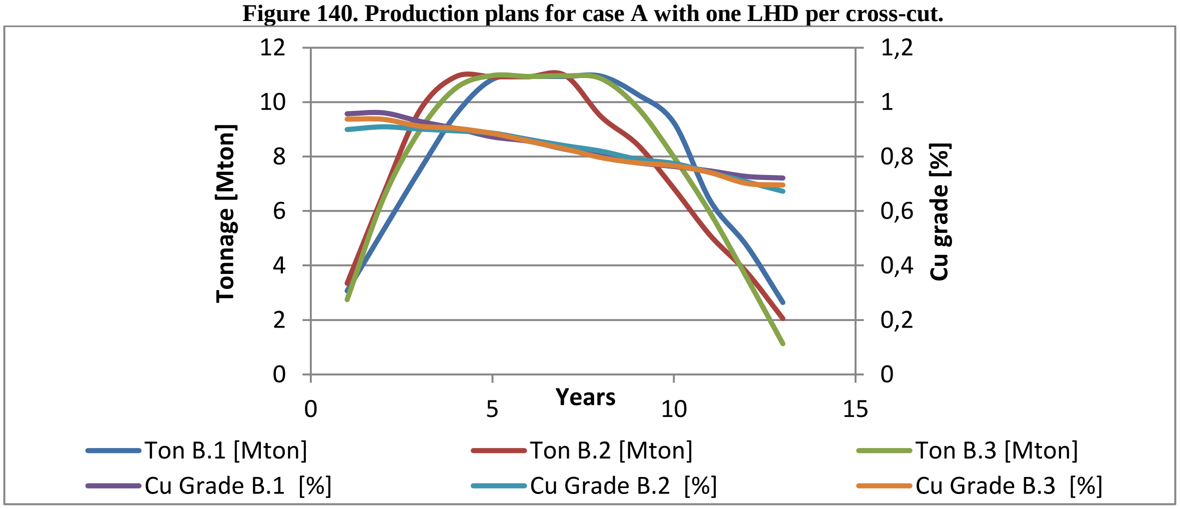

Figure 141. Production plans for case B with one LHD per cross-cut.

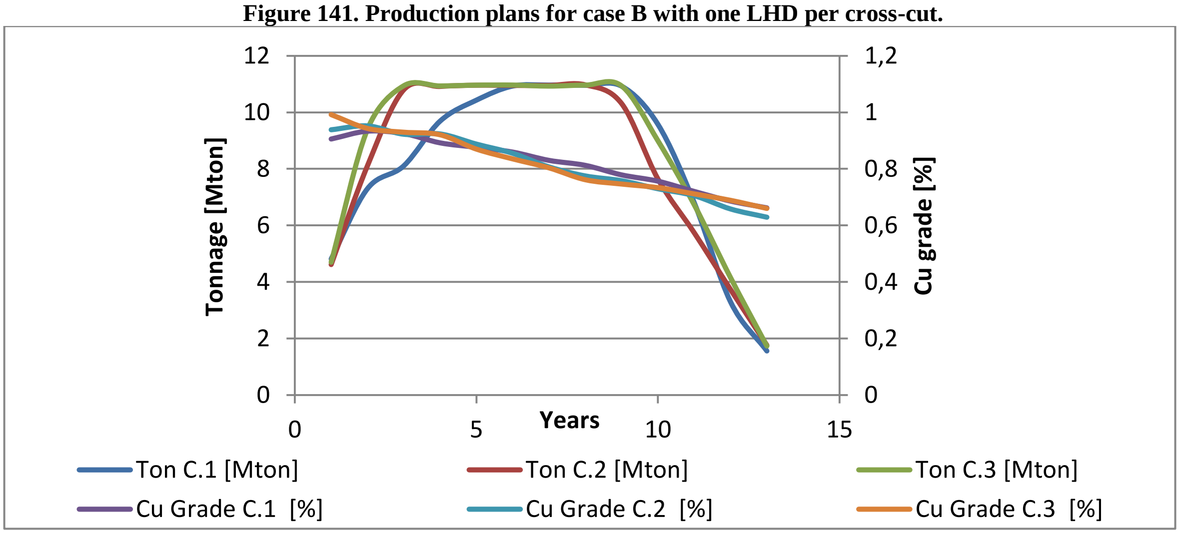

Figure 142. Production plans for case C with one LHD per cross-cut.

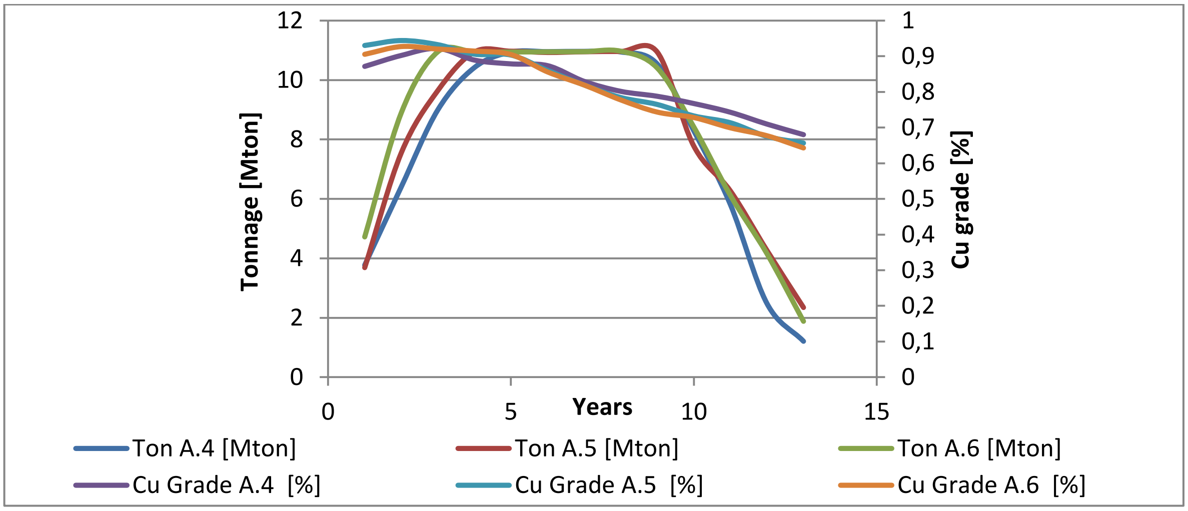

Figure 143. Production plans for case A with two LHD per cross-cut.

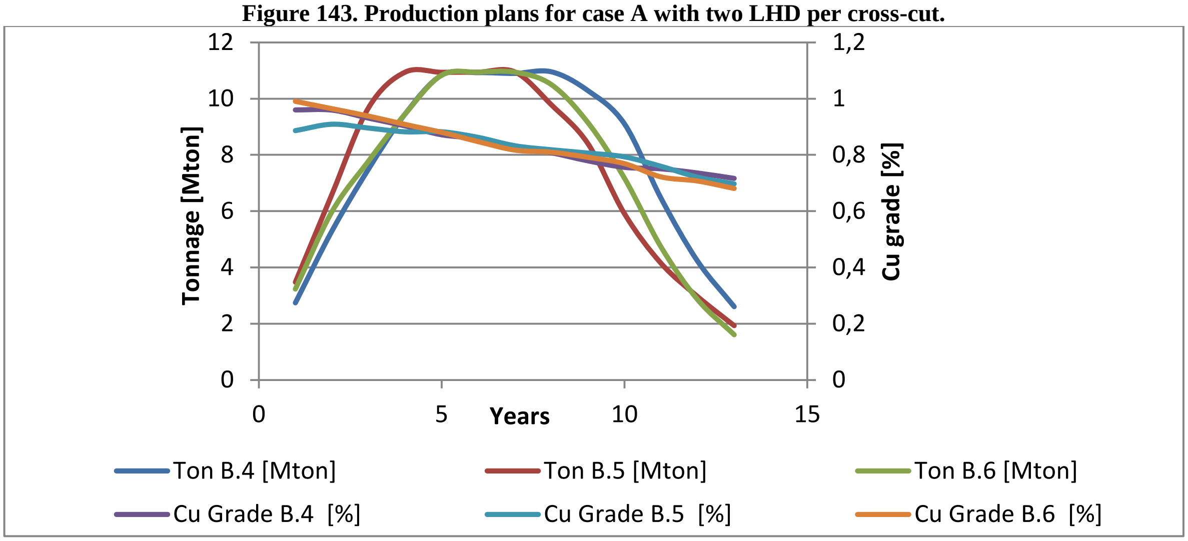

Figure 144. Production plans for case B with two LHD per cross-cut.

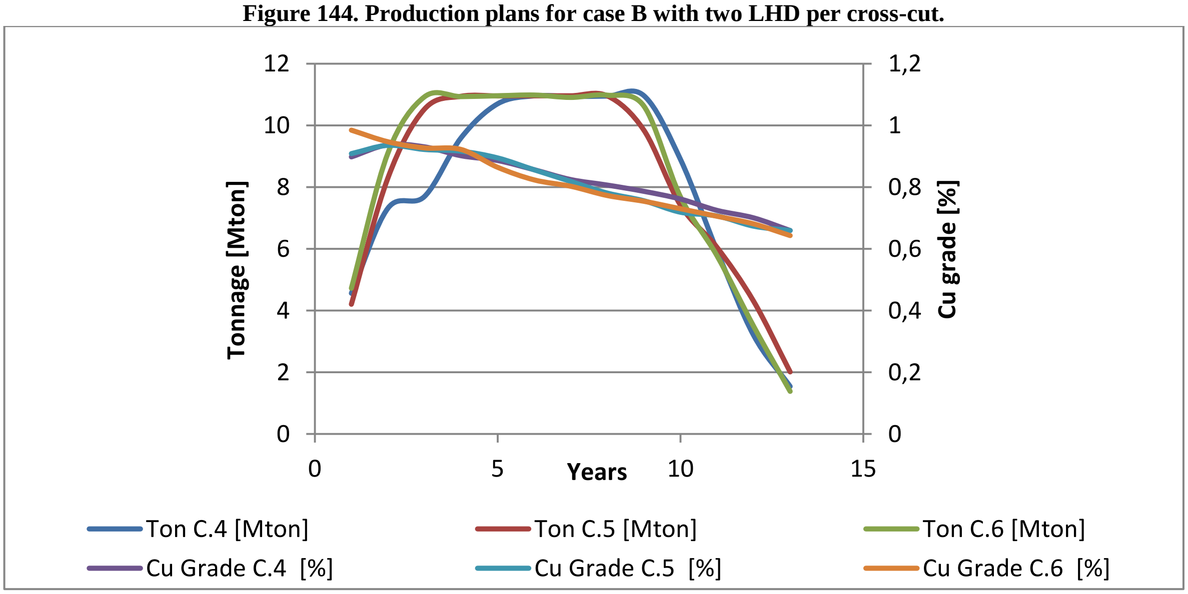

Figure 145. Production plans for case C with two LHD per cross-cut.

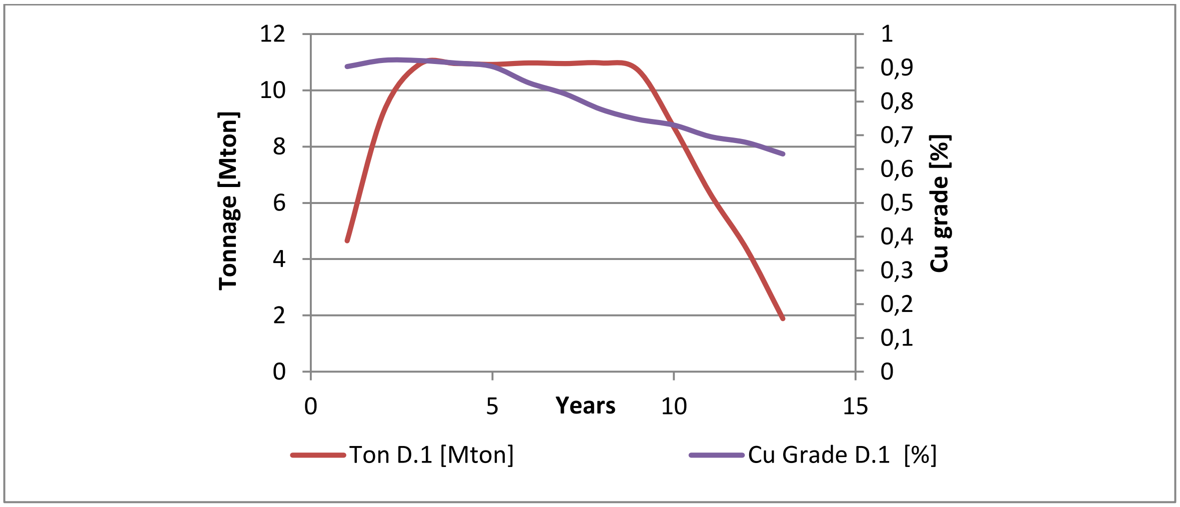

Figure 146. Production plans for case D with two LHD per cross-cut.

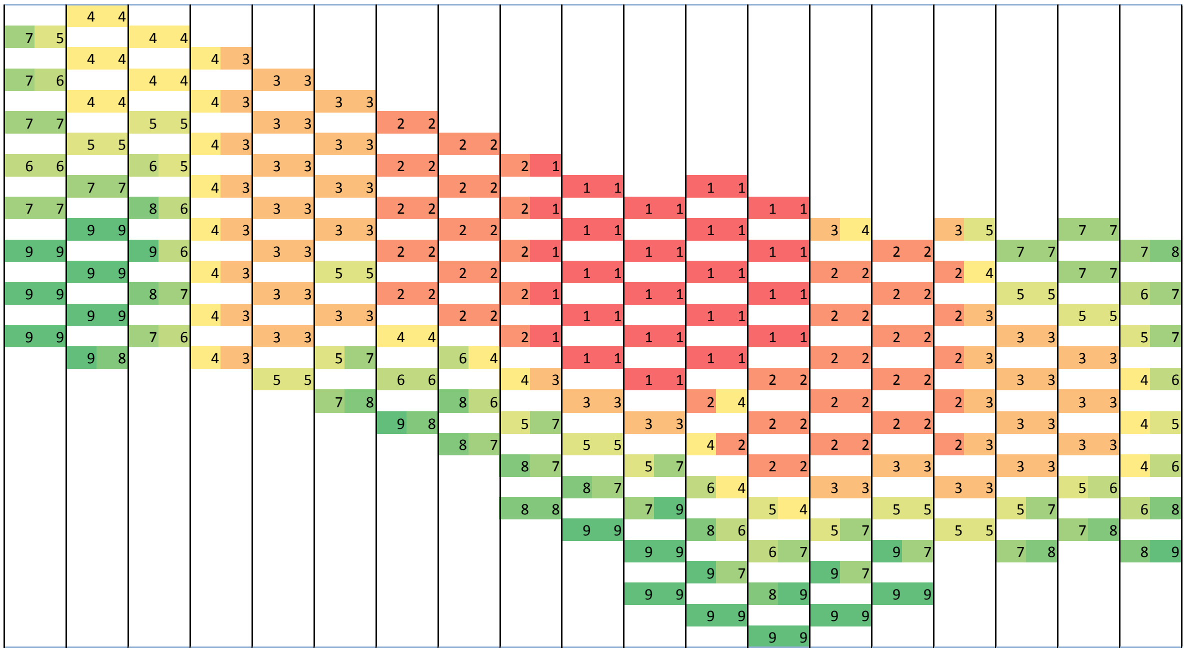

Figure 147. Drawpoints opening sequence for case A.1 with one LHD per cross-cut.

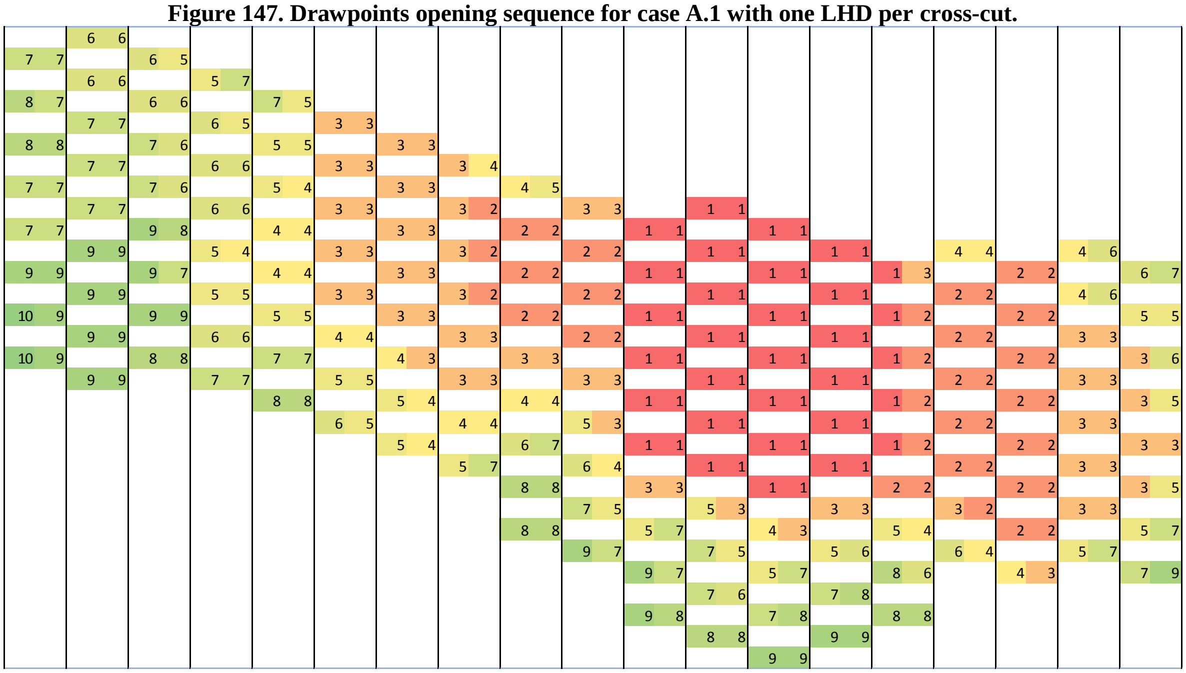

Figure 148. Drawpoints opening sequence for case A.2 with one LHD per cross-cut.

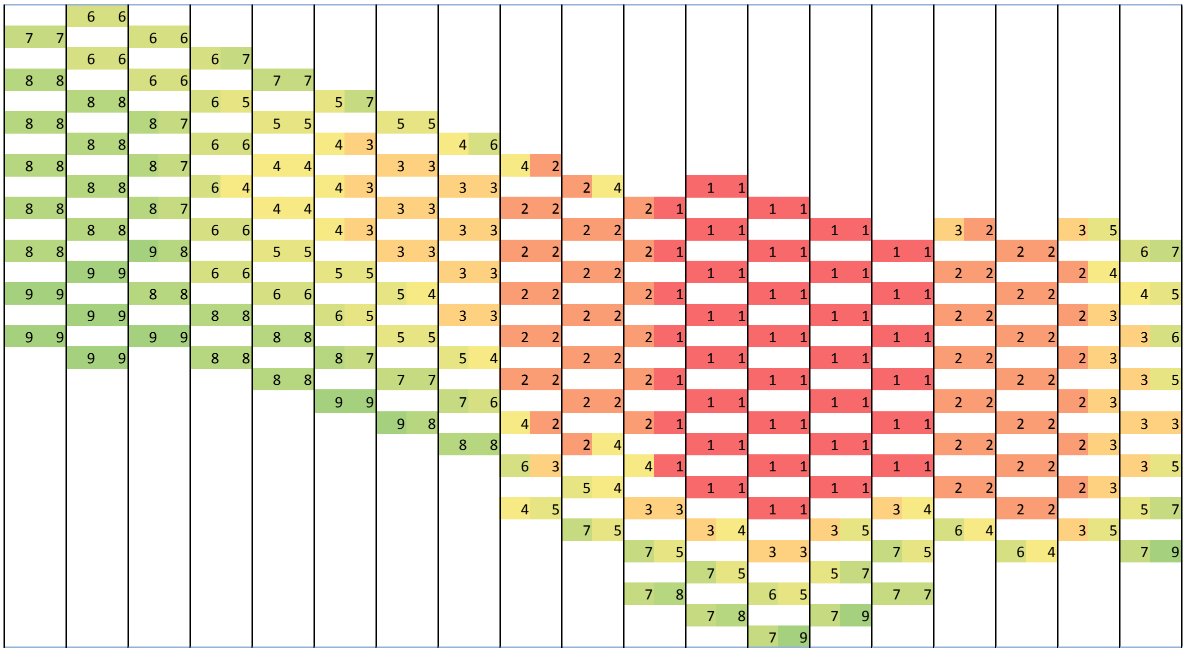

Figure 149. Drawpoints opening sequence for case A.3 with one LHD per cross-cut.

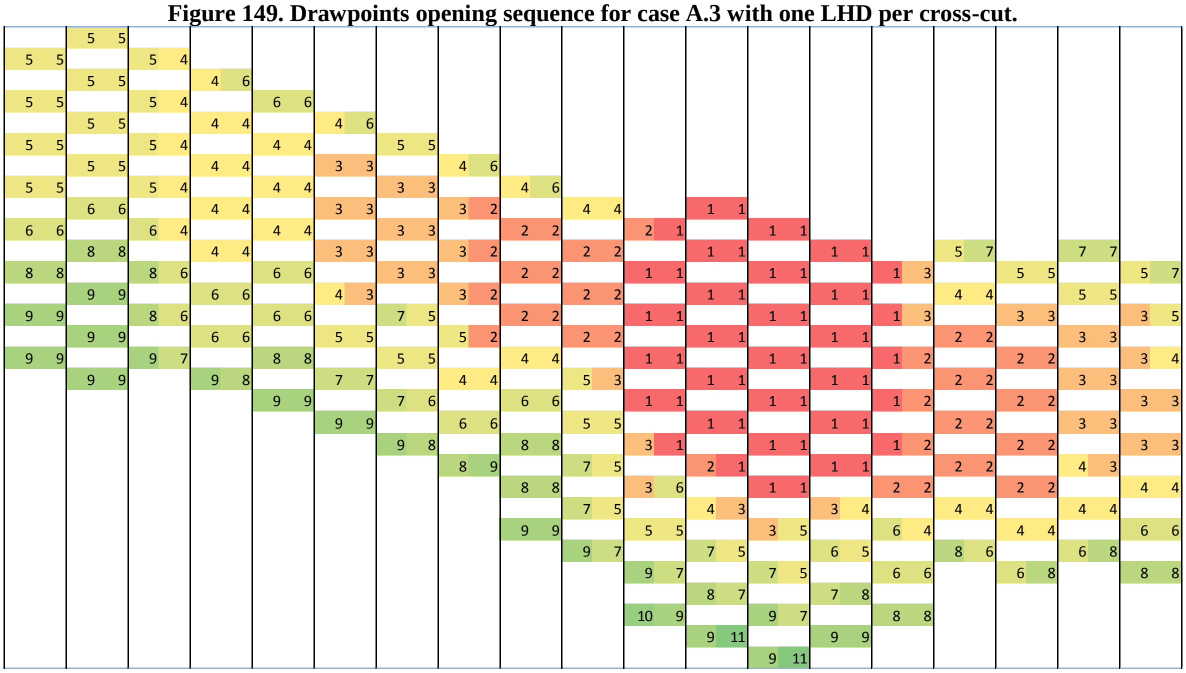

Figure 150. Drawpoints opening sequence for case B.1 with one LHD per cross-cut.

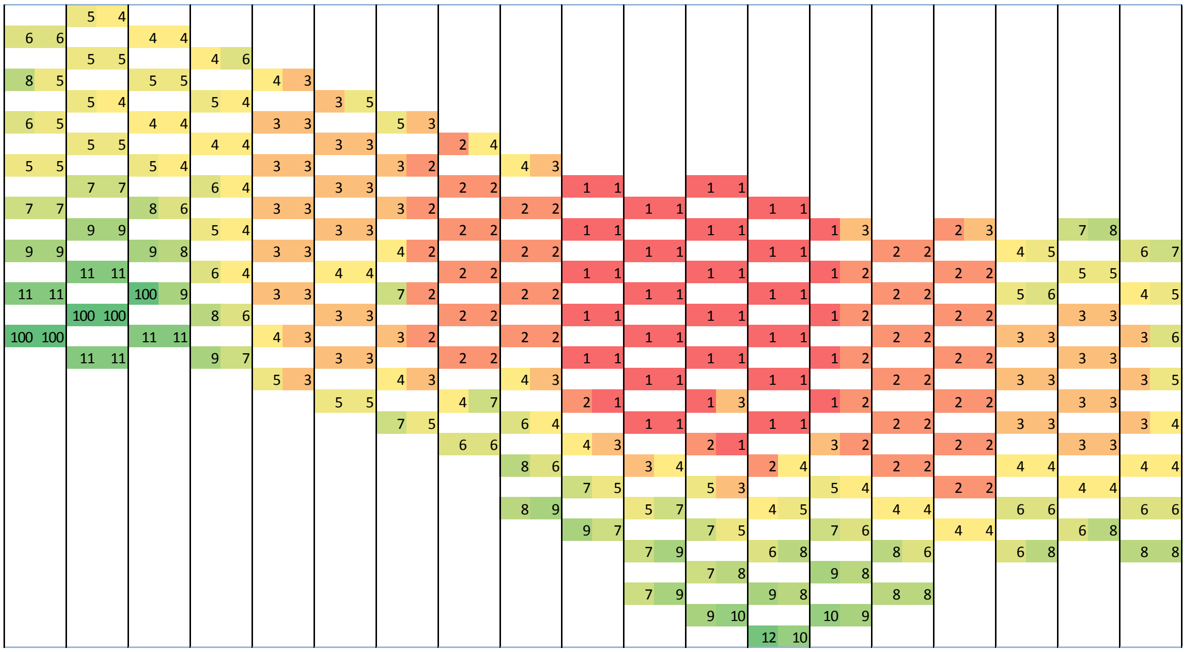

Figure 151. Drawpoints opening sequence for case B.2 with one LHD per cross-cut.

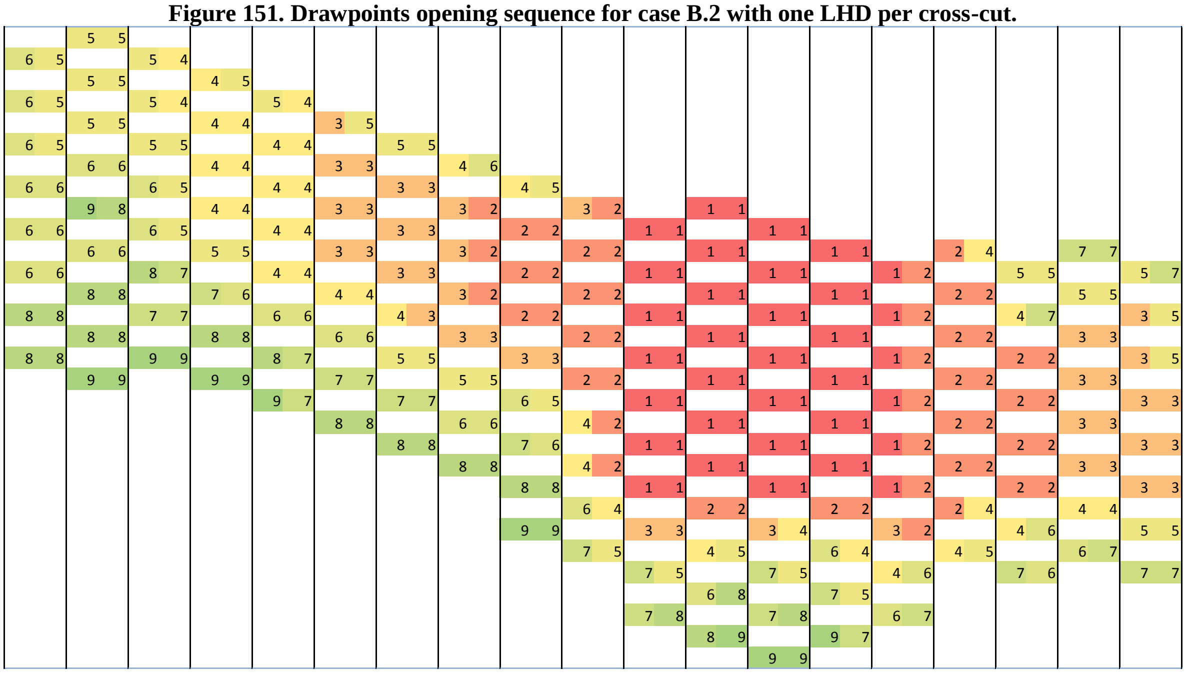

Figure 152. Drawpoints opening sequence for case B.3 with one LHD per cross-cut.

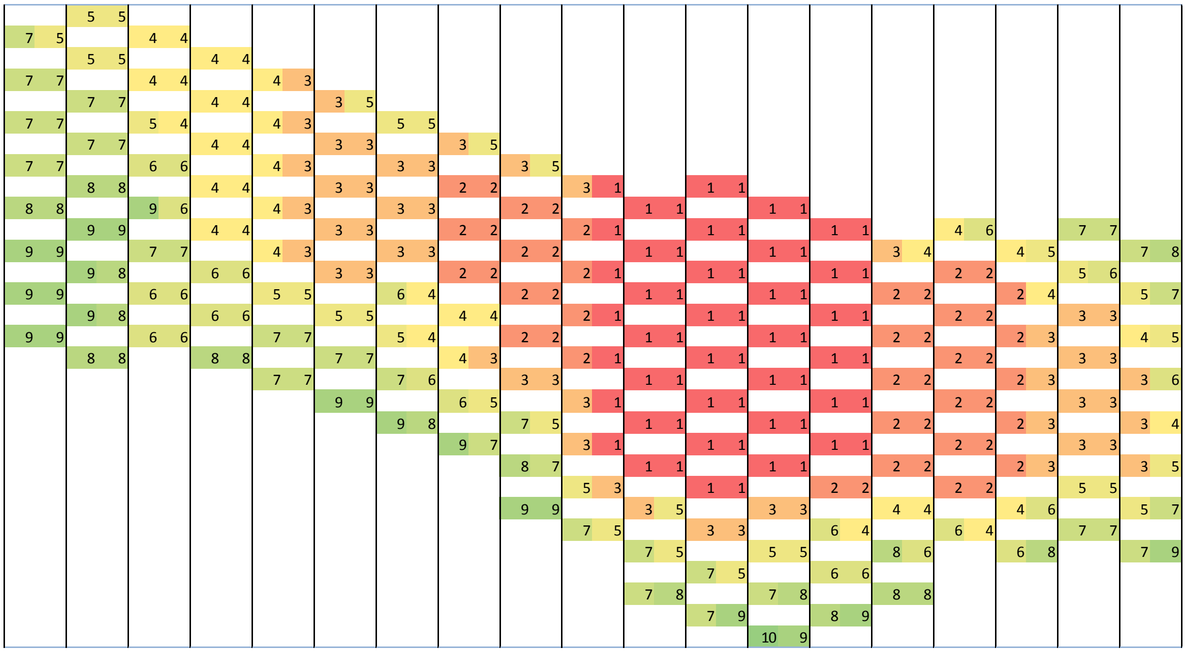

Figure 153. Drawpoints opening sequence for case C.1 with one LHD per cross-cut.

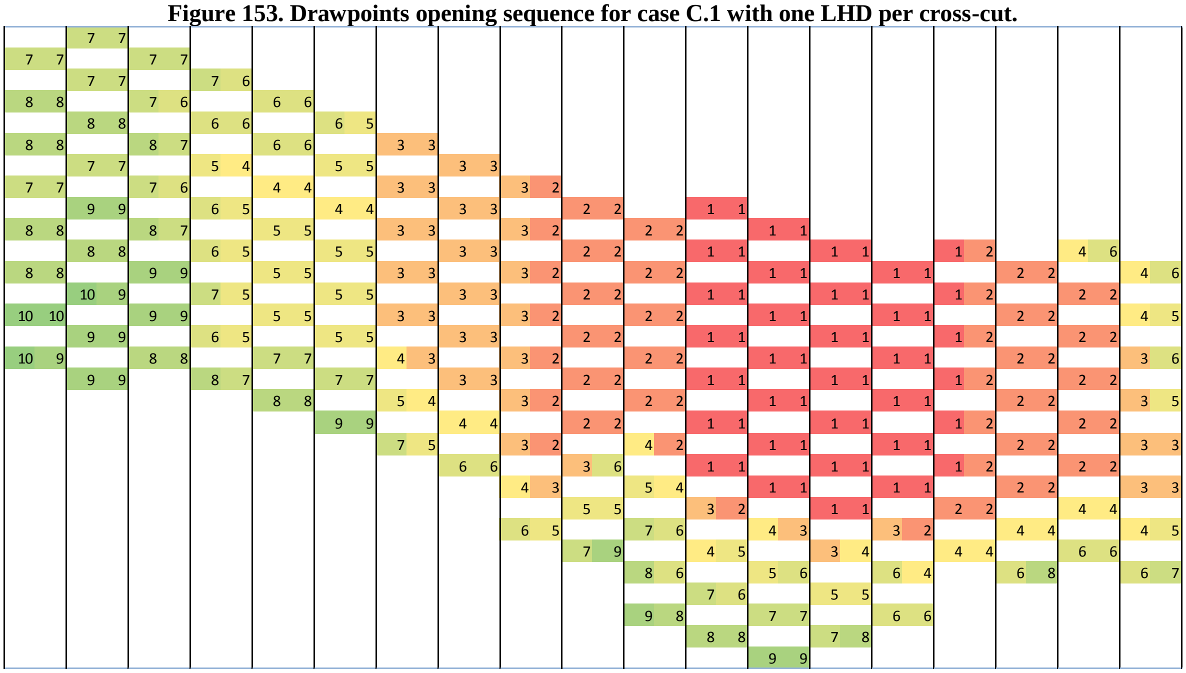

Figure 154. Drawpoints opening sequence for case C.2 with one LHD per cross-cut.

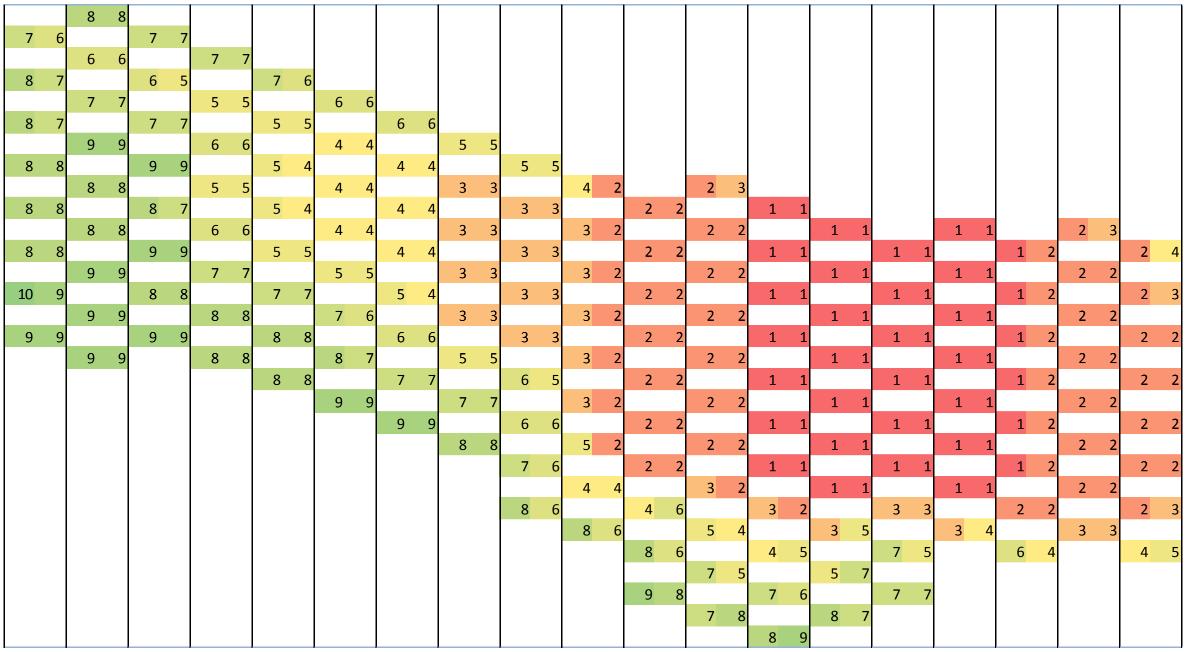

Figure 155. Drawpoints opening sequence for case C.3 with one LHD per cross-cut.

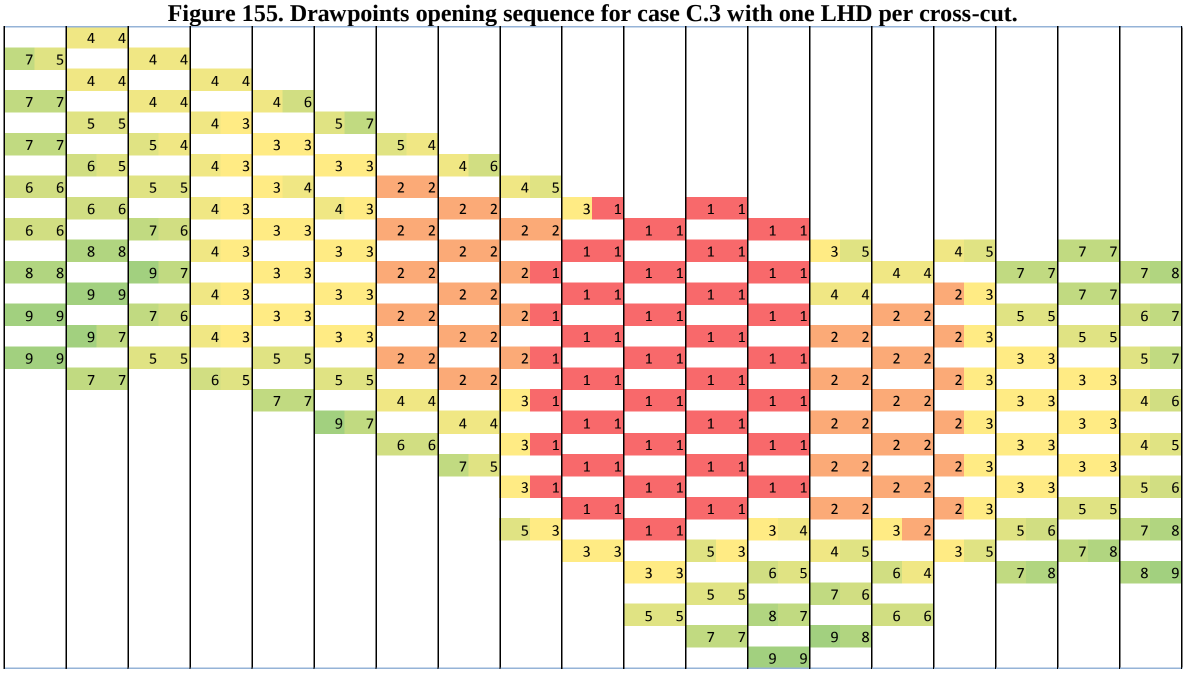

Figure 156. Drawpoints opening sequence for case A.4 with two LHD per cross-cut.

Figure 157. Drawpoints opening sequence for case A.5 with two LHD per cross-cut.

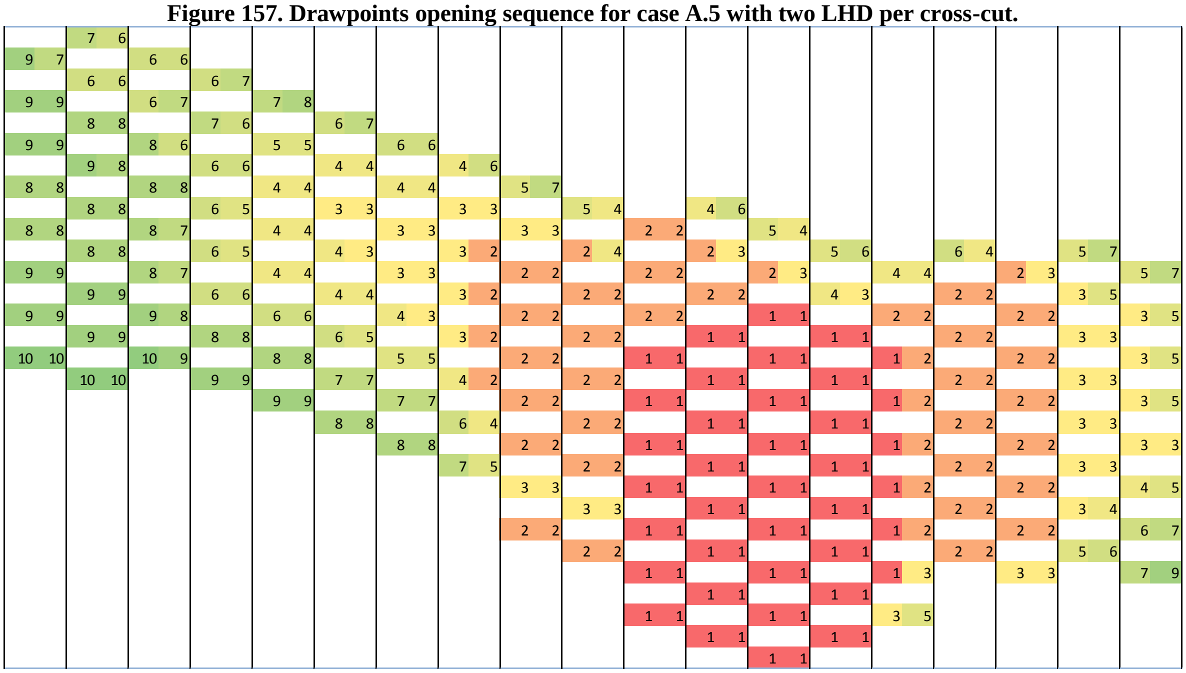

Figure 158. Drawpoints opening sequence for case A.6 with two LHD per cross-cut.

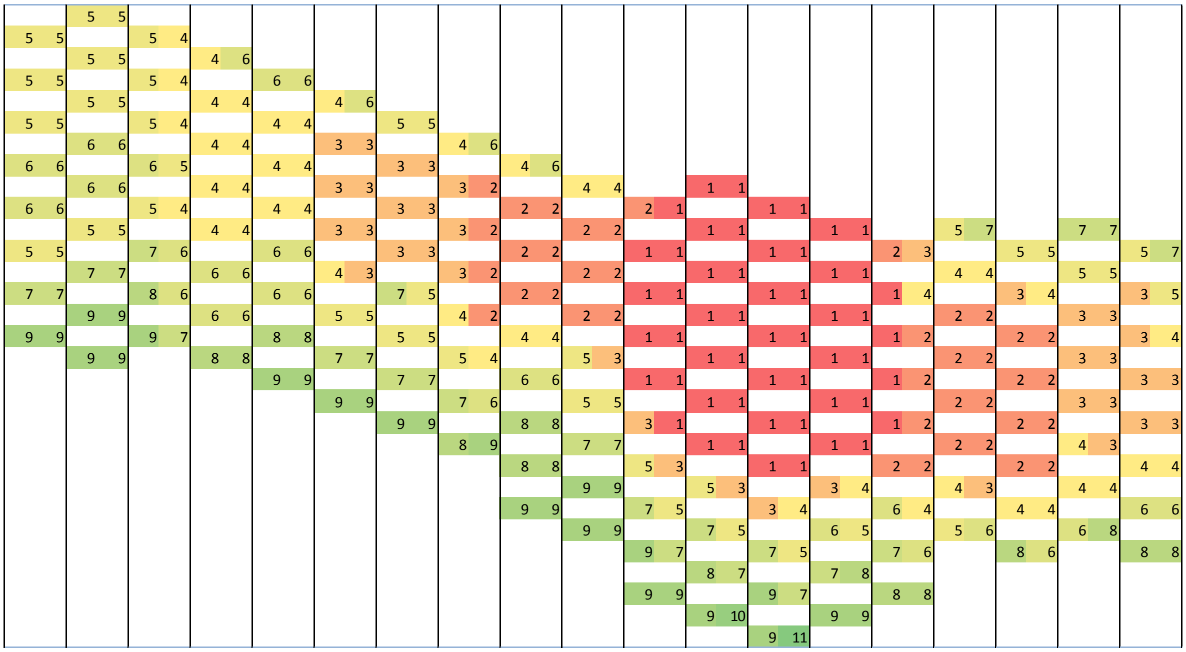

Figure 159. Drawpoints opening sequence for case B.4 with two LHD per cross-cut.

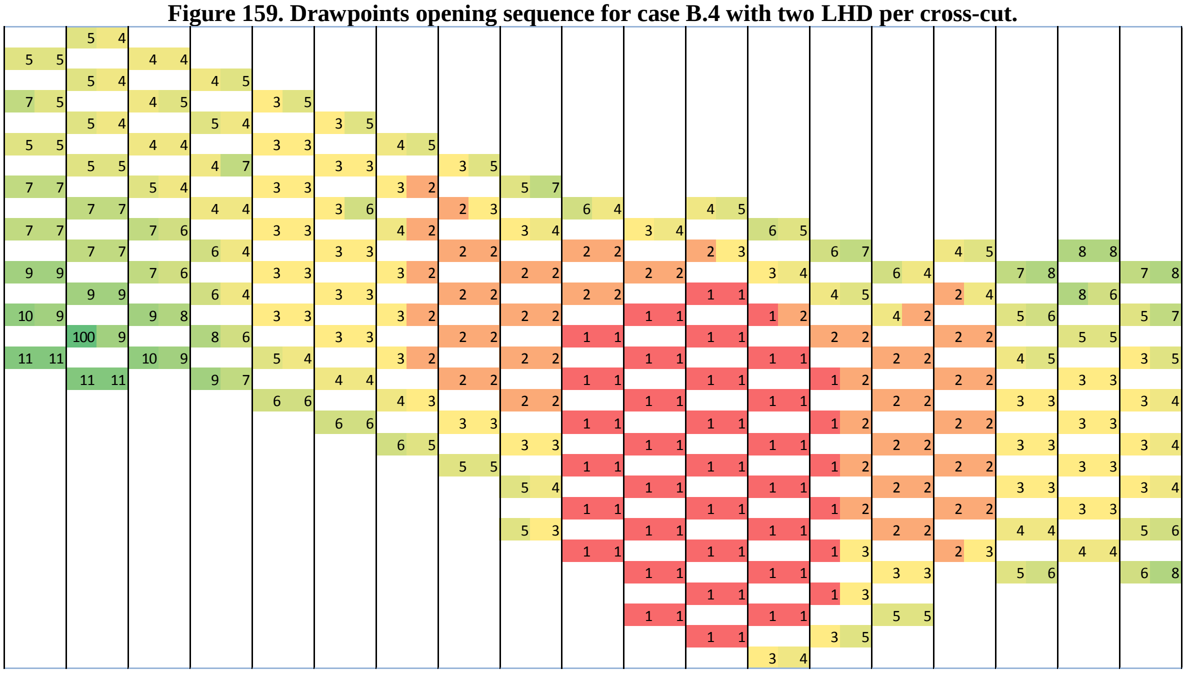

Figure 160. Drawpoints opening sequence for case B.5 with two LHD per cross-cut.

Figure 161. Drawpoints opening sequence for case B.6 with two LHD per cross-cut.

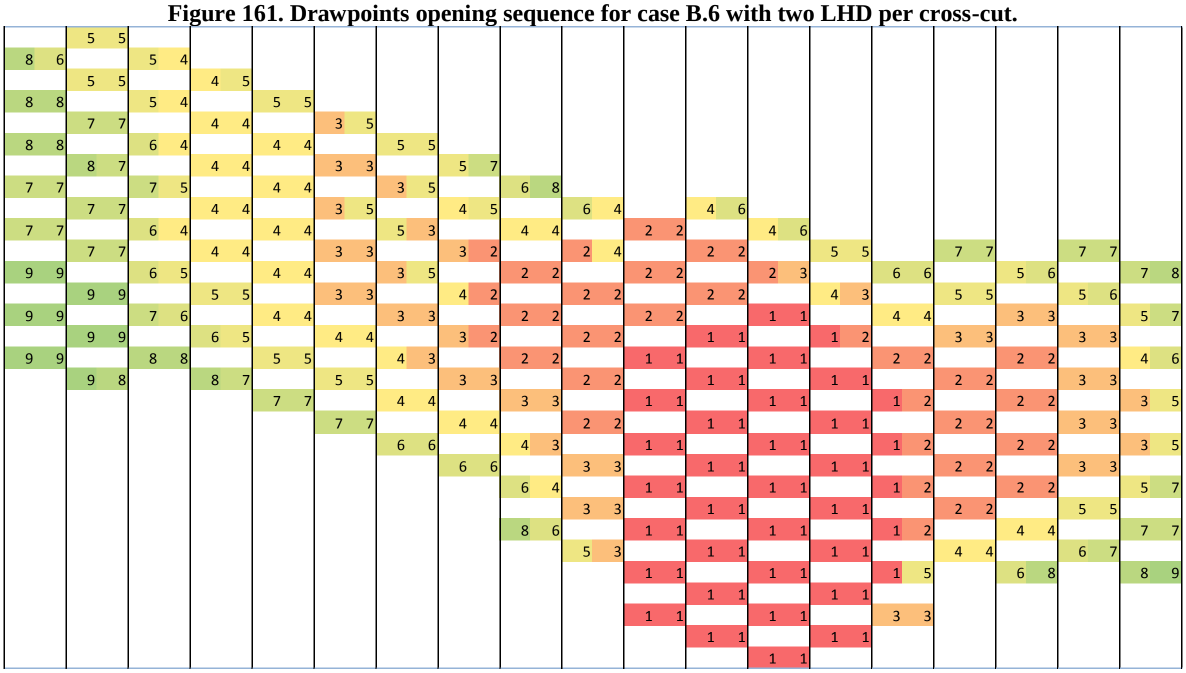

Figure 162. Drawpoints opening sequence for case C.4 with two LHD per cross-cut.

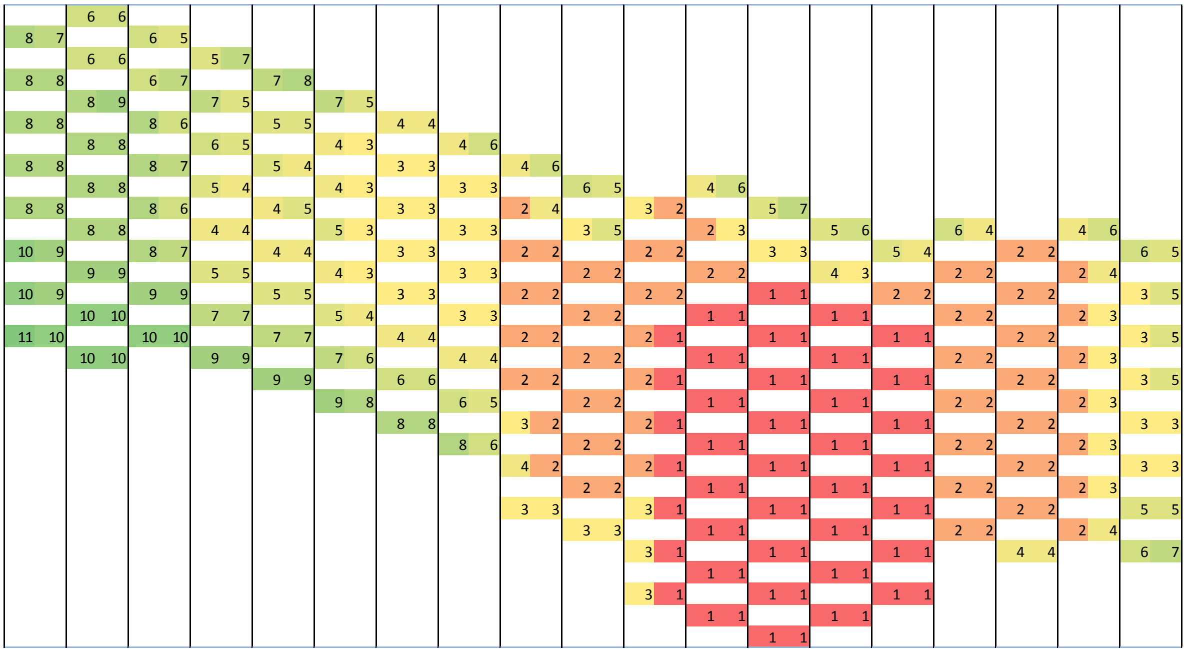

Figure 163. Drawpoints opening sequence for case C.5 with two LHD per cross-cut.

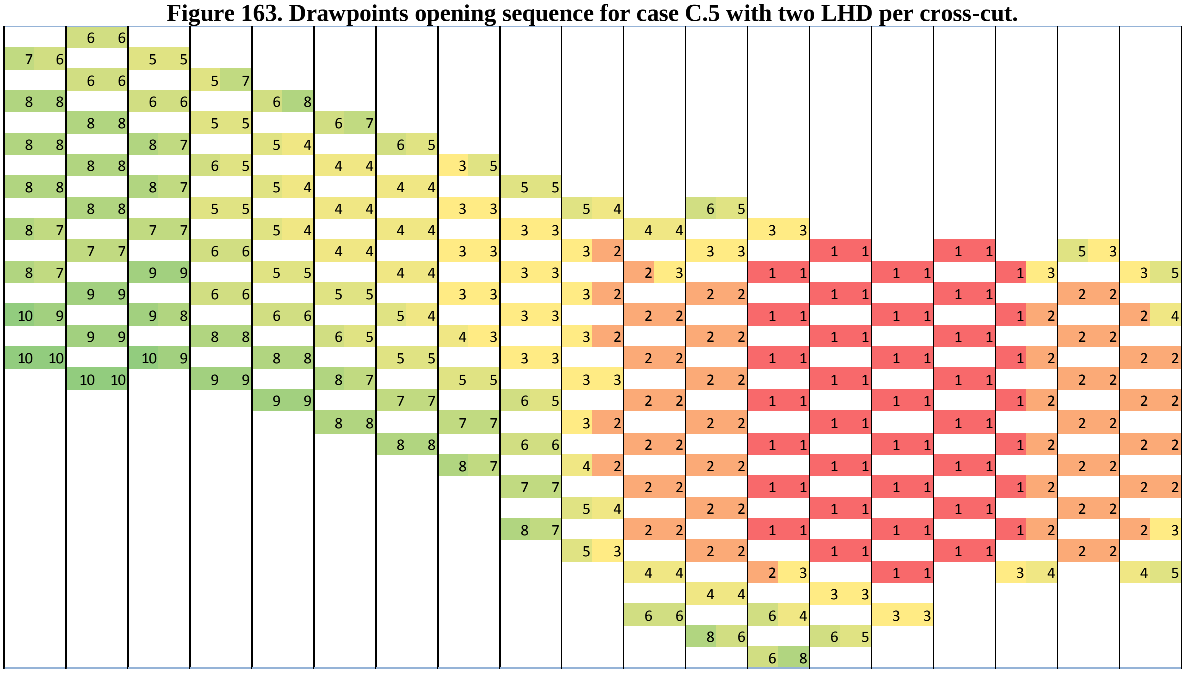

Figure 164. Drawpoints opening sequence for case C.6 with two LHD per cross-cut.

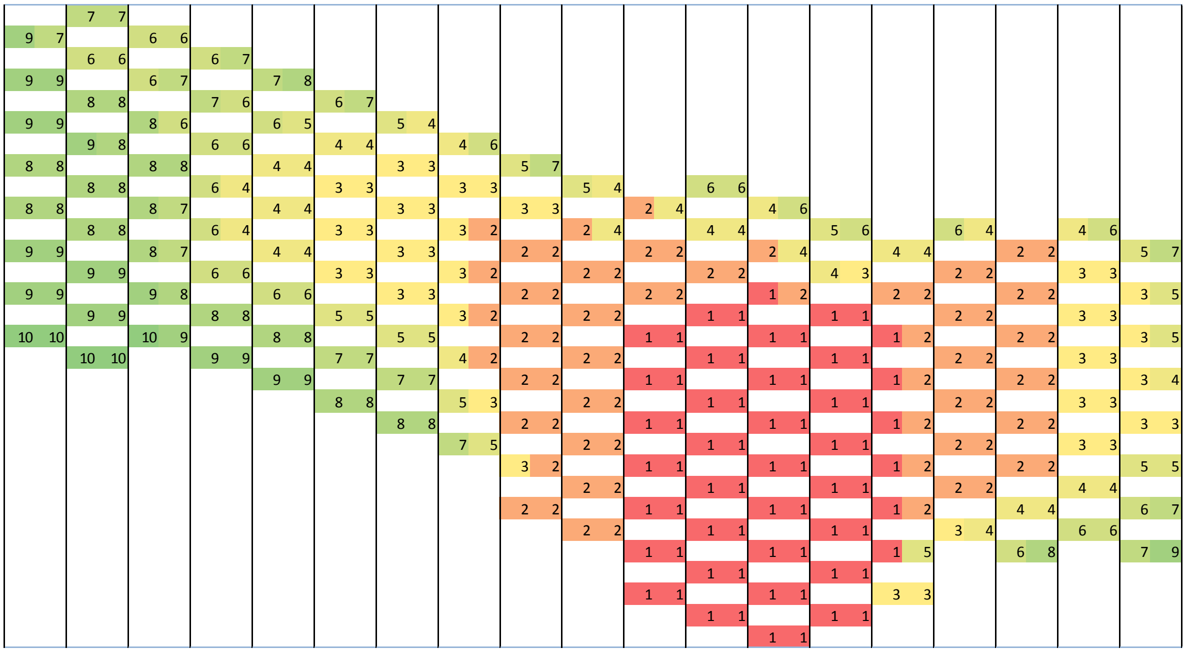

Figure 165. Drawpoints opening sequence for case D.1 with two LHD per cross-cut.

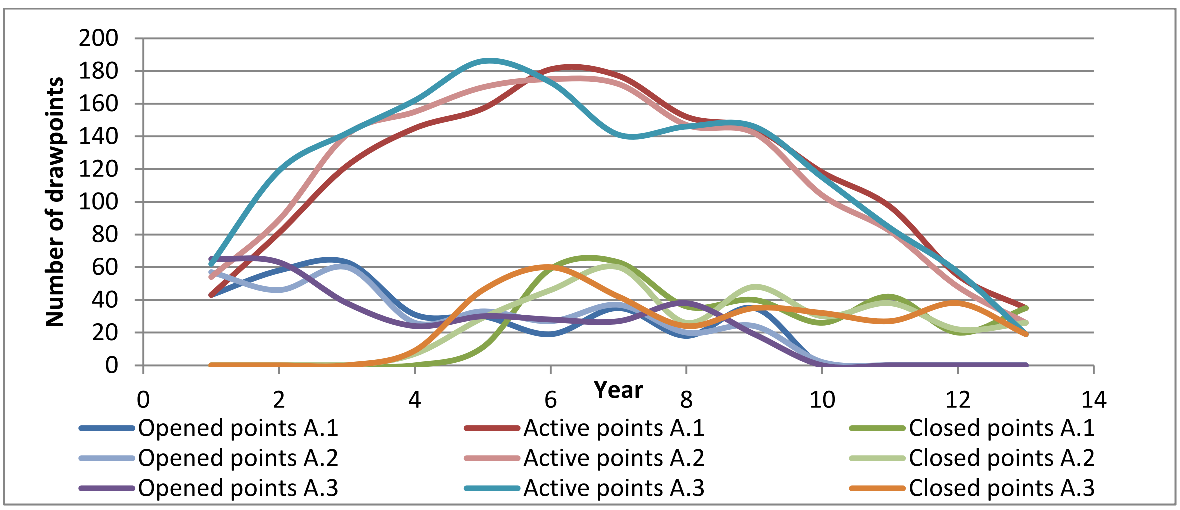

Figure 166. Drawpoints state in case A with one LHD per cross-cut.

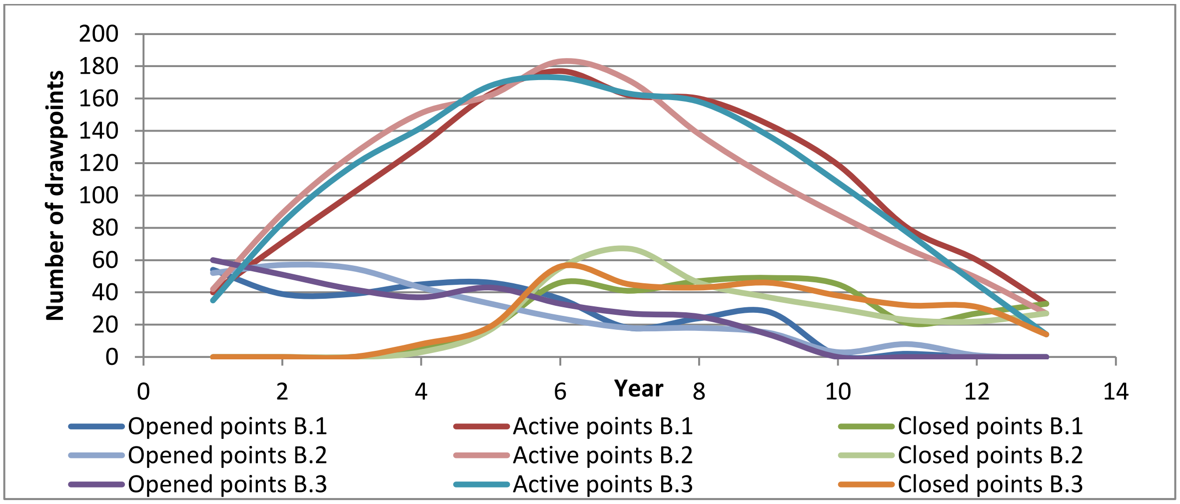

Figure 167. Drawpoints state in case B with one LHD per cross-cut.

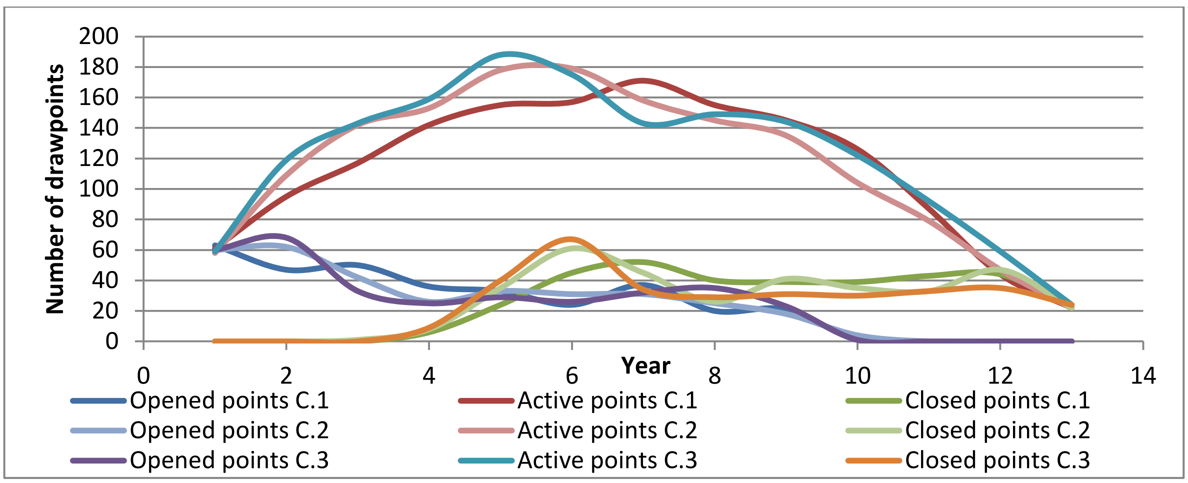

Figure 168. Drawpoints state in case C with one LHD per cross-cut.

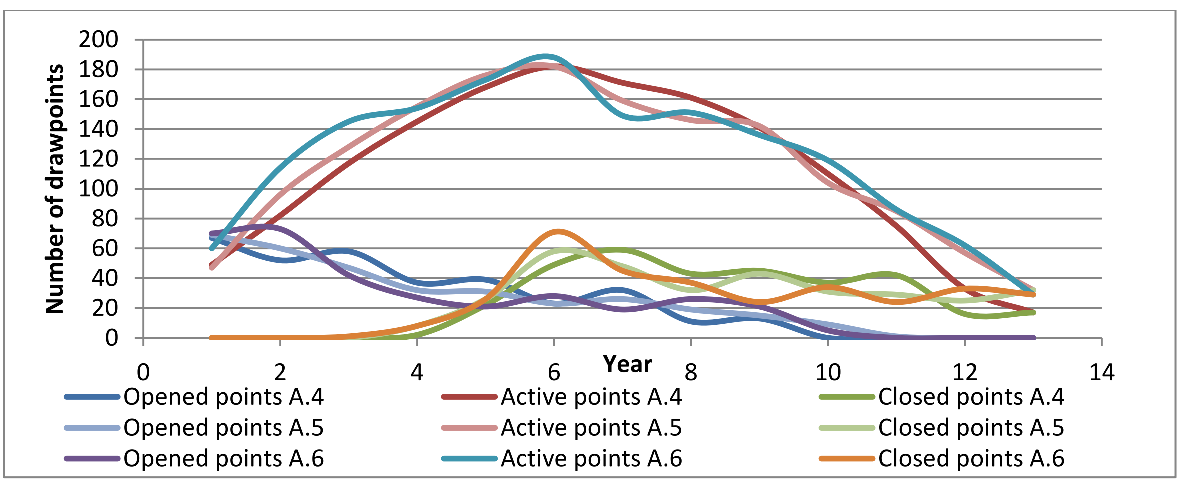

Figure 169. Drawpoints state in case A with two LHD per cross-cut.

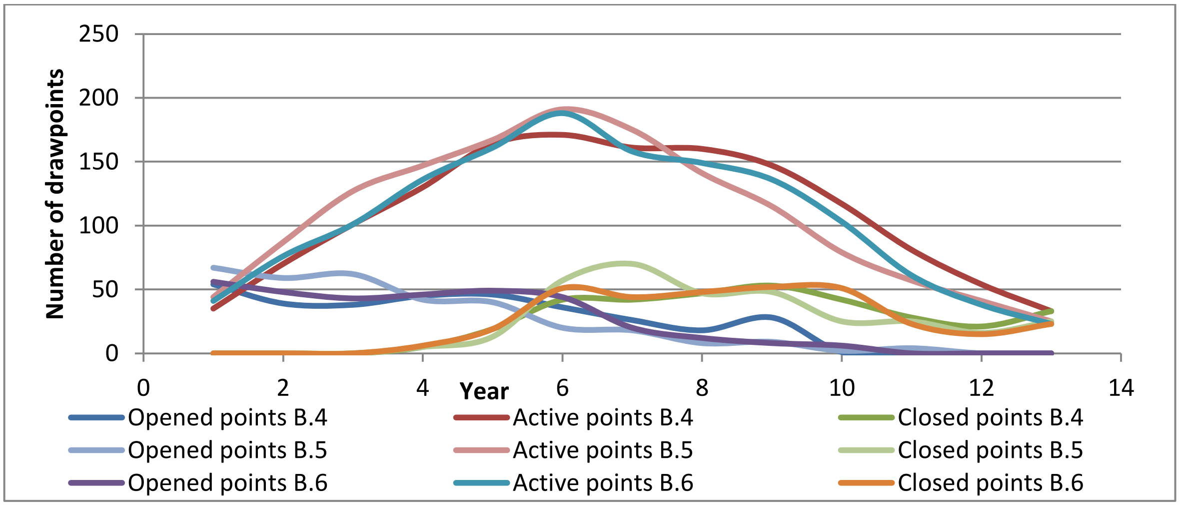

Figure 170. Drawpoints state in case B with two LHD per cross-cut.

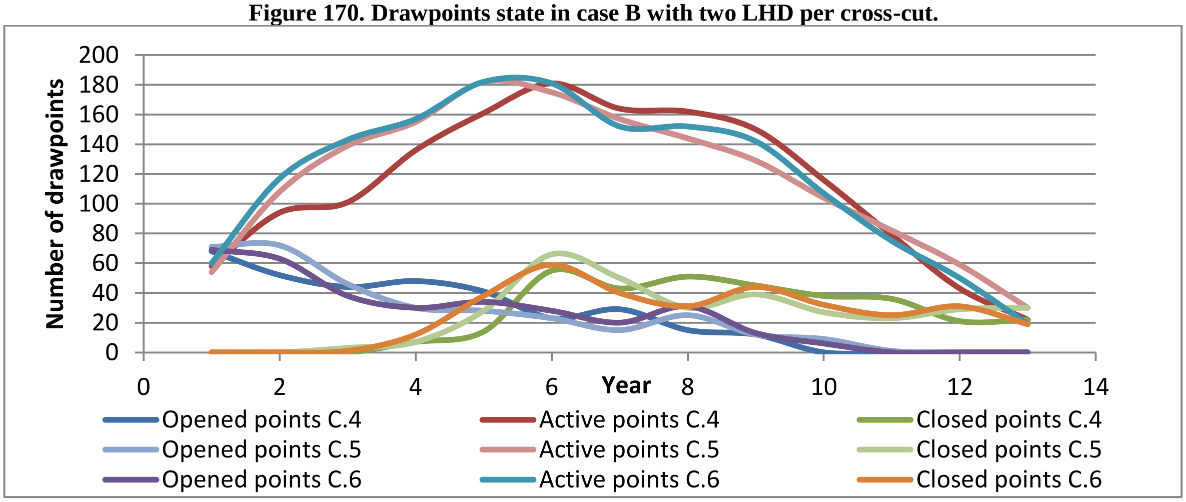

Figure 171. Drawpoints state in case C with two LHD per cross-cut.

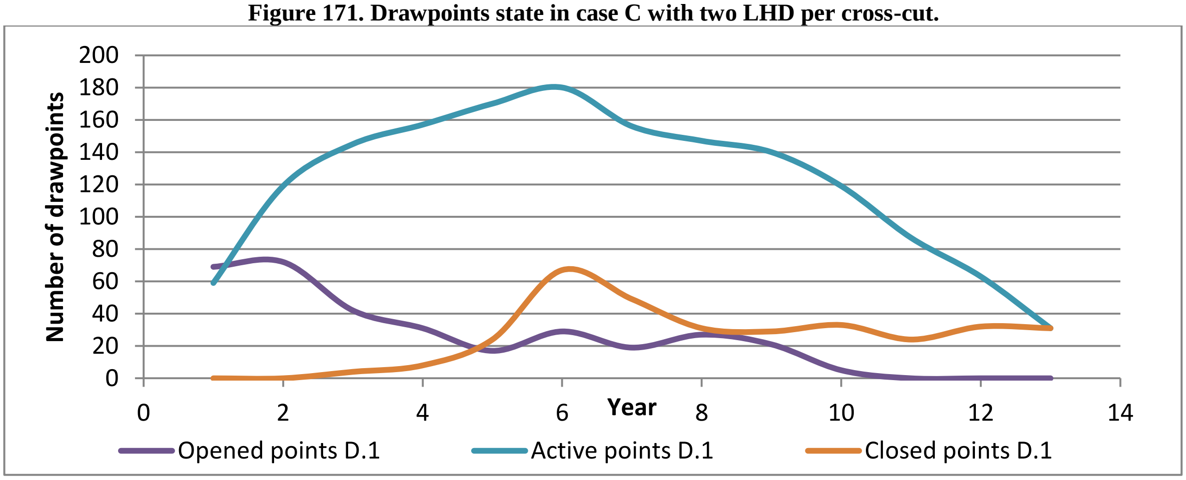

Figure 172. Drawpoints state in case D with two LHD per cross-cut

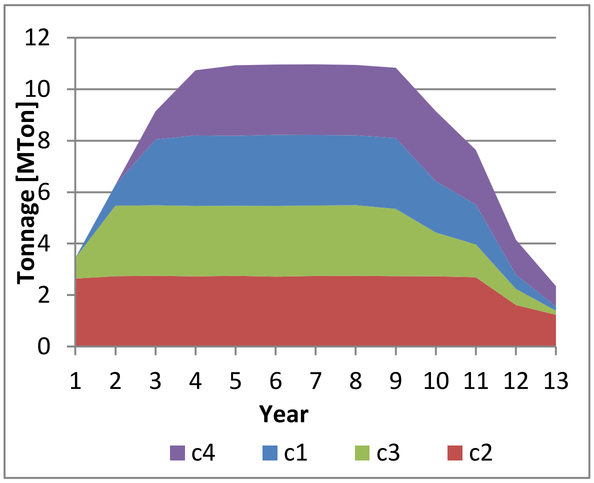

Figure 173. Production plan per crusher for case A.1.

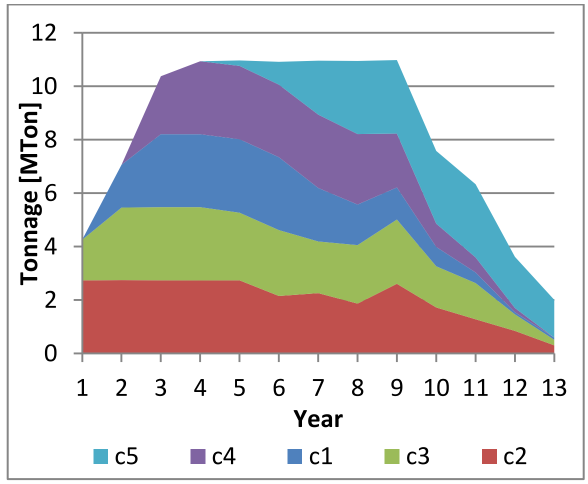

Figure 174. Production plan per crusher for case A.2.

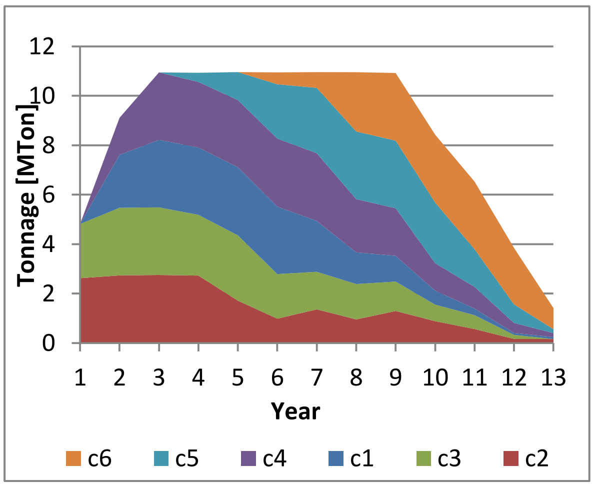

Figure 175. Production plan per crusher for case A.3.

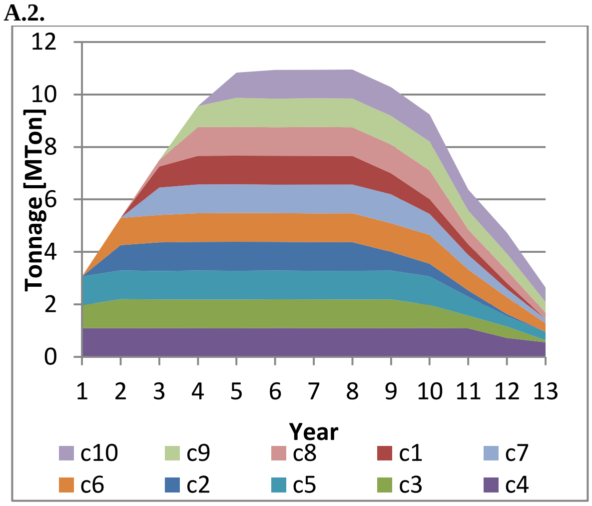

Figure 176. Production plan per crusher for case B.1.

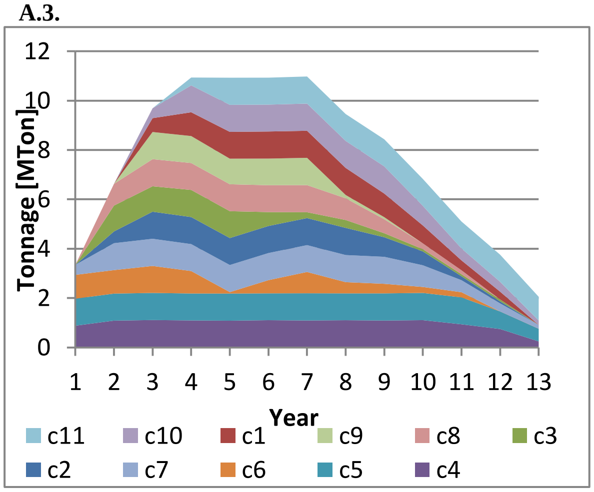

Figure 177. Production plan per crusher for case B.2.

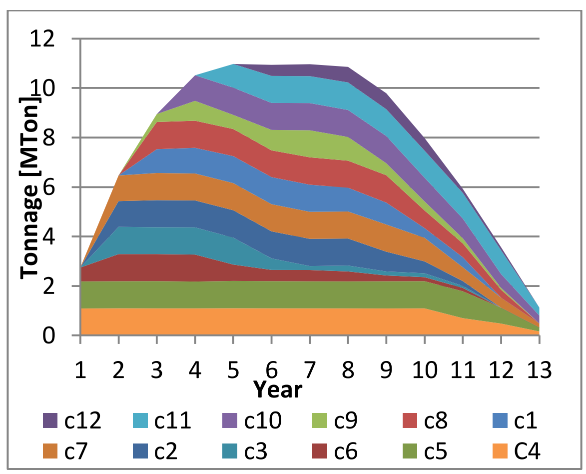

Figure 178. Production plan per crusher for case B.3.

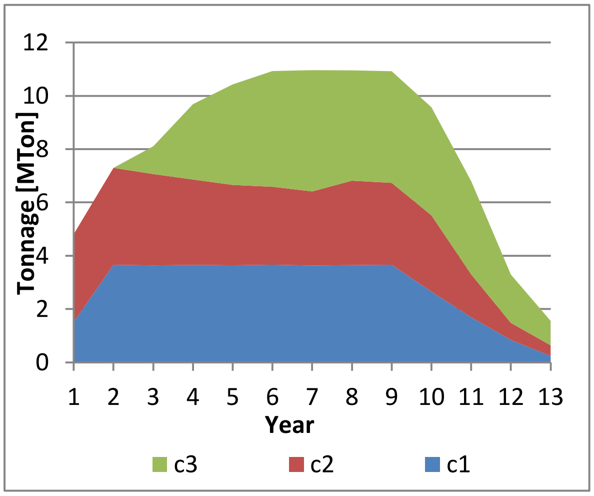

Figure 179. Production plan per crusher for case C.1.

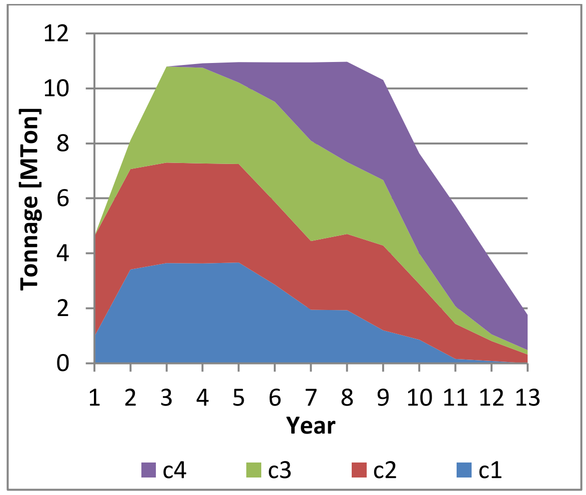

Figure 180. Production plan per crusher for case C.2.

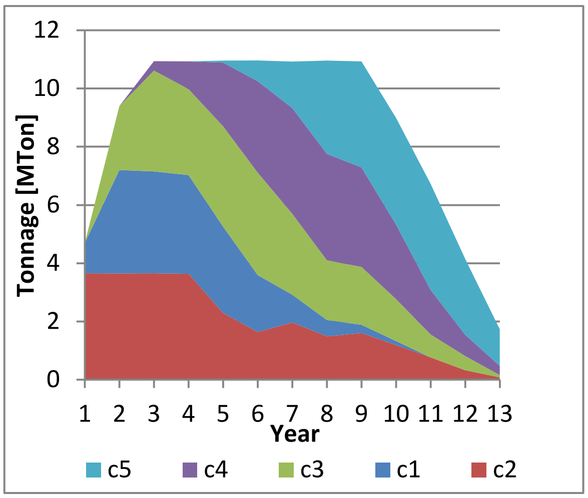

Figure 181. Production plan per crusher for case C.3.

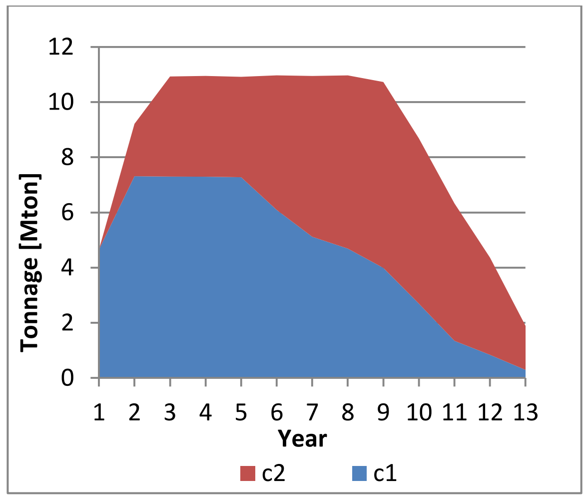

Figure 182. Production plan per crusher for case D.

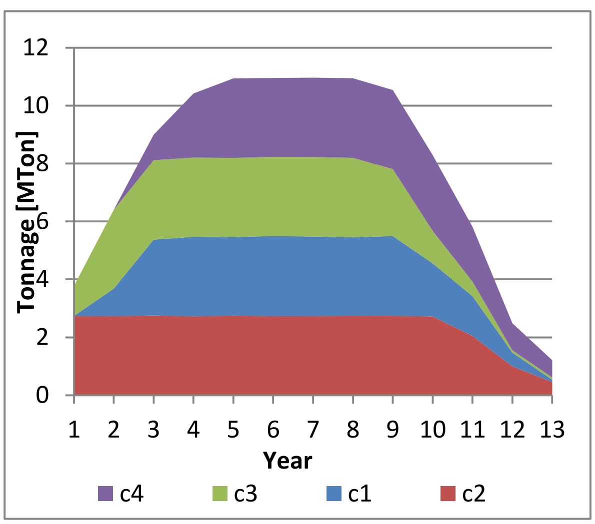

Figure 183. Production plan per crusher for case A.4.

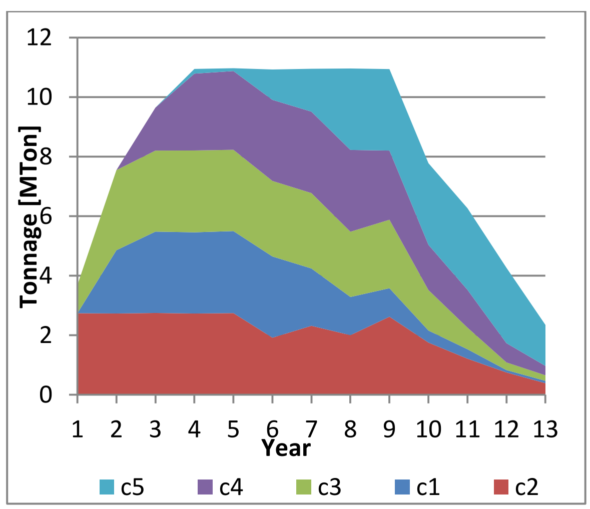

Figure 184. Production plan per crusher for case A.5.

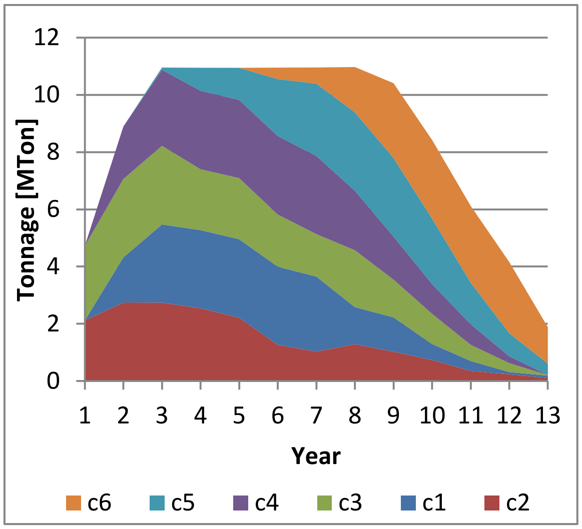

Figure 185. Production plan per crusher for case A.6.

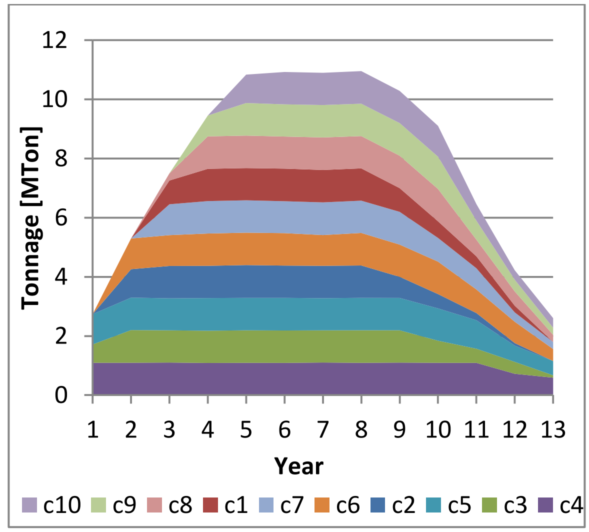

Figure 186. Production plan per crusher for case B.4.

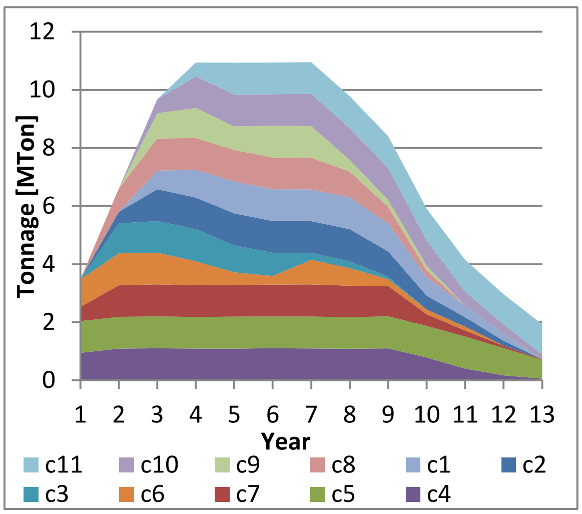

Figure 187. Production plan per crusher for case B.5.

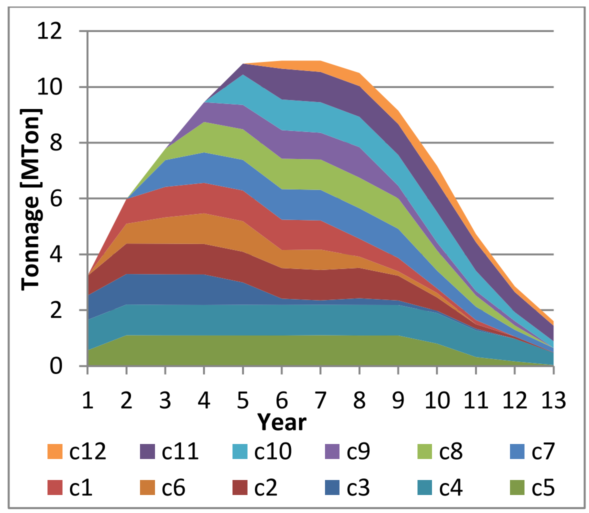

Figure 188. Production plan per crusher for case B.6.

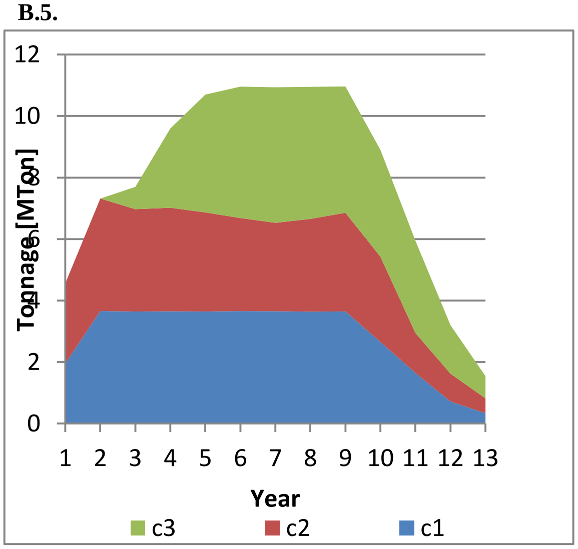

Figure 189. Production plan per crusher for case C.4.

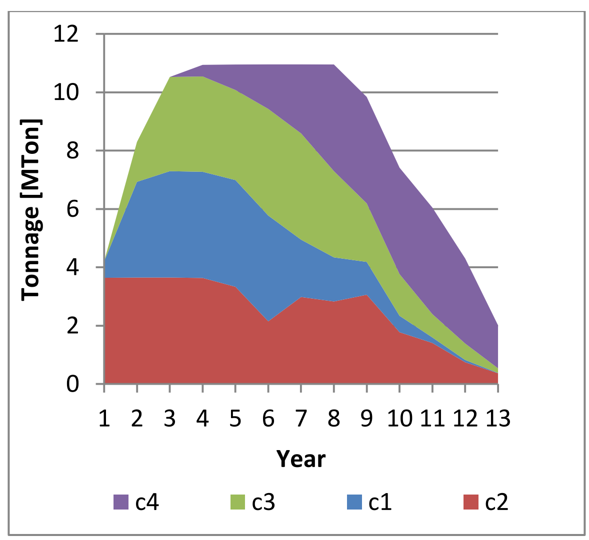

Figure 190. Production plan per crusher for case C.5.

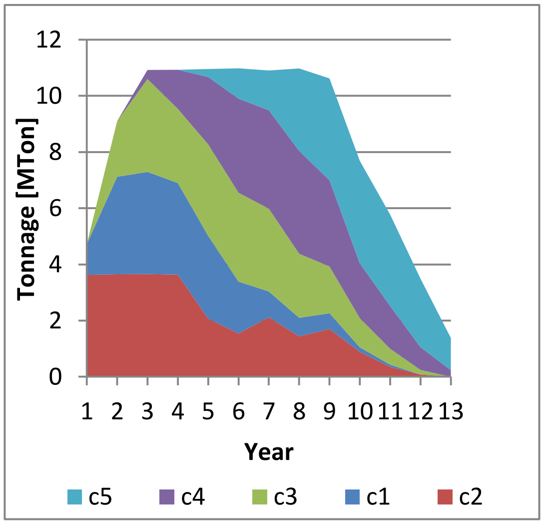

Figure 191. Production plan per crusher for case C.6.

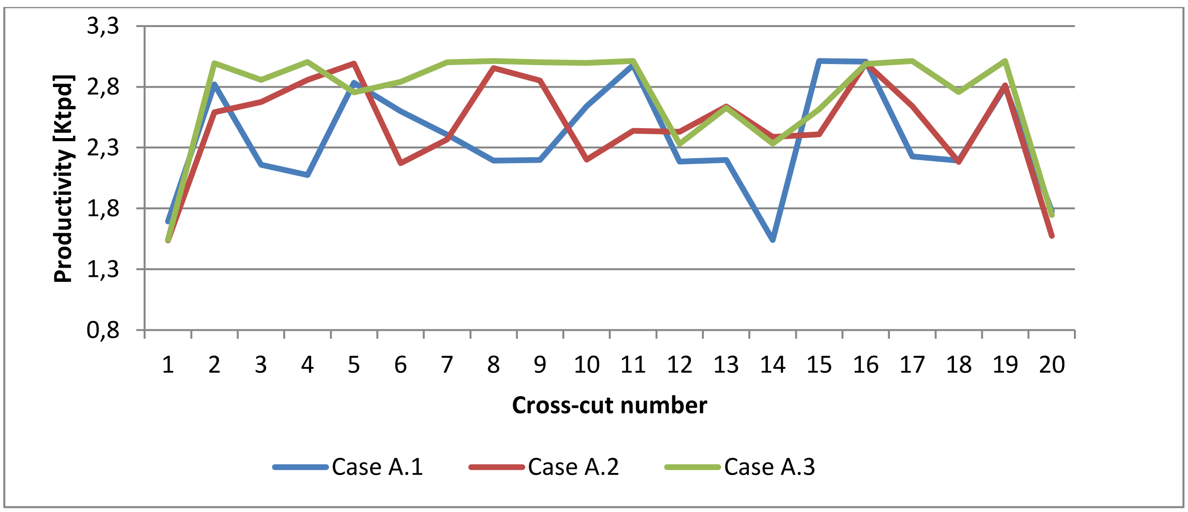

Figure 192. Productivity per cross-cut case A, 1 LHD per cross-cut.

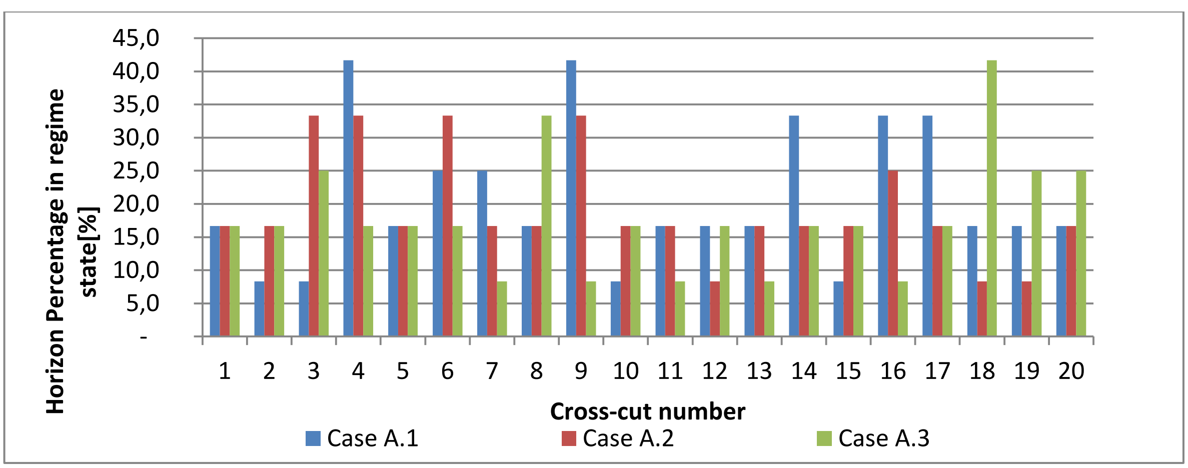

Figure 193. Horizon percentage in regime state case A, 1 LHD per cross-cut.

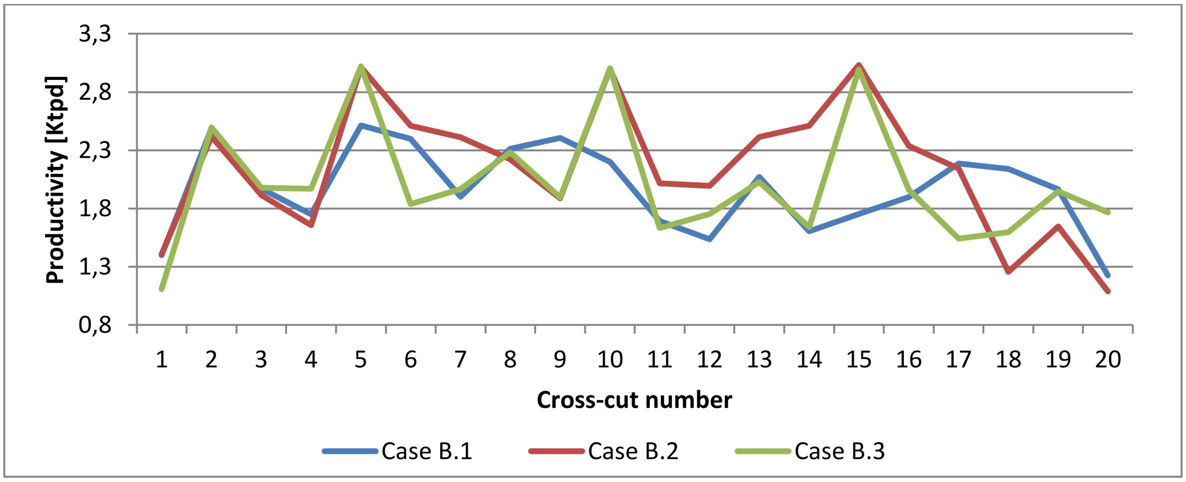

Figure 194. Productivity per cross-cut case B, 1 LHD per cross-cut.

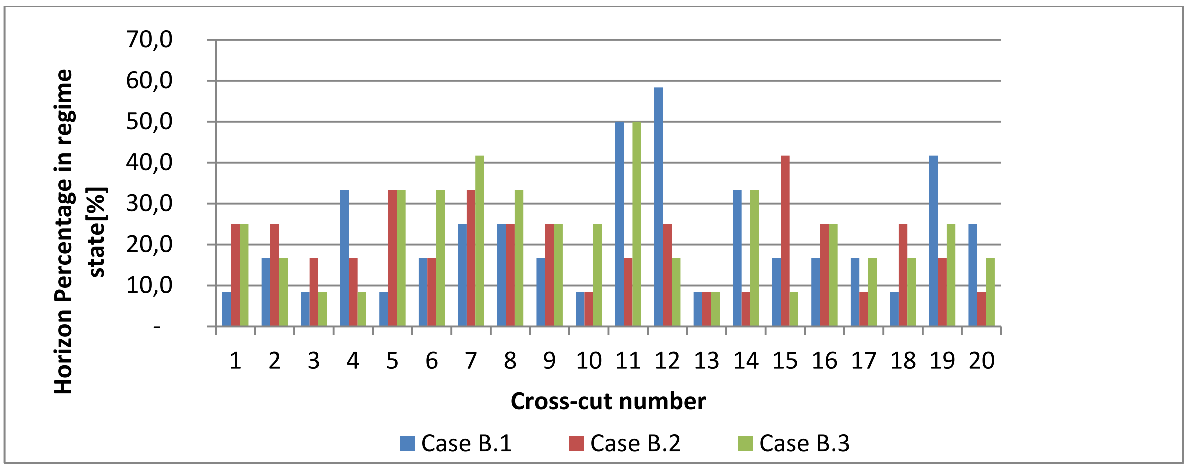

Figure 195. Horizon percentage in regime state case B, 1 LHD per cross-cut.

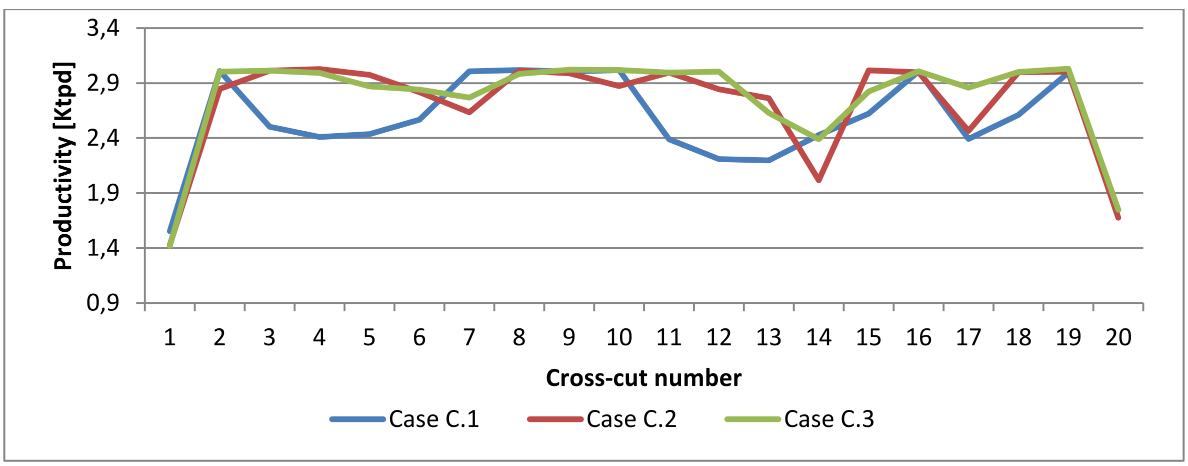

Figure 196. Productivity per cross-cut case C, 1 LHD per cross-cut.

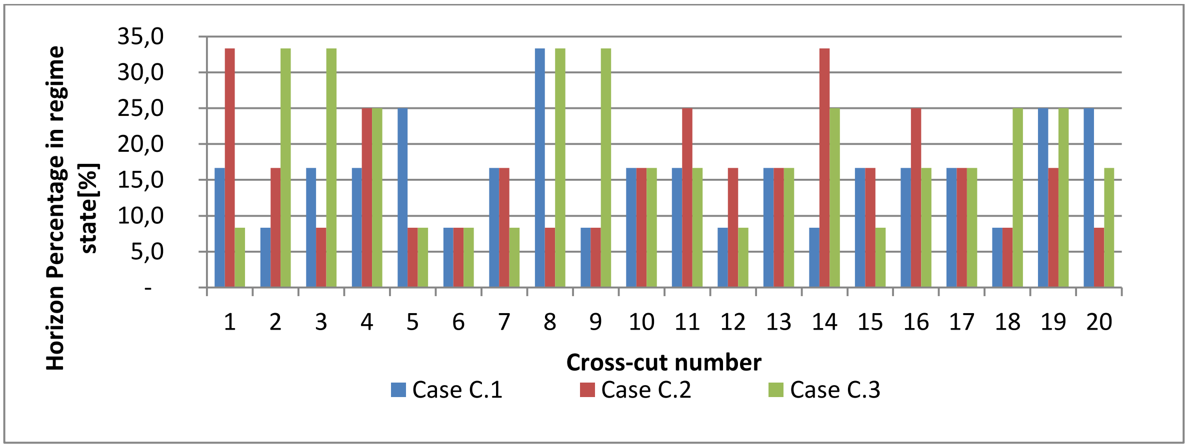

Figure 197. Horizon percentage in regime state case C, 1 LHD per cross-cut.

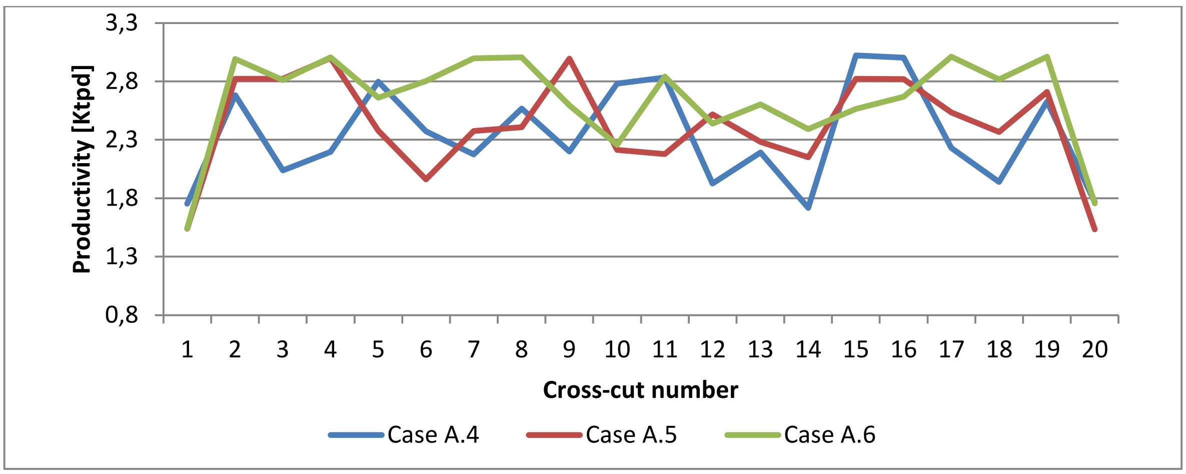

Figure 198. Productivity per cross-cut case A, 2 LHD per cross-cut.

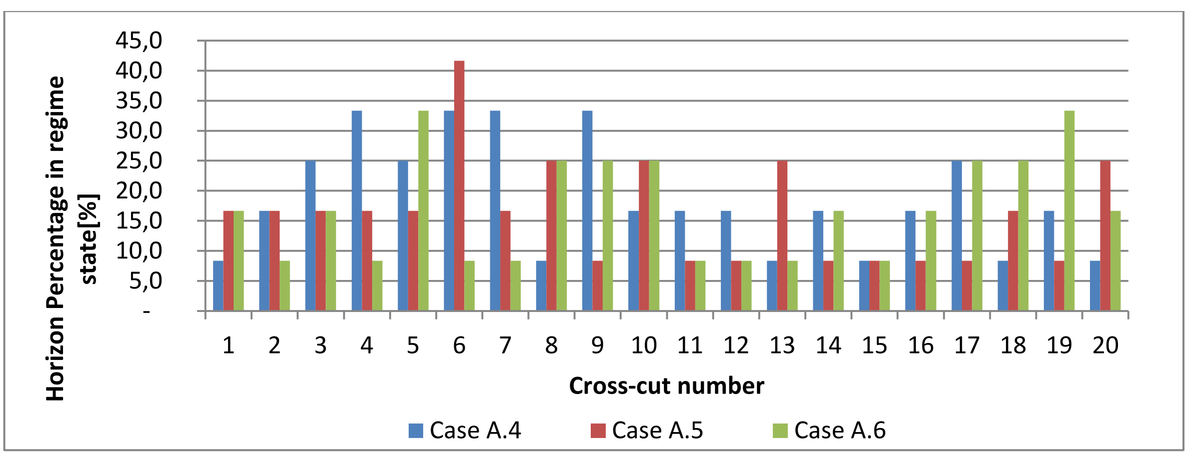

Figure 199. Horizon percentage in regime state case A, 2 LHD per cross-cut.

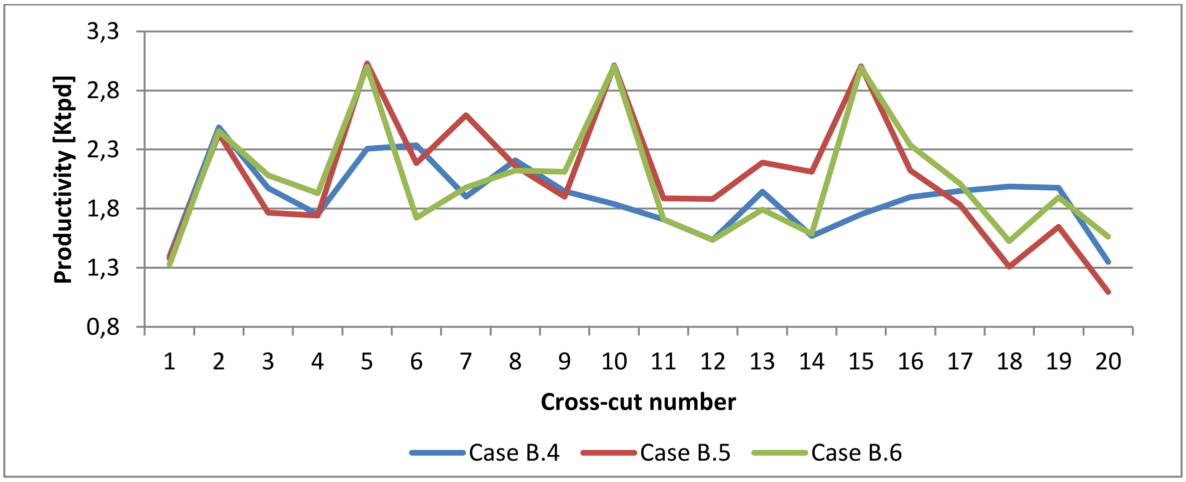

Figure 200. Productivity per cross-cut case B, 2 LHD per cross-cut.

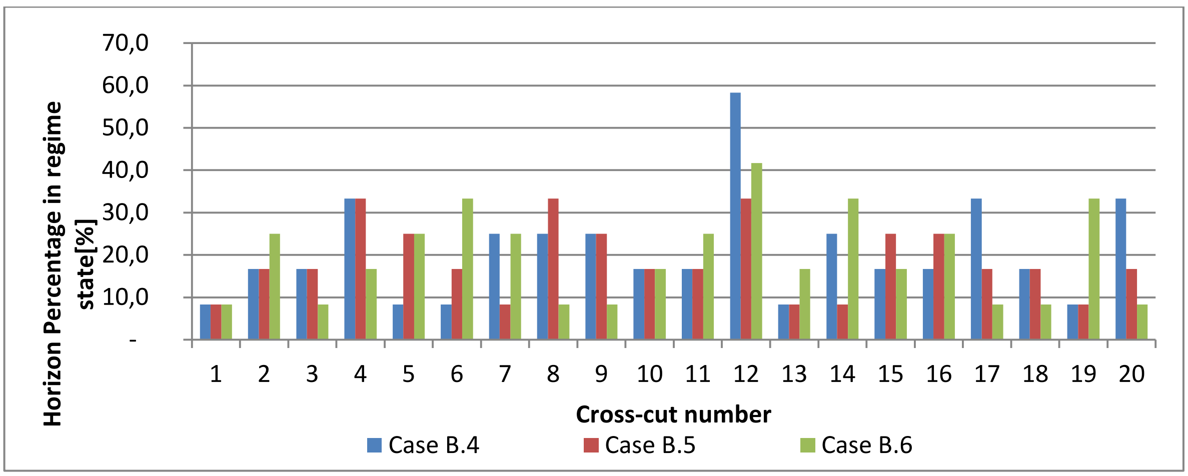

Figure 201. Horizon percentage in regime state case B, 2 LHD per cross-cut.

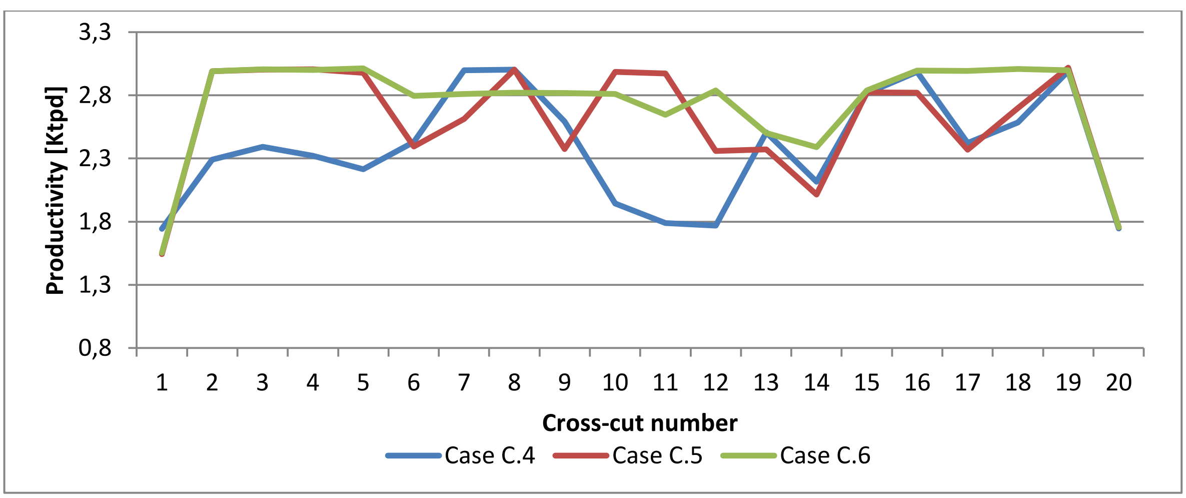

Figure 202. Productivity per cross-cut case C, 2 LHD per cross-cut.

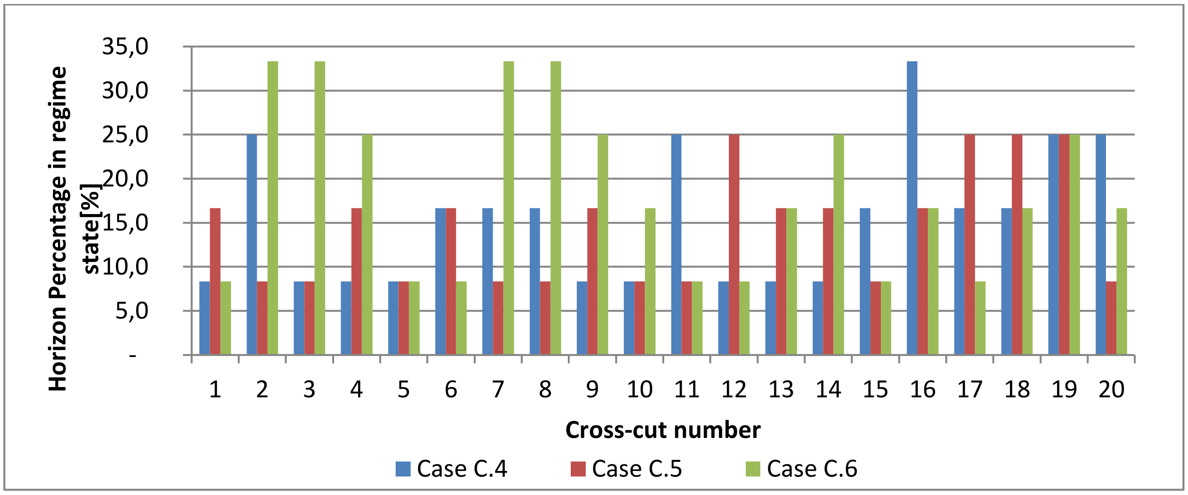

Figure 203. Horizon percentage in regime state case C, 2 LHD per cross-cut.

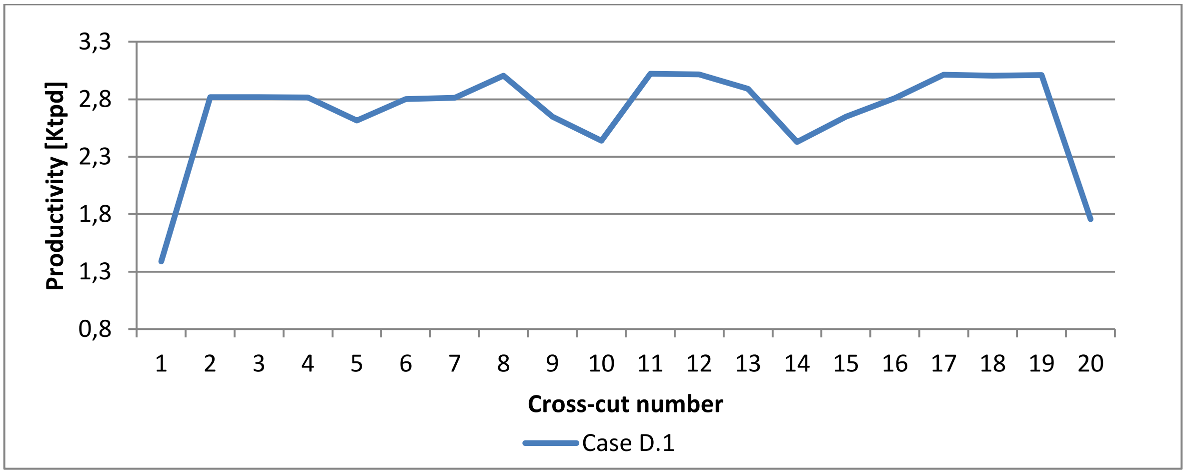

Figure 204. Productivity per cross-cut case D, 2 LHD per cross-cut.

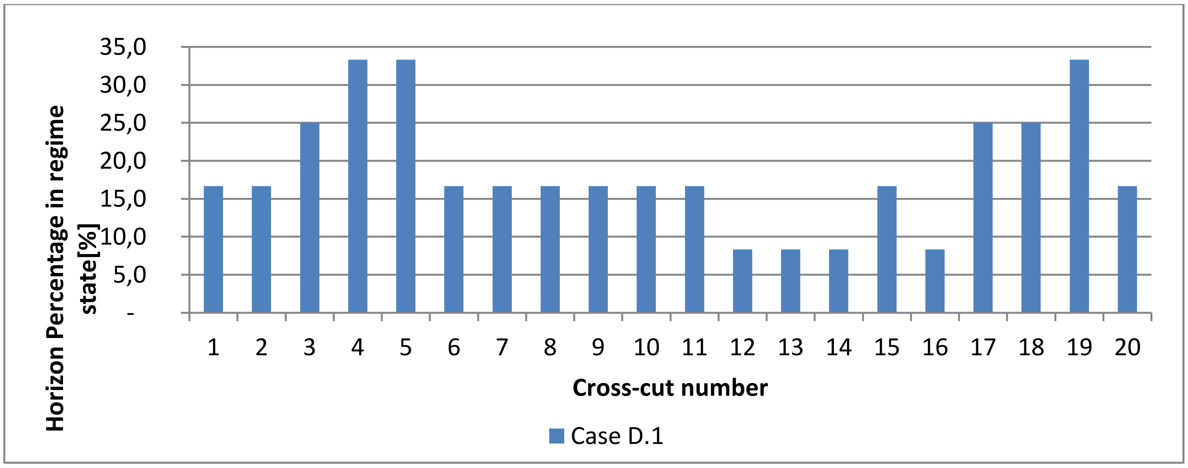

Figure 205. Horizon percentage in regime state case D, 2 LHD per cross-cut.

APPENDIX B: The paper presented in Apcom 2011, Wollongong, Australia.

HOME

Panel Caving Scheduling Under Precedence Constraints Considering Mining System

M Smoljanovic[1], E Rubio[2] and N Morales[3]

ABSTRACT

Currently, mine plans are optimised by using several criteria as objective functions, like profit, life-of-mine, concentration of some pollutants, mining costs, confidence level or ore resources, with consideration of constraints related to production rates, plant capacities and grades. Whilst this approach is successful in terms of producing high value production schedules, it uses a static opening sequence of the drawpoints and therefore the optimisation is made within the level of freedom left by the original opening schedule, and as a result it is far from the true optimal value of the project.

This paper presents a model to optimise the sequence of drawpoint opening over a given time horizon. The emphasis is in the precedence constraints that are required to produce meaningful operational sequences considering the exploitation method (panel or block caving), physics considerations and logical rules. Further on, while it applies the standard approach of maximising net present value (NPV), it considers other targets for optimisation, like the robustness and constructability of the plans. Finally, it applies the model to real data to obtain feasible plans by means of this model. The first tests were done varying the production capacity of the mine.

INTRODUCTION

As the industry is faced with more and more marginal reserves, it is becoming imperative to generate mine plans which will provide optimal operating strategies and make the industry more competitive (Chanda, 1990). To obtain these strategies, it is important to consider many constraints, like mining and processing capacity and geomechanical constraints, among others. The construction of the optimisation problems has required rational studies of which mining constraints are applicable in each case (Rubio and Diering, 2004). These constraints are important, because they limit the objective function and define the set of feasible solutions. Obviously, the idea is to get the best solution using an optimisation engine that could search throughout all the feasible solutions that are constrained by the mine design and the geomechanical constraints of a given mining method.

This paper reviews the importance of other variables in underground planning, specifically for the panel caving method. Thus, this paper shows a mathematical model that represents this fact. The model incorporates, the majority of important constraints, including the sequencing (viewed like a set of constraints. The idea is to show the importance of the sequencing in scheduling, and to incorporate an integrated manner to solve the optimisation problem.

As an example that shows what happens if a sequence changes in a fixed 2D model, showing value in $/t (Figure 1).

In Figure 1, there is a set of blocks (each block could be a drawpoint), with a value. This value is the profit of block. For each period the profit has been calculated, adding block values, and the net present value (NPV) calculated for each case, concluding that the third sequence is the best, this demonstrates the influence sequencing can have on the final result for the objective function, in this example the NPV.

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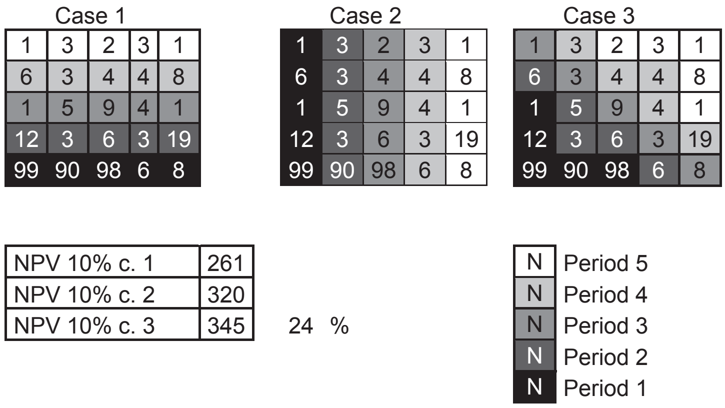

FIG 1 - Alternative sequences for a given two-dimensional fixed value block model.

STATE-OF-THE-ART

A problem close to the one considered in this paper is studied by Chanda (1990), who uses a computerised model for short-term production scheduling, combining simulation with mixed integer programming. He studies the problem of scheduling drawpoints for production, the goal being to reduce as much as possible the fluctuation between periods in the average grade drawn. This model does consider geometric constraints between drawpoints (eg precedence).

Jawed (1993) used another model with the same objective function but focused on operational constraints, manpower requirements, extraction capacity, ventilation requirements, plant capacity and lower bounds on extraction quantity. It was for a room and pillar mine.

Trout (1995) used a model to optimise the mine production schedule. He maximised NPV, and it was applied for sublevel stopping with backfill. He considered sequencing, but the constraints for sequencing of sublevel stopping are very relaxed. For panel or block caving this model is a good start point, but the constraints of precedence and capacities should be modified. Also Carlyle and Eaves (2001) carried out a similar study for the Stillwater Mining Company.

Rahal *et al* (2003) used a mixed integer linear programming for block caving, to solve the optimisation problem. They used as the objective function the deviation from the ideal draw profile. They consider constraints of capacity, precedence, material handling and maximum and minimum levels of drawpoint rates. They showed interesting conclusions. Kuchta, Newman and Topal (2004), present an optimisation model to determine an operationally feasible ore extraction sequence that minimises deviations from planned production quantities. They used aggregation to optimise long-term production planning at an underground mine. The solution applies for a sublevel caving mine (Kiruna) and geometric precedencies were defined in one direction in the horizontal (enough for sublevel caving, but not enough for block caving or sublevel stoping).

Rubio and Diering (2004) solve maximising NPV, for block caving. They use two slices to simulate columns in a discrete vertical model and tested the same objective function as in the Rahal paper. The model uses precedence constraints, defined only for immediate neighbours. Not appear anything about geometrical precedence, considering the time, which the predecessors drawpoints are mined.

Sarin and West-Hansen (2005) solve the planning optimisation problem with mixed integer linear programming. They use NPV an objective function and add penalties for deviations for production and quality. It was developed for room and pillar and longwall mining. The model contains constraints of capacity, sequence (constraints for immediate neighbours), and construction.

Queyranne *et al* (2008) present a model for block caving that maximises the NPV and uses the capacity constraints of mine production, maximum opened and active, drawpoints, neighbour drawpoints. They consider binary variables, and the drawpoints only can be active in a determined number of periods. Also, the constraints of neighbouring drawpoints do not consider a range of time to mine them, but all neighbours are mined in the same period. The model does not have a constraint capacity per drawpoint.

This paper attempts to incorporate sequencing and capacity constraints, locating the sequence in time. For that the sequence needs to be limited geometrically and in this paper demonstrates that. Also it will compare different capacities of mining. The model is based on BOS2 (Vargas *et al*, 2009), that it was a development of Delphos laboratory for open pit mining. The constraints in the model were the capacity of mining and processing, geometallurgy, stocks and geometric constraints. Obviously it was necessary to adapt the model for underground mining, and add some more constraints.

THE OPTIMISATION PROGRAM SCHEDULING

This problem has been studied using different techniques to solve it, but all of these have a common denominator: the constraints. Rubio and Diering in 2004 identifies which constraints should be an optimisation scheduling for block caving, which are presented below:

- Development rate: states the maximum feasible number of drawpoints to be opened at any given time within the schedule horizon, depending on the construction capacity that exists.
- Precedences: defines the order in which the drawpoints will be open. This constraint usually acts on the drawpoint status, activating those that are at the front of the production face. In this model it is a set of two constraints that indicates the maximum number of drawpoints it is possible to advance between two periods in somewhere direction, defining a ratio. Also it defines the number of neighbouring drawpoints that is necessary to mine, in a determined time.
- Maximum opened production area at any given time within the production schedule has to be constrained according to the size of the orebody, available infrastructure and equipment availability.
- Draw rate controls flow of muck at the drawpoint. Draw rate will define the capacity of the drawpoint and it needs to be fast enough to avoid compaction and slow enough to avoid air gaps. In the model presented this constraint will be the production capacity of each drawpoint.
- Draw ratio defines a temporary relationship in tonnage between one drawpoint and its neighbours. It is important to control the dilution. In the model presented, this constraint will be included in the precedencies constraints, by the geometric requirements of panel caving.
- Capacity constraints: forces the mining system to produce the desired production usually keeping it within a range that allows flexibility for potential operational variations. This model uses mine capacity and subunits of the mining system such as cross-cut capacity.

The variables could be integers or real. Normally, the integers variable is used to indicate the state of a point, specifically if the point is opened or not. The real variables are used to specify how much tonnage of drawpoint has been extracted. The logical constraints permits that these two variables are OK.

This model will use the maximisation of NPV in ranking the scenarios. Each point of layout will be evaluated and the idea is to shows the better sequences. Obviously, the objective function could be changed by other.

THE MODEL

The model formulated in the research has been conceptualised for a panel cave mine having several capacity constraints at the production cross-cuts. Also the model integrates the individual value of a drawpoint derived from a premixing algorithm that simulates the vertical flow as well as the economical benefits of withdrawing a drawpoint and its column in a single time period. There are several geometrical constraints that couple the state of neighbours that are present in a panel cave operation. Although the model has been for block caving it is known that this model can be applied to any underground mine.

Variables

The model identifies two variables. The first indicates when the drawpoint is opened. It is a binary variable, that is zero when the drawpoint has not opened and it changes to one, when the drawpoint is opened. The second variable is a real number that represents the percentage of column extracted. It is determined that this variable is accumulated. It defines a set called B that contains all drawpoints, and T, the horizon time. Formally:

$$m_{bt} = \begin{cases} 1 & \textit{if the drawpoint } b \textit{ is opened at } 1 \ldots t \\ 0 & \textit{otherwise} \end{cases} \tag{1}$$

$$e_{bt} = \textit{percentage of column extracted of drawpoint } b \textit{ until } t$$
$$e_{bt} \in [0,1],\ b \in B,\ t \in \{1, 2, 3, \ldots, T\} \tag{2}$$

It defines: $\bar{m}_{bt} = m_{bt} - m_{b,t\text{-}1}$, which is equivalent to the values per period, in terms of extraction between t and t - 1. These definitions are based in Equation 1. This variable will be one only in the period of construction of a point. It defines also: $\bar{e}_{bt} = e_{bt} - e_{b,t\text{-}1}$. This variable counts the percentage of column that was extracted between t - 1 and t.

Logical constraints

These constraints establish the basic relations between the variables and mainly state that drawpoints can be opened only once, and that material can be extracted only up to 100 per cent. For each b ∈ B, t = 1, ... ,T - 1:

$$m_{b,t} \leq m_{b,t+1} \tag{3}$$

$$e_{b,t} \leq e_{b,t+1} \tag{4}$$

The first two constraints indicate that, the mining and processing of material of a drawpoint must be done one time. For example: if the block is not removed in t + 1, could not mine in t. In the case that has been mined in t, the constraint forces to mine the point in t + 1.

Production constraints

Production constraints are related to physical and economical limitations of the mine operation, like the maximum amount of tonnage to be extracted per time period, or the minimum amount of material to extract for an opened drawpoint.

The overall mine capacity constraint limits the total amount of mineral to be extracted in the mine for each time period. Considering that each drawpoint has tonnage *ton(r)*, and a upper limit of M^+ tons for the mine, the constraint reads:

$$\sum_{b \in B} ton(b)\bar{e}_{bt} \leq M^+ \quad (\forall t = 1,\ldots,T) \tag{5}$$

Similarly, it is possible constrain the total number of drawpoint to be opened at each time period:

$$\sum_{b \in B} \bar{m}_{bt} \leq P^+ \quad (\forall t = 1,\ldots,T) \tag{6}$$

Notice that these constraints do not consider the ramp up and ramp down, as these are the result of geometric constraints.

Apart from the case above mentioned, the model also considers to replace B by a set $B' \subset B$, to allow for specific constraints on given sets of drawpoints. For example: in the case of a subset of points of cross-cut, it is possible to define an upper bound M_c^+ like the capacity per cross-cut *c* and *C* is a set of cross-cut of layout. In this case the constraint is:

$$\sum_{b \in B_C} ton(b)\bar{e}_{bt} \leq M_c^+ c \in \{1,2,3,\ldots,C\}, \forall t \in \{1,2,3,\ldots,T\} \tag{7}$$

where *Bc* is the set of blocks belonging to cross-cut c. Other constraint considers the limit of capacity per drawpoint. This constraint therefore considers a limit M_b^+: the maximum capacity per drawpoint.

$$ton(b)\bar{e}_{bt} \leq M_b^+ \ (\forall b \in B)(\forall t = 1,\ldots,\mathrm{T}) \tag{8}$$

There is also a constraint limiting the minimum per cent $L \in [0,1]$ to extract from a column if the drawpoint is opened. Notice that this constraint bound the final percentage mined from the column (hence the right side has subindex T).

$$m_{bt}L \leq e_{bT} \quad (\forall b \in B)(\forall t = 1,\ldots,T) \tag{9}$$

Finally, we consider the lifetime of a drawpoint and as upper bound in the number of period it can be operational since it is opened. This is expressed as:

$$\bar{e}_{b,s} \leq \bar{m}_{bt} \quad (\forall b \in B) \ (\forall s = t + A_b, \ldots, T) \tag{10}$$

Geometric constraints

This set of constraints limits the order in which the drawpoints are opened, so this is consistent with technology and geomechanics. The model considers two types of constraints in this category:

1. connectivity constraints, and
2. shape constraints.

To impose these constraints, the model considers a graph whose nodes are the drawpoints. Two drawpoints are connected in the graph if they are close enough (for a certain distance tolerance).

The connectivity constraints force the exploitation to be connected, that is, there are not isolated drawpoints that are opened. This is enforced by considering a set of *access points* from where to start the exploitation is given, so it is possible to calculate a *connected path* $P(b) = (b_1, b_2, b_3, \ldots, b_{k-1}, b_k)$ with $b_k = b$ that goes from the (unique) access point of drawpoint b to Drawpoint b (Figure 2). If we denote $prec(b) = b_{k-1}$ in the path, the connectivity constraint is therefore:

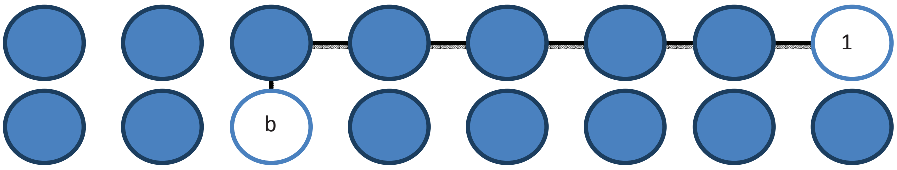

FIG 2 - Example of path from access point to drawpoint.

$$m_{b.t} \leq m_{prec(b),t} \quad (\forall b \in B)(\forall t = 1, \ldots, T) \tag{11}$$

The model considers also two shape constraints. The first one limits the progress of the opened drawpoints on the paths described above: In Figure 3 with red colour is mark that situation. But this constraint not provides the case that in one direction do not mine any block and continue with the others. This case was cover with other constraint that will explain later.

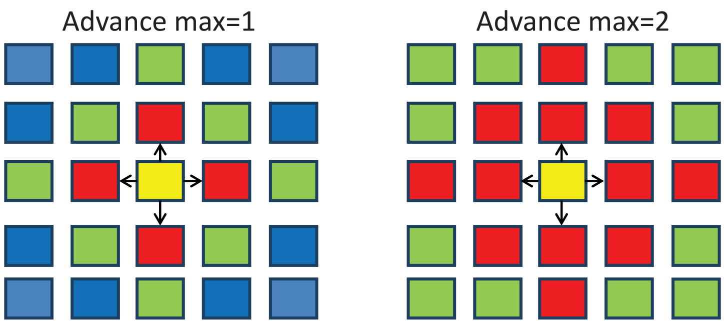

FIG 3 - Example of maximum advance.

$$m_{b+d,t} \leq m_{b,t} \quad (\forall t \leq T) \tag{12}$$

$$m_{h,1} = 0 \ if \ h > d$$

The second type of shape constraints forces that not only drawpoint cannot be opened in an isolated manner, but also that the opening of a drawpoint forces also neighbouring drawpoints to be opened too. Again, in the connectivity graph described before, let $\mathcal{N}(b)$ be the set of drawpoints that are neighbours (connected to) b. This constraint takes also two parameters: K, which is the number of neighbours for a drawpoint to be mined, and Δ, that corresponds to an additional time to do the mining of all the neighbours of some drawpoint. The constraint is:

$$Km_{it} \leq \sum j \in N_N(i) m_{j,t+\Delta} \tag{13}$$

where:

$\#N_N(i)$ is number of elements of $N_N(i)$

Figure 4 shows an example of this constraint. Clearly in this example the constraint is fulfil, because only matters the beginning and the end and not necessarily the analysed drawpoint should be the last mined, because the constraint permits that the block i to be mined in t, provided that all the neighbours were mined until t + Δ (before is OK). In the case of example (Figure 4), t = 2 do not have importance, because the constraint is applied on t = 3 and t = 1. Even is possible, that in t = 2 don not happen anything, provided that in t = 3 all the neighbours were mined.

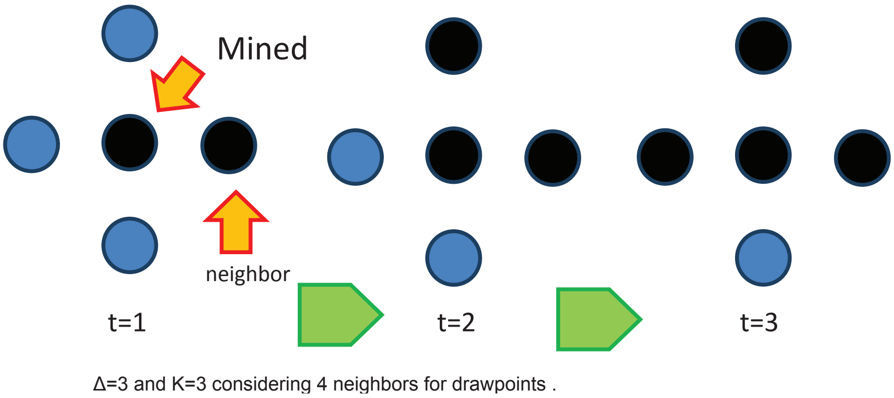

FIG 4 - Example of minimum neighbours.

CASE STUDY

The case study is a mine that has a 30 000 t/d run of mine production. The layout has 332 drawpoints. Actually the sequence was developed, but the idea is to show how varies when capacities per drawpoint or capacities per cross-cut is changed. Production is driven into four crushers located on the orebody footwall (Figure 5). A three-dimensional view of the database is shown.

Obviously all the parameters defined in the last part are need defines.

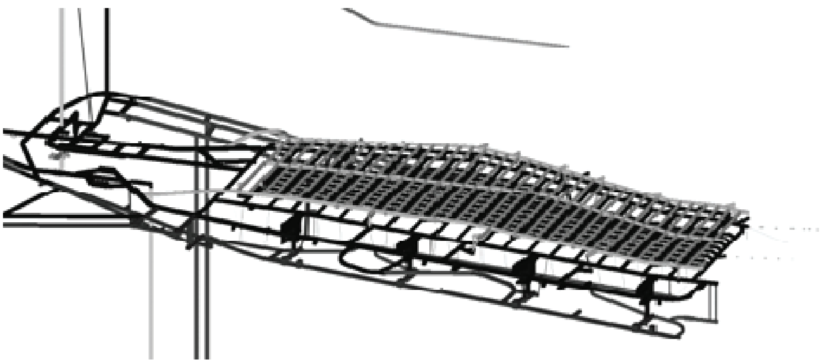

FIG 5 - Case study mining system.

Model inputs

The model has been tested using a 332 drawpoints distributed into 20 production cross-cuts the parameters that remained invariant. These parameters are showed in Table 1.

To begin to study the influence of capacity constraints, the first element of the mining system was the cross-cuts. Also it has considered the capacity per drawpoint. The idea is to run the model with different scenarios and it was selected five to this paper (Table 2), to represent different behaviours. Each case was running considering each drawpoint like a possibility of access.

TABLE 1

Principal static parameters used in the model.

Production capacity	30	Kt/d
Horizon	12	periods
Discount rate NPV	10	%
Maximum advance	3	Dpt/period
Minimum neighbours	6	dpt
Periods to mine neighbours	2	periods
Periods to finish mining of drawpoint	3	Periods
Minimum exploitation column	0.3	%

TABLE 2

Five cases studied varying production.

	Capacity per drawpoint (Kt/yr)	Capacity per cross-cut (t/d)
Case 1	200	5000
Case 2	200	7000
Case 3	200	6000
Case 4	300	6000
Case 5	400	6000

RESULTS

This test was performed with the same 332 drawpoints, that in the last part. All drawpoints were access and after the run all, it was selected the best solution for the objective function (NPV).

Major production capacities got better results. Low capacities of production shows low NPV and with a high dispersion. Lower capacities need more drawpoints to reach the production, so it opens more sideways (Figure 6).

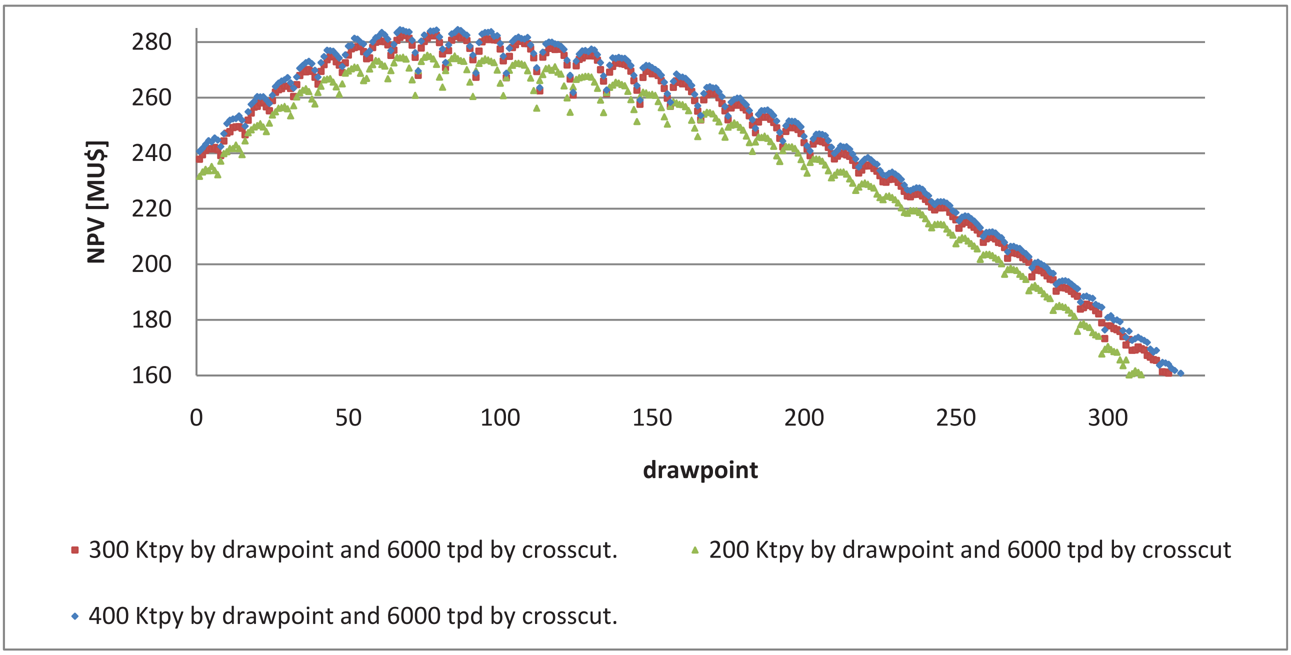

FIG 6 - Net present value considering each drawpoint like access and varying the production per drawpoint.

Other important aspect to review is grade, because objective function was NPV. In the follow graphic It can be seen the difference in the worst grade and the better grade for a same period.

At the ends of the horizon the grades has more dispersion, than in the centre (Figure 7). This is probably because the better grades are not in the centre of the layout. The asymmetry of curves shows that. Obviously this graphic is very valious, because shows clearly, that is not the same to start on a drawpoint or on another.

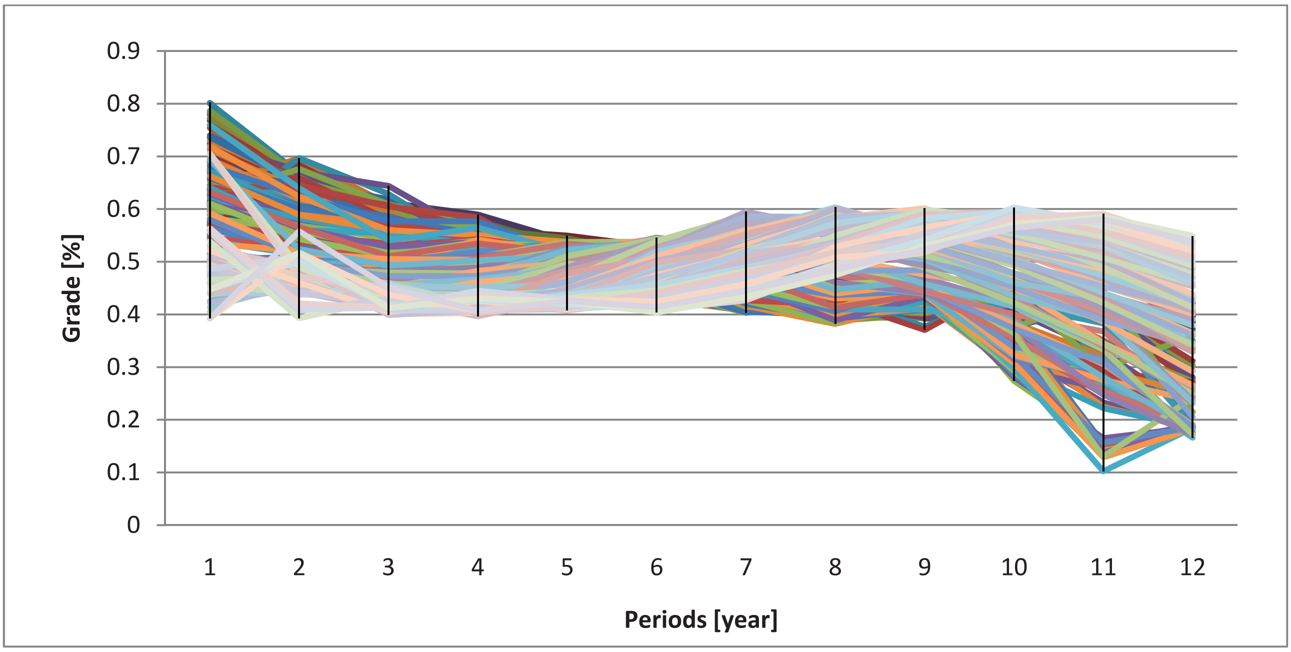

FIG 7 - Behaviour of Cu grade when the access is changed. This is the case with 200 Kt/a per drawpoint and 5000 t/d per cross-cut.

Not important variations could be seen in the grades if it considers a change in a production per cross-cut (Figure 8). The other constraints permit flexibility to these changes in tonnages per cross-cut. It is a good begin to start to incorporate more components of mining system like a crusher.

In reviewing the production plan (Figure 9) it is interesting to note that the plans are similar, but the NPVs are very different. The production capacity constraint was the same for all mining systems, to be evaluated each one, in the same production conditions. For example each rate per cross-cut could mean a different technology to primary crusher, or diameter of shafts. Also the production per drawpoints perfectly could be different technologies of charging material like LHD, Scoop among others. The interesting thing is to evaluate these systems and watch the effects in the objective function, in grades, in mining plans, among others.

The last result to show on this paper is the difference of objective function for the five cases:

Where to start mining is very important, because the difference borders 50 per cent. Could not be attractive for shareholders. The change of technology could be evaluated in a five per cent of the NPV. The idea is to run the model with the complete mining system (Table 3).

Another test was performed was the application of the model shown in this paper for six different mining systems, which differ in the number of crushers for the layout and different number of LHD per cross-cut.

TABLE 3

Results of net present value for each case considered.

	Case 1	Case 2	Case 3	Case 4	Case 5
Min NPV (M US$)	149.2	154.3	152.6	153.6	154.9
Max NPV (M US$)	281.4	282.4	282.3	286.5	287.3
Difference (M U$)	132.17	128.08	129.66	132.89	132.40
Per cent diff (%)	46.97	45.36	45.93	46.38	46.09

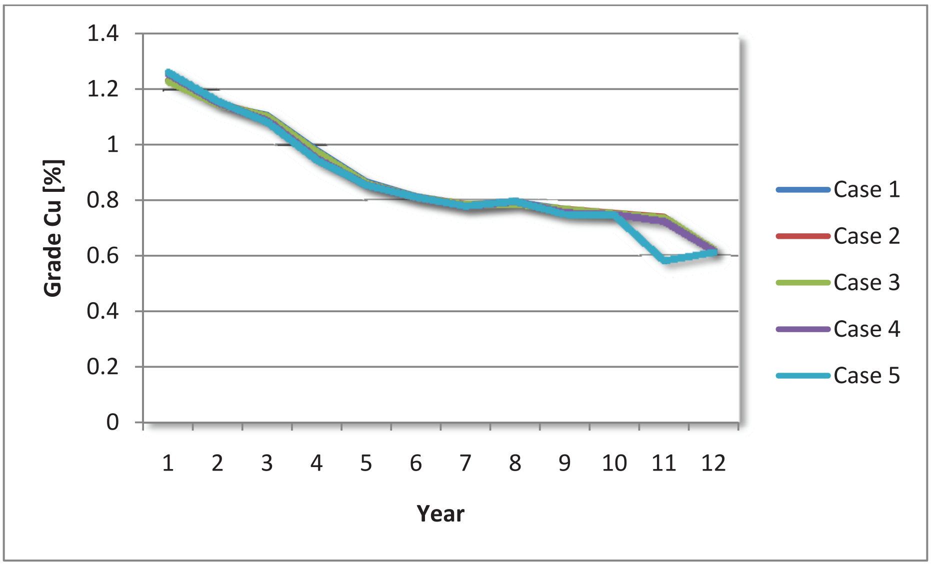

FIG 8 - Grade considering each drawpoint as access. Different production per cross-cut.

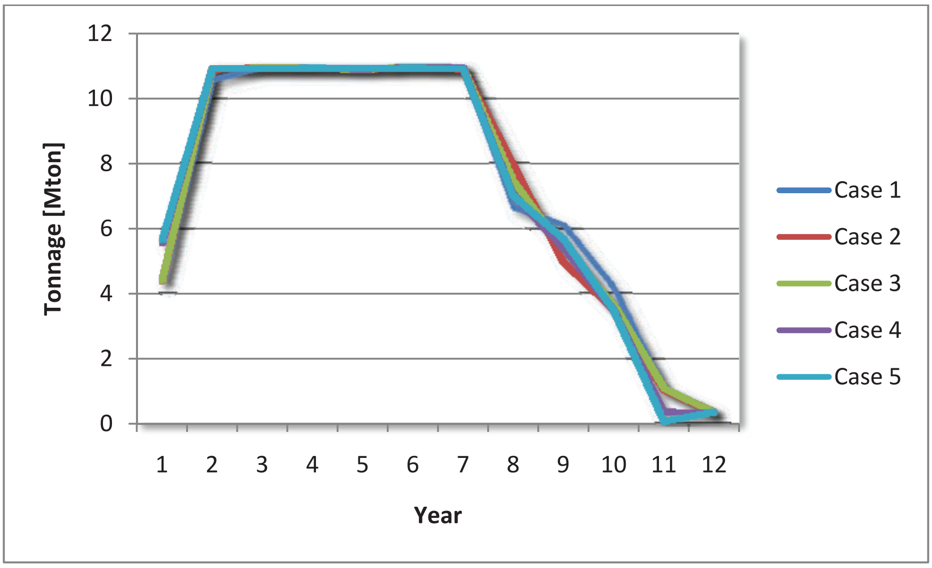

FIG 9 - Grade considering each drawpoint like access, varying the production per drawpoint.

Mining systems considered 20 cross-cuts with a productivity of 3000 t/d by cross-cut, with one or two LHD whose productivity is 3000 t/d to 1500 t/d, respectively. Crushers production capacities was chosen as 7500 t/d. Testing with four, five and six crushers was done to generate six mining systems: the number of crushers increases, production tends to peak in less time, ie the mining plan remains more years in steady state (Figure 10). The grades are similar in the three cases with one LHD per cross-cut. The three cases with two LHD per cross-cut are very similar to the three last cases.

Differences in NPV generated by the different mining systems (Table 4). The best case was the case with six crushers. It is interesting to note that the maximum percentage variation between the best and worst case is around six per cent.

The production by cross-cut could be appreciated in Figure 11, whereas the maximum is 3000 t/d. The rate of each cross-cut corresponds to the peak on the horizon periods. This chart shows cross-cuts with a productivity of between 2000 - 3000 t/d. The maximum capacity is reached in certain periods. It is seen that the upper bound has been somewhat oversized, and there is no uniformity in the extraction rate per cross-cut.

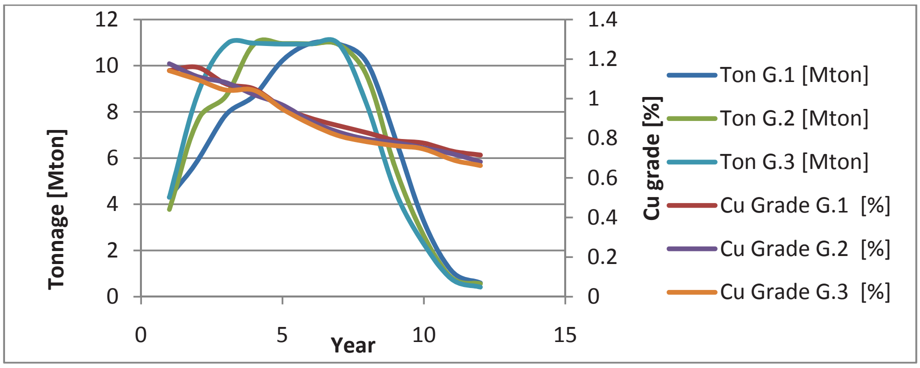

FIG 10 - Production mining plan to the cases with mining systems with four, five and six crushers (one LHD per cross-cut).

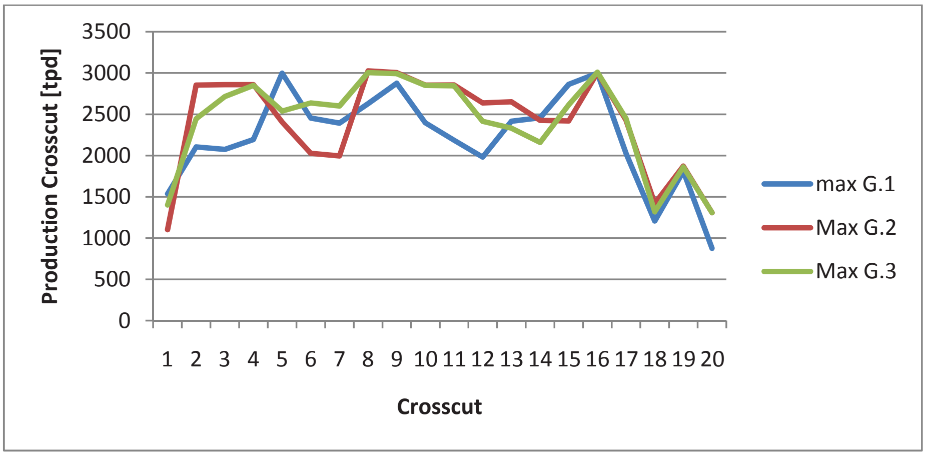

FIG 11 - Grade considering each drawpoint like access, varying the production per drawpoint.

TABLE 4

Net present value results for cases with one and two LHD per cross-cut.

	1 LHD per cross-cut	2 LHD per cross-cut
4 cruchers (M US$)	254.3	252.6
5 crushers (M US$)	263.7	262.0
6 crushers (M US$)	270.5	267.9
Maximum (M US$)	270.5	267.9
Minimum (M US$)	254.3	252.6
Difference (M US$)	16.2	15.3
Per cent (%)	6.00	5.71

In the case of crushers, in most cases, results were obtained with saturated crushers, except the sixth crusher, in the case with six crushers, which had a production of about 4000 t/d. In the case of the cross-cuts, something different happens than with the crushers, as it shows a very irregular behaviour, reaching the 3000 t/d in some cross-cuts. The end of the graph is similar for all three cases.

CONCLUSIONS

Sequence changes the value of objective function significantly. The difference is 50 per cent. The variations in mining plan was because leave free the low limit of capacity. The idea was to show the differences with a sequenced plan and the worst case.

Capacity constraints for different mining system have five per cent of difference in NPV, but it is important that only it has considered the capacity per cross-cut and the capacity per drawpoint. It wills future work to incorporate other components to complete the set of constraints.

By incorporating the capacity of each mining system component as a constraint to the proposed model, there are important NPV differences between different mining systems. However, it is very important to review the productivity obtained for the solution to reach the desired production rate mine.

The main conclusion is that having a proper optimisation engine to assist mine planner to compute the best sequence that suits the strategic objectives of a company is extremely necessary. This initial work has shown that different sequences can show significant differences depending on how the geometries are set up and how the mine design is layout for a given orebody.

ACKNOWLEDGEMENTS

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