Market Driven Mine Planning: Optimizing Products Portfolio, Muzo Emerald Mine Case Study

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ABSTRACT

Mine planning is the mining engineering that transforms a geological ore body into a business promise that shall optimize shareholder s value. Traditionally this process commences with the geological modeling stating the estimation of ore resources, then these resources are subject to an economic envelop which is after sequenced defining mining methods and finally a production schedule is computed in order to provide the financial team the best offer to generate the sales contracts. In general, this methodology works for commodities and raw materials in which formal contracts are set among the producers and the buyers. In the precious stone business and in particular in the emerald business the market is much more segregated and different buyers attend emerald auctions to acquired package of emeralds that will be later transform in any form of jewelry. Thus, the business changes depending on how the different emerald packages are offered to a set of buyers. This challenge has motivated the author to device a mine planning methodology to integrate different levels of operational hedging to respond to a market segmentation that could change over time. In particular flexibility has been design and added to: the number of operating mines under production, the rate of development, preparation and production at any given time, the adoption of an inclined draw point caving method, and finally the automated production control system to capture in real time the emerald production. The device methodology is under application by Muzo International at the Muzo underground mine, located in the province of Boyacá Colombia. This paper describes the theoretical framework, the actual tools developed to apply the methodology and full details regarding the mine and plant design to transform an artisanal operation into the first world emerald fabric.

1. Introduction

The mine planning traditional process flow is as follows:

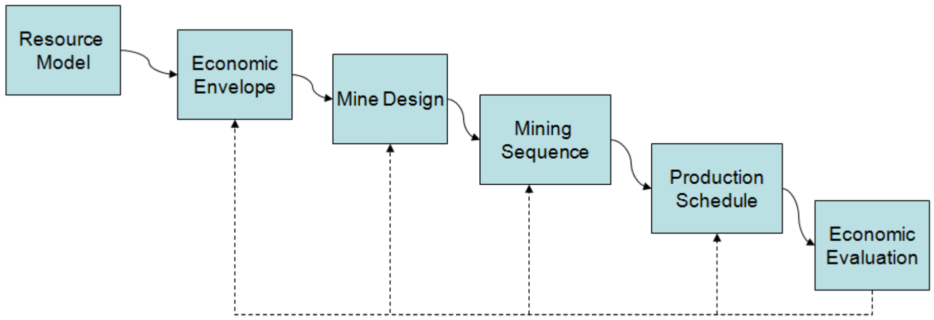
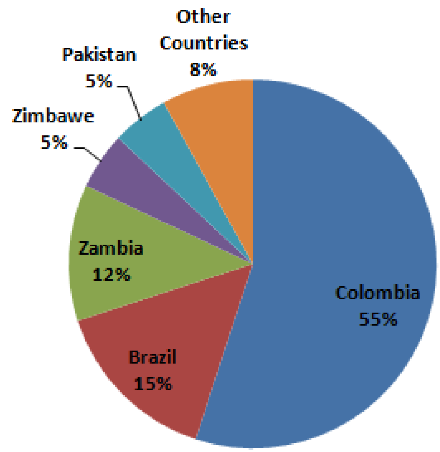


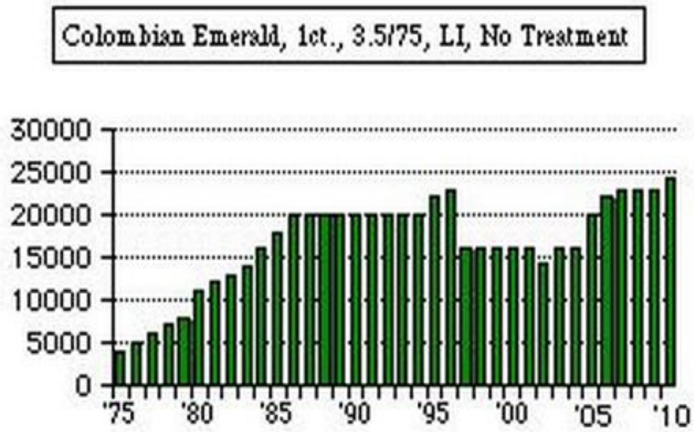
Figure 1: Min Planning Traditional Flowsheet.

In the precious stone business a tremendous factor is played by the intrinsic uncertainty contain in the underlying asset concentration as grades and the market in which those gem stones will be finally commercialized. The following depicture shows the market composition of the emerald production world wide.



Graph 1: World Wide Emerald Production.

Also the price of emeralds play a tremendous role in valuing different mine planning alternatives. The following depicture shows a price trend over a 35 years period.



Graph 2: 35 Years Emerald Prices, National Gemstone Company.

A typical commercialization scheme to market Emeralds is the one shown below.

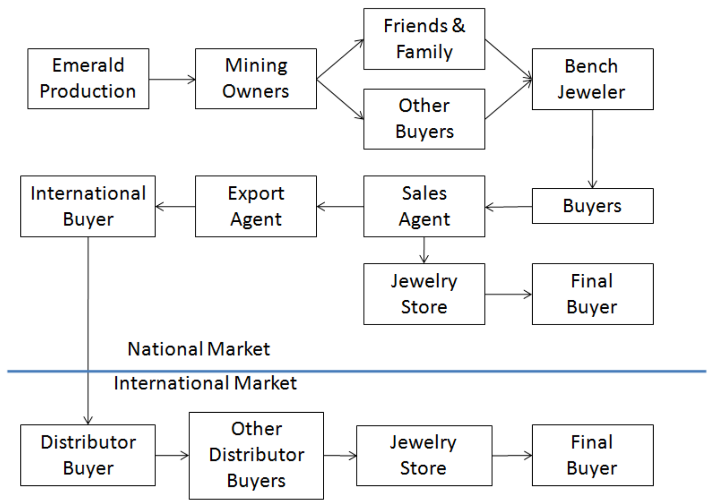


Figure 2: Commercialization Scheme, Agents.

It is shown that there are several steps from mine to market that make the whole Emerald business extremelly volatile. Tipically in the emerald business there will be at least 3 main products depending on gems quality (size, cut, clarity, greenningless, shape), chispero, Morralla and Perma. The following diagram shows the percentage of each potential product from the mine to market. It is important to note that cutting and polishing in average has a 50% recovery as a process.

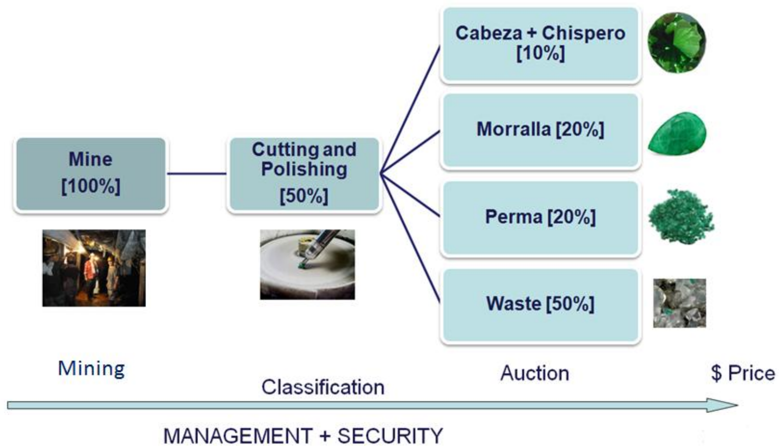


Figure 3: Value chain Muzo Emerald Mine project

From the total material recovered from the mine emerald product of the methodology described above, 50% was classified as waste. From the 50% remaining, 10% corresponds to the highest quality emeralds and gems named Chispero, the second 20% quality emeralds is named Morralla, 20% is named Perma or emeralds that can be treated to become "artificial emerald" and lowest 50% is Waste. The products of this chain are emeralds that are grouped in lots for auction, then get the final price (see Figure 1). Critical points are the Robberies at the mine, the Classification stage and finally the Auction, the engineering, development and management should aim to control these items to ensure the success and sustainability of this business.

In terms of pricing GemFields the largest public company Emerald producer reports high variability as a function of time and underlying contracts existing between the intermediate agent and the final jewelry.

Table 1: Sales per Auction, Gemfield report 2010.

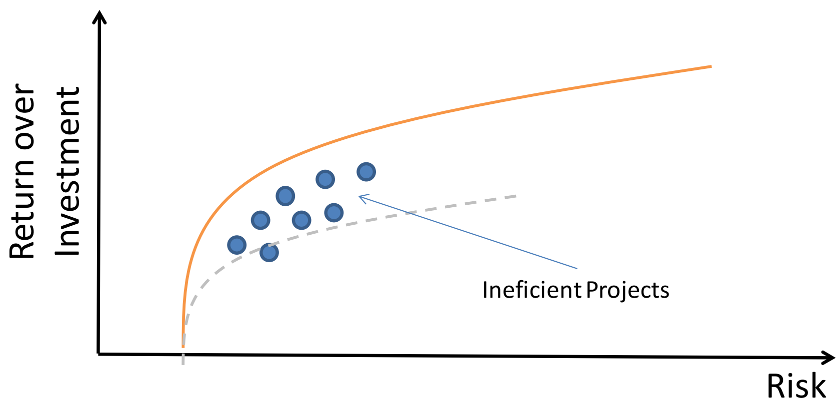
AUCTION RESULTS SUMMARY	JULY '09 AUCTION	NOVEMBER '09 AUCTION	MARCH '10 AUCTION	JULY '10 AUCTION	DECEMBER '10 AUCTION
Dates	20-24 July 2009	23-27 November 2009	11-15 March 2010	19-23 July 2010	6-10 December 2010
Location	London, England	Johannesburg, SA	Jaipur, India	London, England	Johannesburg, SA
Type	Higher Quality	Higher Quality	Lower Quality	Higher Quality	Higher Quality
Carats offered	1.36 million	1.12 million	28.90 million	0.85 million	0.87 million
Carats Sold	1.36 million	1.09 million	22.80 million	0.80 million	0.75 million
No. of companies placing bids	23	19	25	37	32
Average no. of bids per lot	10	13	8	18	16
No. of lots offered	27	19	56	27	19
No. of lots sold	26	14	49	24	18
Percentage of lots sold	96%	74%	88%	89%	95%
Percentage of lots sold by weight	99.8%	97.2%	78.9%	94.2%	86%
Percentage of lots sold by value	82%	76%	89%	87%	99%
Total sales realised at auction	USD 5.9 million	USD 5.6 million	USD 7.2 million	USD 7.5 million	USD 19.6 million
Average per carat sales value	USD 4.40 per carat	USD 5.10 per carat	USD 0.31 per carat	USD 9.35 per carat	USD 26.20 per carat

These two sources of uncertainty create a great deal of volatility when valuating any of the main components of the traditional mine planning process. Therefore, set up a mine planning model upon expected values of prices of main outcome production and the production itself would be extremely dangerous in which there are certainly a tremendous gain potential as well as a lost. Thus, a different methodology has been device in order to derive the main mine planning decisions such as economic envelop, mining sequence and production scheduling as a result of a portfolio optimization exercise in which the expected return over the investment as well as its volatility are taken into account.

2. Proposed methodology

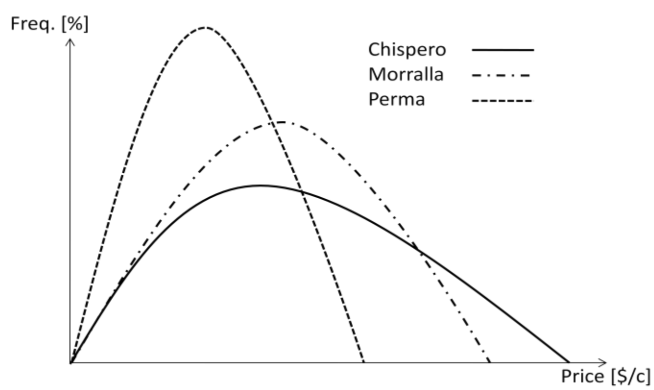
Efficient portfolio has been discussed extensively by Samis et al (2006), and Davis and Newman (2008) using real options and quantifying the risk of different mining strategies and also reviewing value at risk method. In this paper, the author wanted to give a fresh review at the Markowitz method (1959) and complemented by Haugen (1990) and Merton (1990) in which he defines a frontier efficient optimization method to allocate resources to a portfolio of assets with different return over investment and risk. The methodology consists of computing the cross covariance of all the possible combination of assets in a portfolio to compute the medium -. variance space upon which a given portfolio is efficient to be invested in. So for instance in the following depicture the highlighted dots represent a portfolio that is inefficient since there are combination of assets that could provide a higher return for the same computed average risk.

Note that the risk in this context is seeing as the average volatility of the underlying asset portfolio. Then the mining application will be to mimic several mining decisions such as mining methods, production rate, mining sequence and production schedule as if these decisions where component of a portfolio. Then the covariances of different decisions will define the variance of a given decision subject to the other status such as mine, production rate, sequence and others.



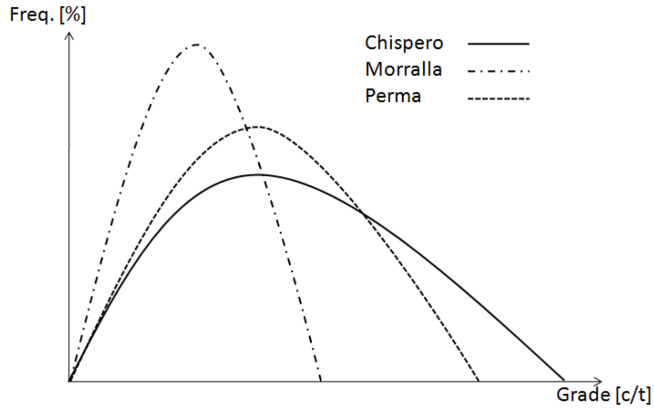
Graph 3: Frontier efficient for portfolio optimization

The first step to use this methodology is to model the probability distribution of the main products of interests, in the case of Emeralds these products would be heads or Chisperos, Morralla and Perma. The following depicture shows probability density functions for those three prices taken for a given historical time interval.



Graph 4: Price probability density functions for different products.

The following step consists of modeling the grade concentration of the main products (Chispero, Morralla and Perma) as a probability density functions for every different mining method to use as a extraction system. The following chart depicture these functions for a given mining method.



Graph 5: Grades probability density function for different products for a given mine and mining method.

After defining the probability distribution of the main sources of return volatility of interest to integrate in the decision model the asset portfolio should be define. In this case corresponds to define for every one of the mine or sectors under study the possible mining method. In other words being a mine $m = 1..M$ and alternative mining methods $u = 1..U$, an asset can be defined as the combination of a mine and a method as A_u^m. Then the grade of product k for the mine m and the method u can be defined as follows $g_k(m,u)$, the expected price for product k is defined as P_k, the mining recovery can be defined as $r(m,u)$, the processing recovery can de defined as R. For the different products a price that is distributed following a known density function can be modeled P_k. Then a value function is proposed as follows

$$v(m,u) = \left\{\sum_k g_k(m,u)\, r(m,u) R[P_k - cf_k] - C(m,u) \right\} T(m,u)$$

Where,
cf_k is the selling cost of cutting and polishing of product *k*
$C(m,u)$ is the mining cost of mine *m* using extraction method *u*
$T(m,u)$ is the productivity of mine *m* using extraction method *u*

Note that grades, prices and method productivity are all of them random variables with known probability density function. Thus the return over the investment is computed as follows

$$rr(m,u) = \frac{v(m,u)}{\{\sum_k g_k(m,u)\, r(m,u) R[cf_k] - C(m,u) \} T(m,u) + Fc(m)}$$

Where,
$Fc(m)$ is the fixed cost of moving one ton of ore from mine *m*.

Then several simulations are performed over the defined random variables sampling the probability distribution that defines the uncertainty of grades, prices and method for a given time period at the mine. Then the expected rate of return can be defined as $E[rr(m,u)]$ for a portfolio of *n* assets $cov(i,j)$ would be the covariance of asset *i* respect to *j*. Thus the average standard deviation of a given portfolio of components x_i is defined as follows:

$$\sigma = \left[\sum_i \sum_j x_i x_j cov(i,j) \right]^{0.5}$$

Then the above formulation can be optimize by minimizing the standard deviation subject to a given minimum expected rate of return and assuming that the portions of the portfolio x_i should add at the most 1, being x_i the percentage of capital to develop asset *i*.

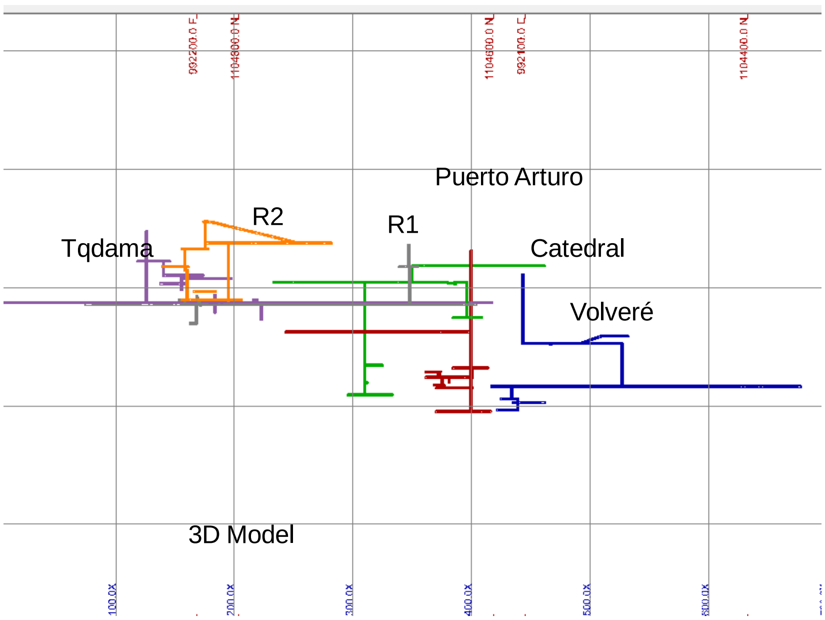
3. Case Study: The Muzo Strategic Planning

Emerald Muzo Mines are located to 815m over sea in the Occident Department of Boyacá. The population of this zone is about 15,000 people approximately The zone has special geological/metamorphic features that facilitated the emerald genesis. In spite of there was mining from 1540 by spaniards conquers, it was only in the 60's that bigger emeralds volumes started to be produced. The history of mining methods at this zone is as follows:

- 1960-1970: Surface Mining.
- 1970-1985: Surface Mining with Mining Loaders.
- 1985-current: Underground Mining (Tunnels, Shafts and Chimmeneys).

Figure 4: Boyacá Department in Colombia.

The mine operation until 2009 was divided into a series of shafts: Puerto Arturo, Tequendama, Catedral, Retorno 1 and Volveré in which there were several contractors mining in an artisanal manner without registering neither production information nor plans or topographic features. The following depictures shows a 3D map of the mining at the moment of finding.



Mine	Shafts [m]	Drifts [m]
Tequendama	246	2487
Parturo	154	718
Retorno1	83	1176
Volvere	239	1744
Retorno2	215	476
Catedral	139	1145

Figure 5: 3D Layout of the mine back in 2009.

The owners of the mine Coexminas S.A. made the decision back in 2009 to associate with a North American investment consortium CrestInvestment to take over the operation through an option contract to change the way how the mine as operated and pursue a massive emerald production reducing the robberies from 50% of the actual production down to 10%. In order to implement this objective CrestInvestment contracted the Chilean engineering company REDCO Mining Consultants to conceptually design, implement and operate a solution that could match the budgeting and time constrains of the owners.

The challenge was divided into 4 main areas of development:
1. Modify the current drifting mining method into a more massive and controlled mining system
2. Implement a wireless tracking underground system
3. Implement an optical sorting plant to automate the Emerald classification and cleaning process
4. Modify the mine planning process and production control systems

3.1. Alternative mining methods

Driftting
The method found that was used in past at Muzo consisted of following up the instinct of different mine contractors without taking samples or any geological observation that could facilitate the any engineering procedure at the field.

Drift and fill
Because of the occurrence of successful productions in Tequendama mine due to the identification of a geological emerald belt, it was necessary to incur in subsequent deepening production levels, which constantly weakened the infrastructure of the mine In levels R1 Inf, S1 R1 Inf, S2 R1 Inf, due to this, was proceeded to design and build a concrete slab that could support the vertical and horizontal forces present in the sector, the location of it and its schematic design are seen in the figure below:

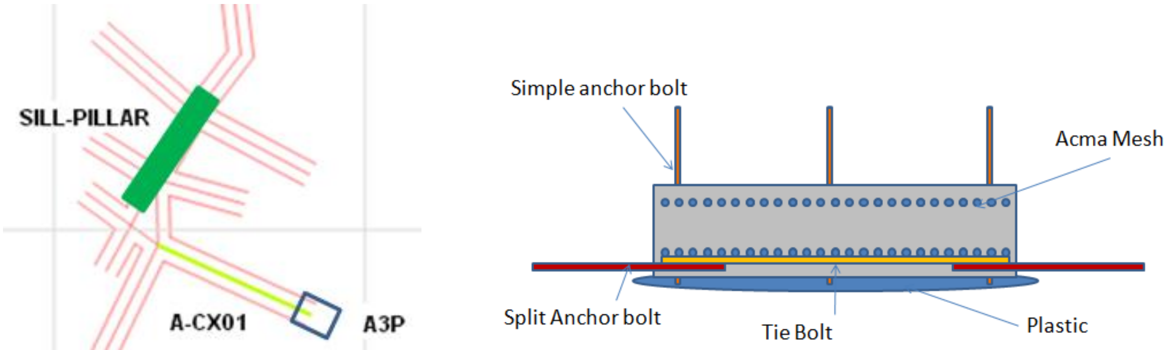


Figure 6: Construction Scheme: construction site (left), design (right)

Besides the two activities described above, a rehabilitation program was implemented all over haulage tunnels, replacing timber pools support in poor condition according to a cost management and a priorities strategy that would not interrupt the production of emeralds and to keep out of risk their stability.

Inclined Draw Point Caving

The design of the explotation method involves the construction of loading stabs, this ones are facing perpendicularly the geological productive zone, and they are connected through a main haulage level, this pattern is repeated vertically if it is to verified a geological and structural productive continuity zone.

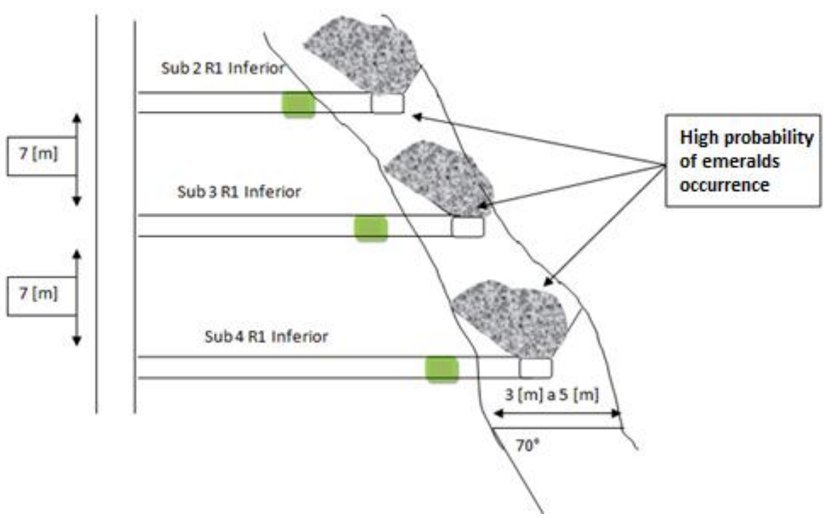


Figure 7: Mineralized zone profile

The plan view of the proposed mine design for this exploitation method is shown in the following Figure. For Tequendama, the access shaft to the productive levels in depth will be made through the CL04 shaft, because of its convenient location in hard rock, which gives us an appropriate support for underground mining and good work perform.

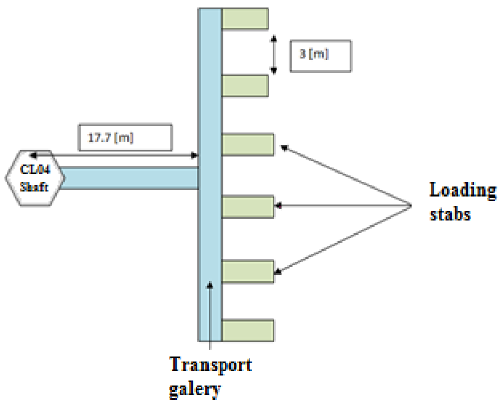


Figure 8: Production level plan view

For Catedral and Puerto Arturo mines it is planned to implement the same system of exploitation according the geological behavior shown and modeled.

A summary of production for the year 2010, with the information accumulated until January 7, 2011, the last day of REDCO team work on the operation of the Muzo emerald mine. During the period mentioned above about 280.000 carats of emerald material was produced, corresponding to approximately 350 tulas and approximately 52.800 cars, with an average of about 32 cars per meter of mining advance. The main productive activities were carried out at Level Tequendama R1inf and SubR1inf, level 11S1 Catedral and Level 12 Puerto Arturo.

Table 2: Operation Performance Indicators 2010

	Units	Q1. 2010	Q2. 2010	Q3. 2010	Q4. 2010
ROM Operation	(Tons)	3.820	4.663	6.382	3.286
ROM Mx Zone	(Tons)	2.674	2.798	4.468	3.244
Drifting	(m)	222	223	390	264
ROM production	(carats)	121.244	60.637	16.850	80.760
Grade	(c/t)	45,3	21,7	3,8	18,3

***ROM: run of mine material.**

The following graph shows the operational performance measured in terms of drifting, cars and tulas, it is noted that 50% of the activity is concentrated in TQDMA, 35% in PA and 15% in Catedral and Volvere

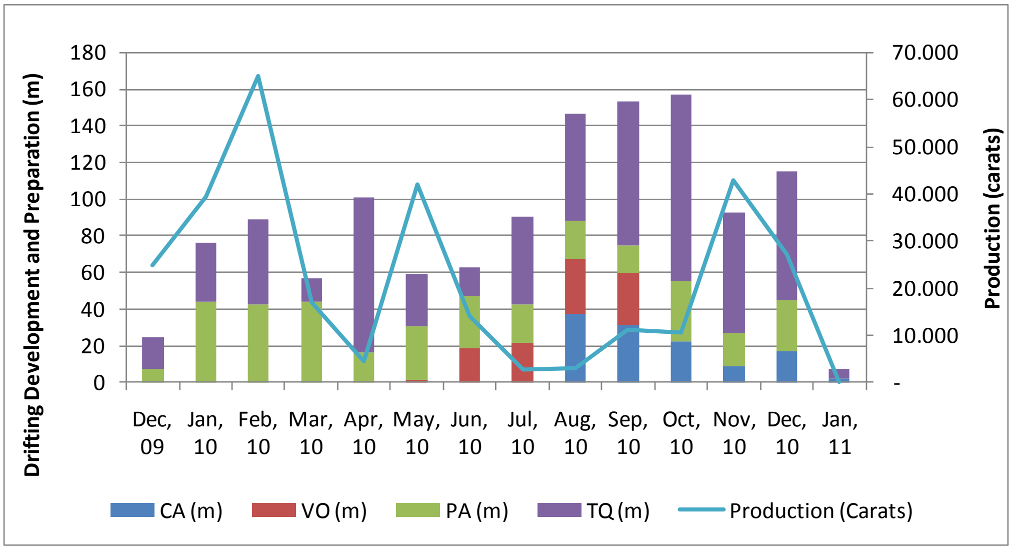


Figure 9: Production and Drifting

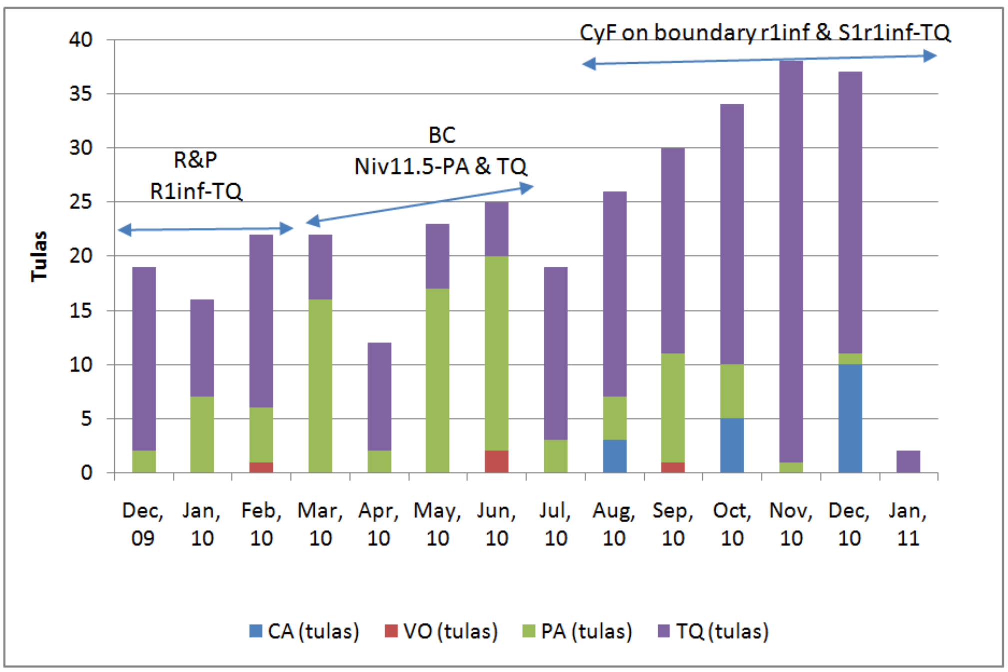


Figure 10: Mining Operation and Productivity

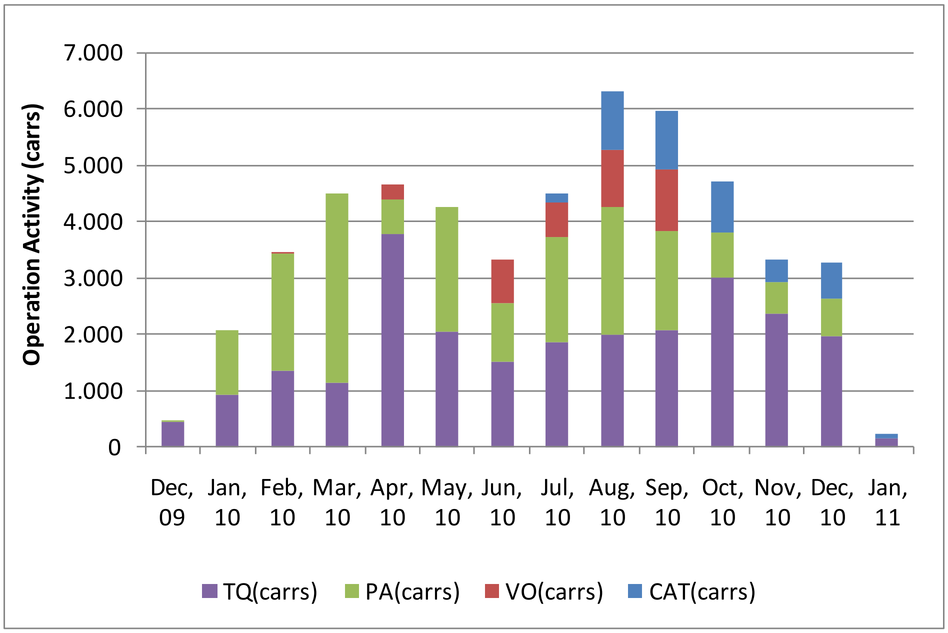


Figure 11: Operational Performance

Note that towards the end of the year the mine production was more concentrated into the mineralized zone which is not wider than 2.5 m. Thus in November and December of year 2010 there was higher emerald production and less carrs moved. This indicates that the trace of lithologies and metasomatic evidence found on the hanging wall are tremendously relevant for the Emerald production.

3.2. Underground production management system

This project involves the installation of an underground network based on fiber cables and extremely resistant wires for electricity, optical switches sealed and wireless access points, in Puerto Arturo and Tequendama mines, in order to provide video monitoring service, tracking people and cars, IP telephony and sensor network systems inside the mine.

The system consists of a set of networking equipment, cameras, special cables, tags and electronic tags, sensors and other devices, all with maximum protection standards for underground mining conditions and high quality and continuity of service. There will be installed approximately one hundred meters of compound cable, and 500 meters of red cable with special coverage, a set of approximately 30 high resolution video cameras, 200 tags for tracking, 20 wireless access points and antennas high fingertips. Fixed cameras will be installed at intersections of movement corridors, fixed cameras with variable focus in arrival places, shafts and extraction points and easy mounting cameras for extraction points and advancement tunnels, which will be illuminated by infra red, for low light conditions. The same wireless network infrastructure allows to have 7 mobile phones, 3 inside of each mine and one for surface to maintain communications with the engineers in charge of the operation at all times, particularly in Figure 12 is possible to appreciate the location of network components control in TQDMA and Puerto Arturo.

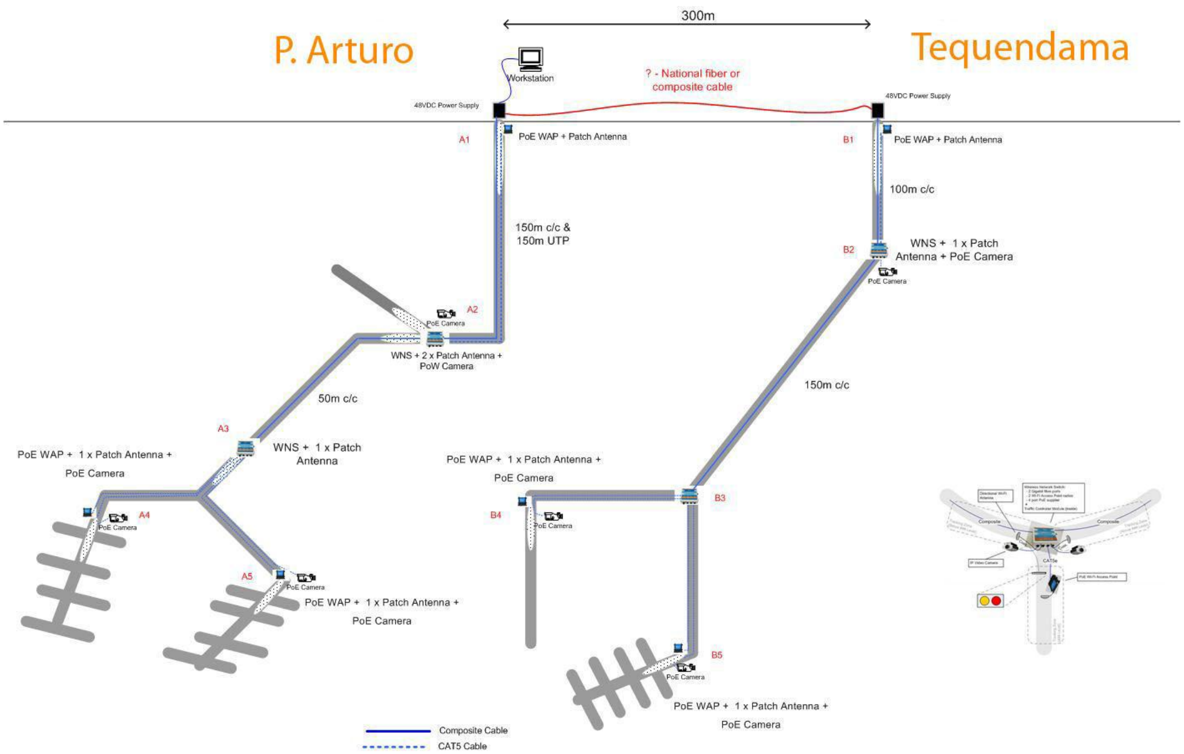


Figure 12: Production control system at Tequendama and PA mines

A control room is planned to be implemented on the second floor of the offices of Puerto Arturo, with a video surveillance server, which will monitor and record the information of the cameras. There will be a computer displaying the position of cars and people in real time (online), through a tracking application that will use the signal emitted by the tags inside the mine.
The project also includes the future addition of sensors to expand the network infrastructure coverage. The information that they will deliver will be processed through an application, optimizing the operational activities. The system has been designed in a modular fashion, aiming to meet the needs of coverage as the mine expands, and therefore it is considered to have parts for immediate extensions.

3.3. *Processing plant for the MUZO Operation*

In order to facilitate the classification and cleaning process of Emeralds from the Puerto Arturo and Tequendama mines to the Processing Plant it will be necessary to establish a management system to stock mobile mineral containers, a storage silo, discharge grills and pick hammers for the over-size and a feed belt to the processing plant.

10 tons containers:
Near the entrance accesses of Tequendama and Puerto Arturo mines there will be located containers of 10 [ton], to be carried by trucks equipped for that purpose and taken to the feed silo. After being unloaded the containers will go back to be filled at the output of both mines.

Road connection, with silo feeder:
To carry the containers from the two mines mentioned above, the roads connecting the mines and the silo must be enabled and repaired.

Puerto Arturo: The road behind the mine facilities in Puerto Arturo must be constructed to connect to the feed silo.

Tequendama: For Tequendama it is necessary to repair the road to the feed silo, because of the important slope.

Surface Silo:
It's planned the construction of a silo to store the ore extracted from Tequendama and Puerto Arturo. The silo must be capable of giving autonomy to the process of optical sorting for at least three hours, and it will also ensure an adequate constant supply for the next process. The Silo is also used to store the material in case of a damage that might occur in the processing plant.

Grid size selection:
The Sorting Plant will process material sizes of less than four inches, so it is necessary that the grid has that aperture setting. This will ensure the mineral to go the following process having the appropriate particle size.

Secondary reduction Hammer:
As the grid will have four inches aperture, it is necessary a flexible secondary reduction system with an hydraulic hammer, the hammer shall reduce the size of all particles exceeding four inches in size. Its action is directly on the grill. It is important to mention that it is expected that only 5% of the ore is greater than four inches. The following figure shows the hammer:

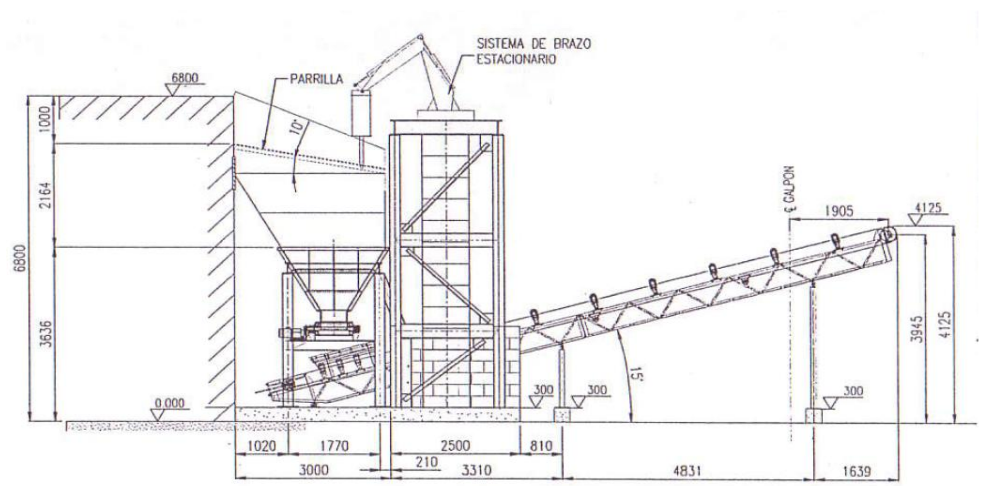


Figure 13: Hydraulic hammer

Silo – Wall:
The storage silo was located immediately below the wall where the trucks unload the ore from mines Tequendama and Puerto Arturo and the Wall has been built to provide maximum security for the trucks to download and to be part of the silo described above.

Extraction belt:
To carry the ore from the silo feeder to the Optical Sorting plant, it is necessary to install a belt for mineral movement, as shown in the figure below. This main belt should be two straps, one that carried the ore to the new processing plant and another to send the ore to the existing processing plant.

Optical sorting plant

The Muzo processing plant was designed for a treatment capacity of 250 [tpd] considering that the plant operates 10 hours per day, being operated and monitored from a control room to be located in a different sector of plant equipment. It mainly consists of two optical sorting equipment, two screeners for selection of size, two washing and drying trays, and transfer belts. Some small equipment which purchase is pending are: belts, transfer chutes, generators, compressors, blowers, among others.

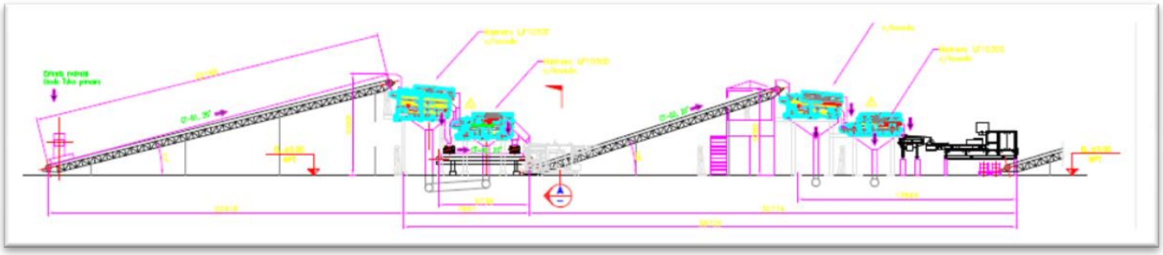


Figure 14: Longitudinal view of the sorting plant

The plant will be located inside a completely locked shed and controlled by video cameras that will be observed from the control room. The following is a brief description of equipment used in the sorting plant.

Sorters

The ore granulometry from the mine is quite variable, therefore was determined to divide the material into 4 fractions

The 4 fractions to consider are:

- -101[mm] +37[mm]
- -37[mm] +19,1[mm]
- -19,1[mm]+9,5[mm]
- -9,5[mm] +4,8[mm]

GEM fine COLOR

This sorter classified the two smaller fractions and their capacity is 8 [TPH]. Its dimensions are 4.6 [m] x 2.3 [m], and its weight is 8,000 kg. Machine of 5 KVA.

Figure 15: GEM fine COLOR

GEM large COLOR

This sorter classified the two bigger fractions and their capacity is 8 [TPH]. Its dimensions are 4.6 [m] x 2.3 [m], and its weight is 8,000 kg. Machine of 5 KVA.

Figure 16: GEM large COLOR

Screeners

These machines split the mineral in 4 fractions, the four machines correspond to the Sandvik LF1030 screener, 1.0 [m] x 3.0 [m], and total weight of 3,000 kg. Each one has two engines of 6.6 [kW].

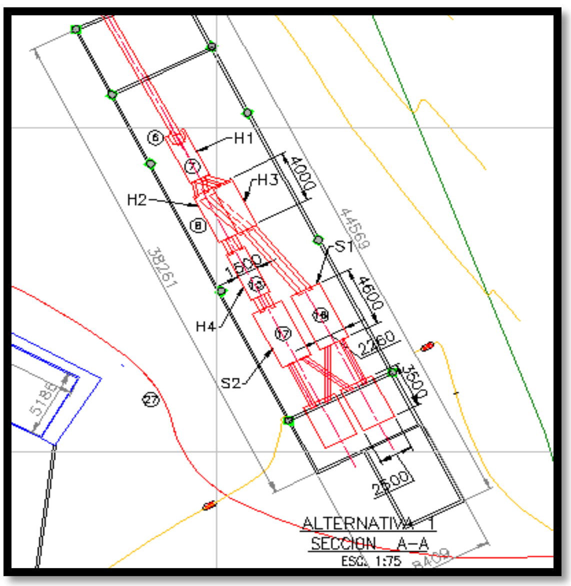


Figure 17: screeners location (screener 1 = H1)

Air blower

It is necessary to wash the mineral to remove dirt and dust, and then proceed to blow the same product to remove product water from the washing process. So you need two machines to deliver 500 [cfm], with a pressure of 100 [mbar]. Each of these machines has a capacity of 7.5 [HP].

Figure 18: Low capacity blower

Air Extractor

Commodas also proposed the installation of an exhaust fan to control airborne dust and the moisture product the particles ejection, this machine must be located on the roof of the hangar and be connected to the two optical sorting equipment.

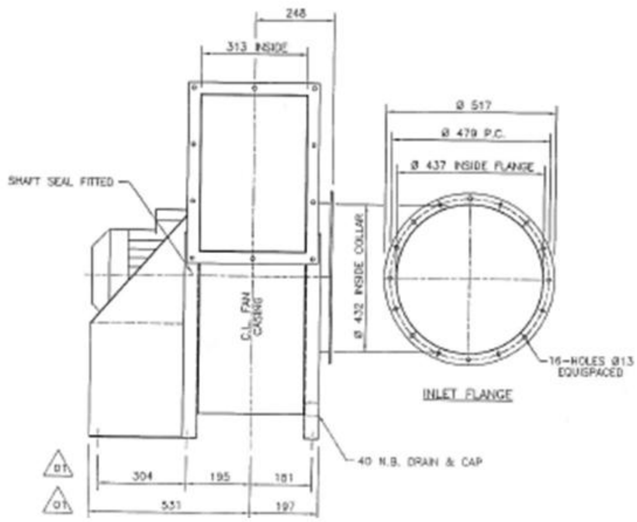
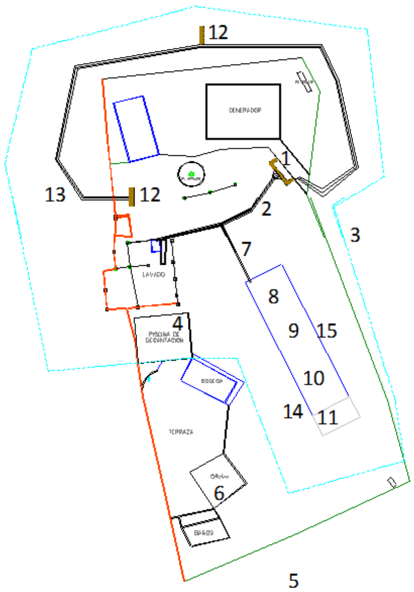


Figure 19: Air extractor

General infraestructure

Below is a map of the location of the elements described above:



01. Main Chute
02. Belt feeder
03. Safe Zone production
04. Water Treatment
05. Volvere Incorporation
06. Headquarters
07. Feed belt Treatment Plant
08. Screeners
09. Optical sorting equipment
10. Recirculation
11. Final cleaning
12. Haulage Bays
13. Haulage level
14. Haulage
15. Home Office Storage

Figure 20: General Infrastructure

Production security area

The production security area is conceived as highly secure area within the mining complex in which production takes place. This area was conceived to be viewed with cameras the whole time and gated locking the access for people not related to the operation. The main areas of this are as follows:

- main access gate and personnel screening
- Control access to Tequendama and Puerto Arturo
- Plant warehouse
- engineering and production control room

3.4. The Mine Planning Process

As can be seen, the business value chain can be set in a circle connecting the stages of exploration, design, production planning, mining operations, production control, sorting, polishing, and finally the sale in the market. Because the strategic objectives of the company that owns the mine, should be the guiding operation based on the strategy of market positioning, conditioning the exploration, operation and all the rest of the chain.

Figure 21: Strategic Methodology

One important aspect of planning Muzo was to find the grade distribution of Emeralds surrounding a geological contact formed in a hydrothermal and post metasomatic metamorphic process. Below is the genetic model in the Muzo Emerald mine and the conceptual summary of mine geological mapping.

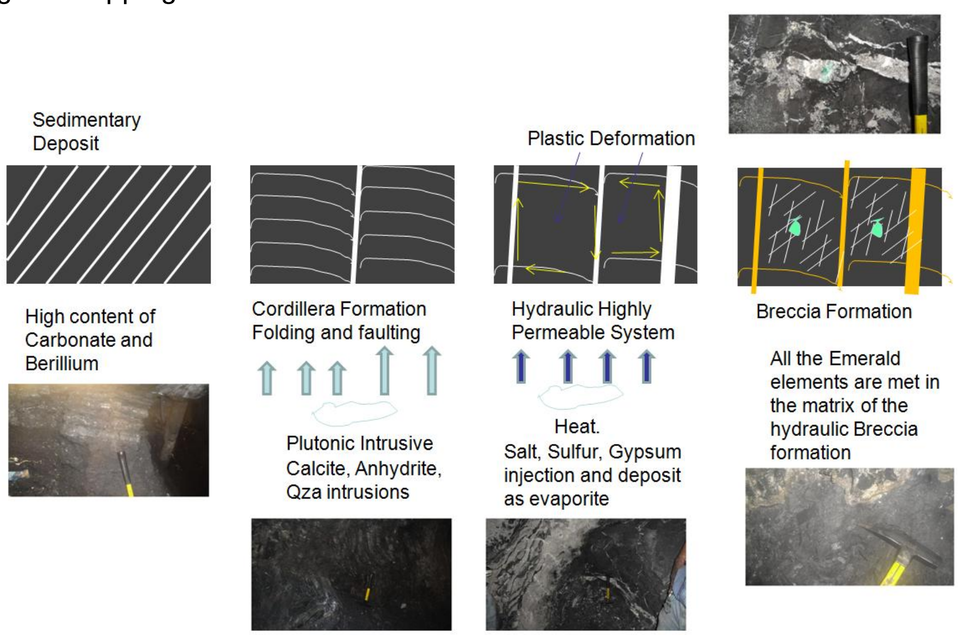


Figure 22: Genetic Model

A study of field geology has been performed for each mine of the Muzo Complex to identify the areas where the emeralds are located. Based on this data, the following provision of lithologies was identified:

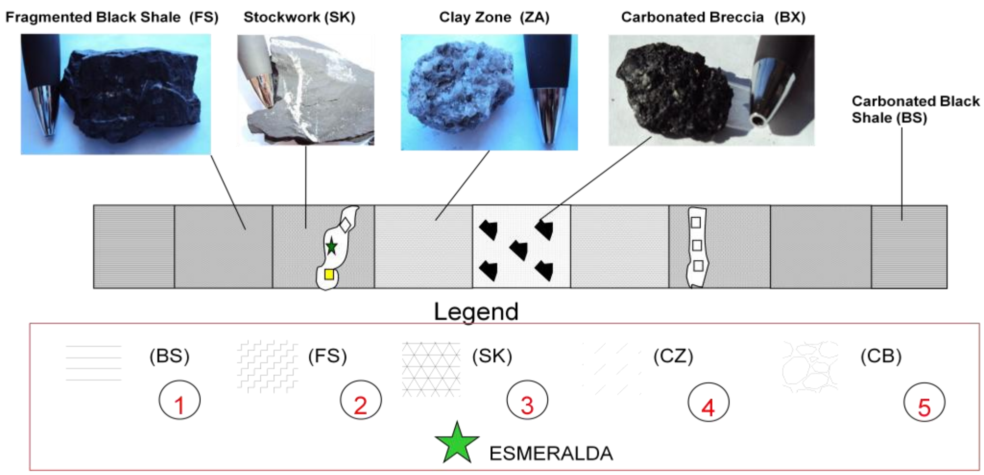


Figure 23: Geological profile Muzo Emerald Mine

Carbonate Black Shale (BS)

- Carbonated shale with average hardness, shows no signs of posthumous tectonics and mineralization. Typically known as a "liso"

Fragmented Black Shale (FS)

- Shale with folding.
- Veins with calcite and pyrite
- The pyrite zones can be seen in disseminated form.

Stockwork (SK)

- Black shale carbonate.
- Veinlets of albite, calcite.
- Disseminated pyrite.
- Veins up to 20 [cm] thick with albite / calcite (average thickness 10 [cm])
- May contain emeralds.

Clay Zone (CZ)

- Gray rock with Highly altered rock textured of breccia.
- Are seen healthy and altered crystals of albite and dolomite.
- Crumbles in your hand.
- Disseminated pyrite.
- Some laminar or banded areas available.
- You can submit mm angular clasts of black shale.
- Some areas carbonated.

Carbonated breccia (CB)

- Very soft black shale that crumbles in your hand.
- Albite veins (altered to clay) and disseminated pyrite.
- Clay matrix

Over the above conceptual diagram over a year of mine production geological maps were set up in order to find the main concentration of Emerald production at different levels of each mine: Puerto Arturo, Catedral and Tequendama. The following depicture illustrates the findings at Tequendama mine.

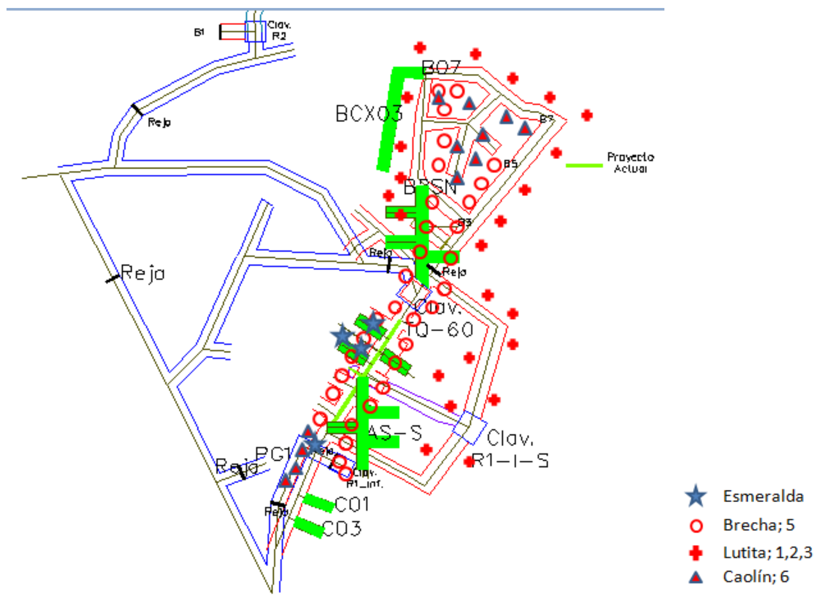


Figure 24: Emerald Findings and Geology at Tequendama

The tipical geological cross sections of the mines are presented as follows:

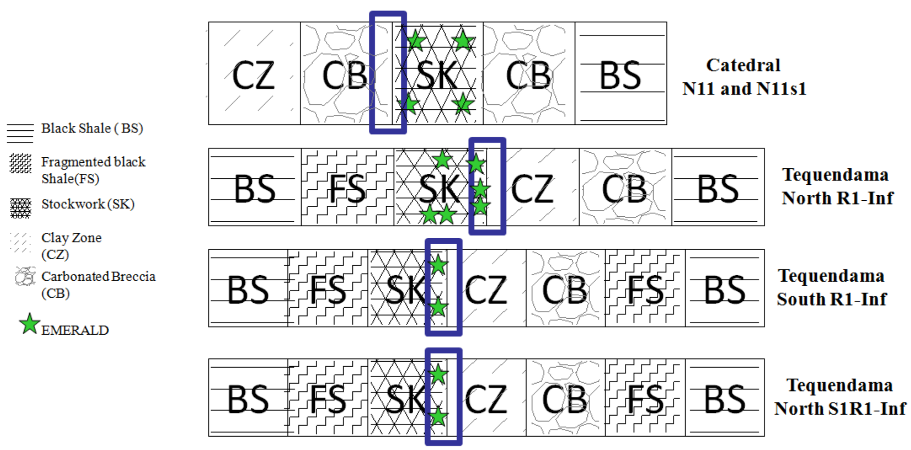


Figure 25: Geological mapping

Geophysics

The aim of this study was to test the resistivity geophysical techniques, IP and resistivity tomography, to determine its applicability in the exploration of emerald mines, and thereby help reduce the uncertainty of occurrence of emeralds.

With resistivity and IP 2 studies were conducted, 500 [m] long each. Data was recorded in the time domain, dipole-dipole configuration, the distance between the electrodes was 50 meters (a = 50), progress was made at every 25 meters, there were 6 levels deep (n = 6) (110 m depth of investigation) and an integration time of 2 seconds was used. In total there were 950 meters linear surface covered.

In Resistivity tomography 10 lines of 45 to 90 meters were studied. Data was recorded in the time domain, dipole-dipole configuration, the distance between the stakes was 5 meters (a = 5), up to 13 levels deep were recorded (n = 13) equivalent to 15 to 20 meters depth of investigation and use an integration time of 0.5 seconds. In total there were 630 meters linear, of which 505 meters occurred in the interior of tunnels and 125 meters at the surface, these last 90, plus 35 test and calibration samples. We used a team scores IRIS SYSCAL-Pro model. Below there is one of the specific outcome figures for Tequendama mine, the most productive mine in 2010.

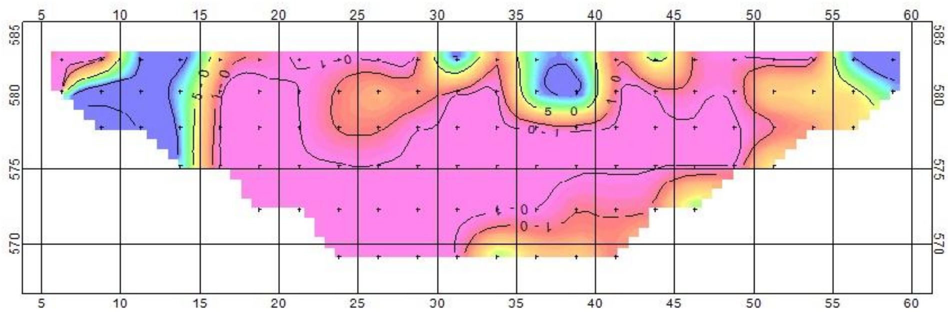


Figure 26: 2D resistivity model TQ-R1Inf sector. Carbonaceous shale and wet (pink), shale, drier and more established (blue, yellow and orange)

It is possible to identify the lithological contact between structures of different hardness, allowing to identify sectors concentrating the high probability of occurrence of emeralds.

Geochemistry

Taking the main objective of defining a system of effective prospecting and exploration that allows increased emerald recovery respect to the number of blocks in production, is of interest to find a relationship between the geophysical results, mineralogy, chemical elements and occurrence of emeralds . Based on this idea, a complete search for equipment that can help obtain the spectrum of mineralogical and chemical elements in rock samples, to create a complete system characterization and identification of areas of high emerald probability. It's been considered the usage of technologies such as fluorescence and X-ray diffraction (XRF and XRD). Some of the results for 12 samples analyzed in the laboratory, are presented below:

Table 3: Samples detail and critical elements content

Nº	Sample	Si (%)	Al (%)	Fe (%)	Ca (%)	Mg (%)	S (%)	Na (%)	K (%)	Ti (%)	P (%)	Mn (%)	Sr (%)	Zn (%)	Cu (%)	Cr (PPM	Ba (%)
1	TQD R1i_S AS-N	36,4	10,3	4,6		2,6	6,3	5,7	0,3	0,4	0,3	0,1	0,0	0,2	0,0	937,0	0,1
2	TQD R1i B03	20,3	7,2	4,8	26,4	5,5	7,3	1,7	1,1	0,3	0,1	0,1	0,0	0,1	0,0	786,0	0,0
3	TQD R1i B01	40,0	11,0	3,2	12,9	4,5	3,0	6,3	0,1	0,5	0,4	0,1	0,0	0,0	0,0	458,0	0,1
4	TQD R1i_S AS	39,2	10,5	2,2	14,6	4,1	1,6	6,3	0,2	0,4	0,6	0,1	0,0	0,0	0,0	511,0	0,0
5	CAT N11 Cx01 (Clay Zone)	0,0	0,2	3,3	29,9	19,4	0,6	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	162,0	0,0
6	CAT N11 Cx01 (Clay Zone)	0,0	0,3	6,5	28,1	18,6	6,5	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	481,0	0,0
7	TQD R1i_S AS-N Cx01	25,1	7,2	6,5	24,4	1,5	8,6	4,1	0,1	0,3	0,2	0,1	0,0	0,0	0,1	519,0	0,0
8	B03 (Left Wall)	33,0	8,2	4,5	14,3	8,0	5,0	4,1	0,2	0,3	0,4	0,1	0,0	0,1	0,0	739,0	0,1
9	B03 (Right wall)	22,2	6,3	6,2	26,9	3,3	7,9	3,5	0,1	0,2	0,1	0,1	0,0	0,1	0,0	459,0	0,0
10	R1i B03 (1)	40,8	10,1	4,6	14,9	3,6	5,7	6,1	0,1	0,5	0,3	0,1	0,0	0,0	0,1	815,0	0,1
11	R1i B01	29,1	9,6	7,0	16,3	6,4	11,2	3,0	1,4	0,4	0,1	0,1	0,0	0,7	0,0	939,0	0,2
12	MORRALLA	5,4	1,7	2,8	44,5	1,6	3,7	0,5	0,0	0,0	0,0	0,1	0,0	0,0	0,0	477,0	0,0

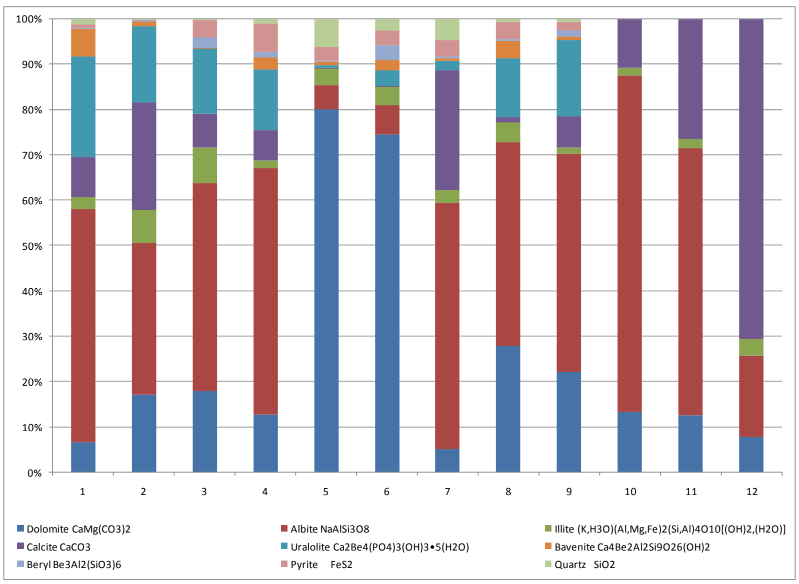


Figure 27: Graph X-ray diffraction results

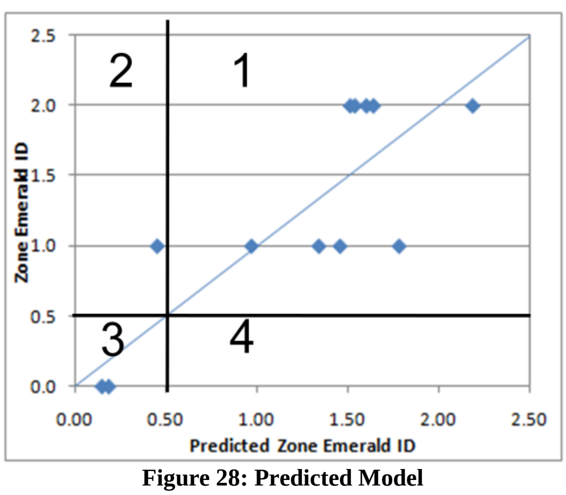


Figure 28: Predicted Model

Emerald Id = (1.957*10^-3 x Na/K) + (3.01*10^-2 x Albite[%])

- Quadrant 1: Model and Reality agree with emeralds occurrence.
- Quadrant 2: Reality with emerald occurrence of Morralla, but the model does not match.
- Quadrant 3: Model and Reality agree on the non-occurrence of emeralds.

After the research process, we recommend testing equipment SAX (Bruker distributor), IGMO (distributor of FEI Company) and Spectral International Inc, performing tests on samples sent from the mine, then do the analysis of what technology is best based on the quality and quantity of the results, and finally define what is the most appropriate equipment for the conditions of use.

4. Mine design and production planning based in portfolio optimization

Based on the geological genetic models presented before a probability distribution of grades for the different products were constructed for the different mines at different widths, with the main axis being the metasomatic contact of hard and soft rock. Every single mining widths represents a different mining method. So for the artisanal method the width happens to be 1.5 m, for the drift and fill 2.5 m and for Inclined Draw Point Caving 4.0 m. The following tables show the log normal grade distribution of Chispero, Morralla and Perma for all three mines for different mining widths.

Gades M1			
Chispero	A1	A2	A3
Media	1.10	0.41	- 0.36
Standard Deviation	0.11	0.04	0.04
Morralla	A1	A2	A3
Media	1.79	0.69	- 0.69
Standard Deviation	0.36	0.14	0.14
Perma	A1	A2	A3
Media	1.57	0.47	- 0.92
Standard Deviation	0.31	0.09	0.18

Grades M2			
Chispero	A1	A2	A3
Media	1.44	0.92	- 0.22
Standard Deviation	0.29	0.18	0.04
Morralla	A1	A2	A3
Media	2.13	1.03	- 0.36
Standard Deviation	0.43	0.21	0.07
Perma	A1	A2	A3
Media	1.91	0.81	- 0.58
Standard Deviation	0.38	0.16	0.12

Grades M3			
Chispero	A1	A2	A3
Media	1.79	1.39	0.41
Standard Deviation	0.26	0.20	0.06
Morralla	A1	A2	A3
Media	2.48	1.39	-
Standard Deviation	0.50	0.28	0.20
Perma	A1	A2	A3
Media	2.26	1.16	- 0.22
Standard Deviation	0.45	0.23	0.04

Figure 29: LogNormal Distribution of grades for the different mines and different mining methods

The price distribution over a period of a year were taken from public reports as well as the 2010 sales performed by Coexminas. The following price distribution per products is shown below:

Prices/products	Chispero	Morralla	Perma
Media	6.68	5.01	3.91
Standard Deviation	0.07	0.10	0.06

Figure 30: LogNormal Distribution of prices taken from a year of mine production

Based on the above several simulations were performed to analyse at least 50 combinations of mining methods (Drifting, Drift and fill and Inclined draw point caving) for the different mining areas. The following parameters of costs and productivity by method by mine are used to compute the rate of return of every combination.

	M1	M2	M3
Productivity Method 1 (t/year)	18,000	12,000	12,000
Productivity Method 2 (t/year)	60,000	42,000	32,400
Productivity Method 3 (t/year)	72,000	60,000	72,000
Cost Method 1 ($/t)	600	400	500
Cost Method 2 ($/t)	200	300	350
Cost Method 3 ($/t)	100	140	180
Mining Recovery of Method 1	0.3	0.3	0.3
Mining Recovery of Method 2	0.4	0.4	0.4
Mining Recovery of Method 3	0.5	0.5	0.5
Process Recovery	0.35	0.35	0.35
Mining fixed cost ($)	3,000,000	1,500,000	500,000
Selling cost ($/c)	20		

Figure 31: Parameters for the portfolio optimization

Finally, the efficient frontier is computed for the Muzo Emerald mines for the three different operating mines and for three alternative mining methods. There was an integer constraint added to the model to avoid solutions such that in a mine there could be two coexistent mining methods at the same time (Norstand, 1999). The following chart shows the result

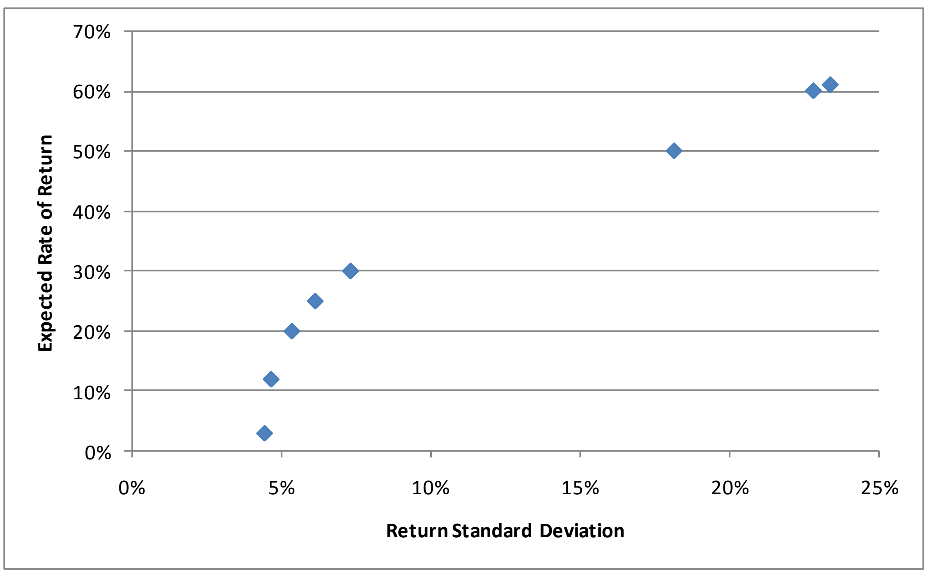


Figure 32: Efficient frontier for the Muzo Emerald mine

It was very much interesting to see that for every combination of return and volatility the production schedule and mining methods per mine change accordingly. The following chart shows the strategy of mining method and proportion of production contributing to the schedule per mine for different rate of return and volatility. For instance the following conclusions can be derived from the analysis:

1. For a high return, high volatility approach the production schedule should concentrate at mine Tequendama using drift and fill method concentrating over 80% of production.
2. For an intermediate return and medium volatility the production schedule should concentrate at Puerto Arturo with Drift and Fill, Catedral with Drift and Fill and Tequendama with Inclined Draw Point Caving
3. For low return but also low risk approach the schedule should concentrate at Puerto Arturo with Drift and Fill method.

The following depicture shows different mining combinations, methods and schedule that could be used at Muzo for different return/ risk approaches.

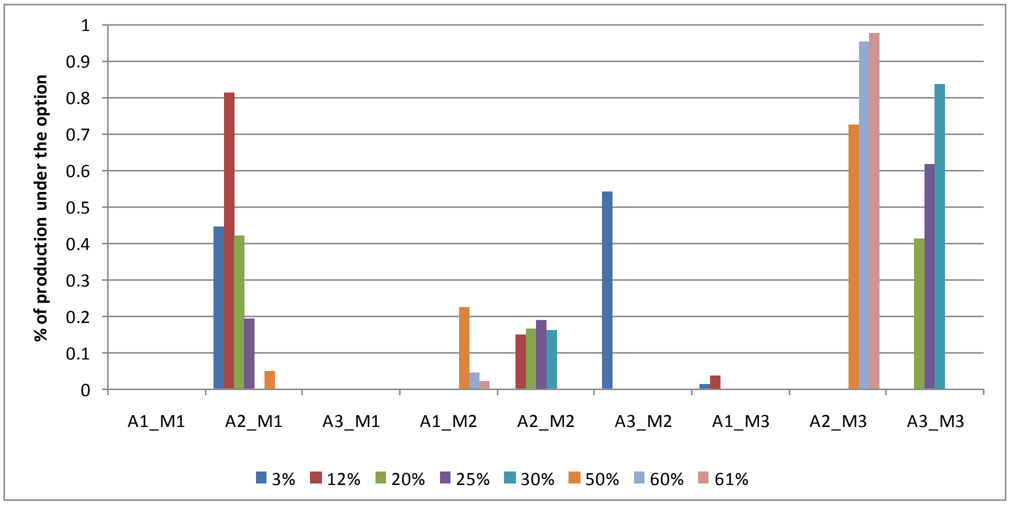


Figure 33: Different strategies and production schedules depending on the return/volatility decision

Based o the above guideline the schedule for 2011 is presented as follows:

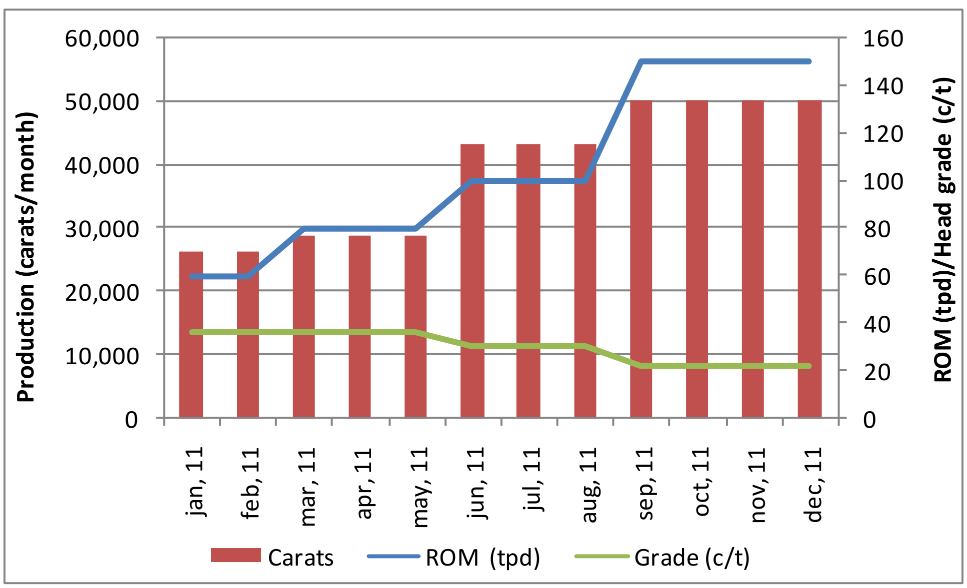


Figure 34: Final proposed production schedule

5. Conclusions and Recommendations

The main conclusion that can be taken from the approach presented in this paper is that uncertainty modeling opens a new way of performing strategic mine planning. It is not possible to integrate uncertainty into our production planning discipline if there are not clear and understandable financial tools that can facilitate the decisions makers to see the value of variability.

Currently there is a plenty of uncertainty modeling methods available that end up being used as a just sensitivity analysis of a fixed production schedule. This ongoing research as shown that when adding uncertainty in the modeling of grades and prices the structural mining decisions may change accordingly based on the acceptance of risk and return.

In terms of the specific results for the Muzo mine it is interesting to outline that a coupled of modeling techniques together with a financial well known approach could contribute in a great deal to the delineation of the ore body, sequence, mine design and production schedule from the valuing of options down to geology.

It is expected that the mining industry understands that the new paradigm of strategic planning would be to concentrate much on the market and how the financial position of shareholders could facilitate the delineation of our mine planning decisions and not the other way around.

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