CUT-OFF GRADE STRATEGY: ANALYSIS FOR DOMINGA PROJECT

by

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Abstract

Cut-off grade is a concept used in the mining industry to decide whether to consider the material from the mine as ore or waste. The decision of the specific cut-off grade used in a mine should be periodically evaluated because this concept involves variables such as commodity prices, mining costs, processing costs, metallurgical and mining recoveries, and it is also necessary to take into account the grade distribution of the deposit.

The Dominga project, an IOCG deposit located in Chile, is studied to evaluate the differences of applying different methodologies to select the cut-off grade that maximizes the discounted value of the project. To work with the Dominga project it was necessary to build a recovery model to meet the requirements of the software involved in this study (Whittle Software, version 4.5.3). After this, three different case studies were developed using different strategies to define an iron cut-off grade that maximizes the NPV. These different strategies are identified as using the marginal cut-off grade, a defined cut-off grade and a cut-off grade optimization.

As a result, from the three different case studies, the improvement in the discounted cash flow generated by applying a strategy of cut-off grade optimization rather than a marginal strategy is 3%. If capital expenditure is considered, an improvement of 8% in the NPV is achieved. If this strategy is compared with using a defined cut-off grade, the results are similar.

As a conclusion, for this particular deposit, where the iron ore grade displays homogenous distribution, the effect of applying cut-off grade optimization and the use of a defined iron cut-off grade is very similar.

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List of Abbreviations

Abbreviations	Description
Au(ppm)	Gold content in parts per million
CAP-CMP	Compañia Aceros del Pacífico
CFR	Cost and Freight
CIF	Cost, Insurance and Freight
COG	Cut-off grade
COGO	Cut-off grade optimization
Cu(%)	Copper content in percent weight
dmt	Dry metric tonne
dmtu	Dry metric tonne unit
DN-DS	Dominga Norte – Dominga Sur
DRI	Direct-Reduced Iron
DSO	Direct Shipping Ore
FeM(%)	Magnetic iron content in percent weight
FeT(%)	Total iron content in percent weight
FOB	Free on Board
IOCG	Iron-Oxide Copper Gold Deposit
kton	Kilo (thousand) metric tonne
ktpd	Kilo (thousand) metric tonne per day
L&G	Lerchs & Grossman
LOI	Loss on Ignition
MBIO	The Metal Bulletin Iron Ore
Mt	Million metric tonne
Mtpa	Million metric tonne per year
NPV	Net Present Value
NSR	Net Smelter Revenue
PCAF	Processing Cost Adjustment Factor
PLA	Pit Limit Analysis
tonne	Metric tonne
TSI	The Steel Index
US$/lb	US Dollars per pound
US$/oz	US Dollars per ounce
US$/t Conc	US Dollars per metric tonne of concentrate
US$/t Ore	US Dollars per metric tonne of ore
US$/t pellet feed	US Dollars per metric tonne of pellet feed

Chapter 1

Introduction

1.1 Overview

Strategic mine planning is a very important stage in the development of a mine. This stage is where different profitable extractive scenarios are studied and analyzed. These different scenarios identify, for example, the mining method(s) to be adopted (open pit or underground mine), how to extract the mineralized ore body, the limits of the mine (final pit limit or extent of underground development), the mining sequence. Strategic mine planning identifies the critical questions or issues facing a project and proposes answers to these questions. This process is repeated throughout the life of the project because the resulting plan depends on many factors that will likely change during the mine life.

One of the topics a strategic mine plan must address is the use of a cut-off grade (COG) to define the ore from the deposit for a defined period of time. The COG is the tool that defines the ultimate destination of mined material, that is, whether the material should be considered as waste, or as ore and sent for processing. The use of a COG depends on many factors and the implementation must be studied independently for every deposit because every deposit is different in terms of the grade and tonnage distribution, cost structure, etc. The COG strategy must also take into account the goals of the company developing the deposit. The COG strategy developed should be consistent with the corporate strategy, for example to maximize profits, to maximize net present value (NPV), to maximize mine life, cover at least two price cycles of the metal.

In this thesis, different methodologies to develop a COG strategy are reviewed and commented on, from the traditional (and still common) use of a marginal COG through modern developments in the use of cut-off grade optimization (COGO). Every strategy has different considerations and the objective of the review is to identify appropriate and practical applications of COG strategies in iron ore deposit.

1.2 Hypothesis

COG strategy is an important consideration in mine planning. The application of advanced COGO has the potential to improve the value of a project to the mine's developer, even where feasibility studies have been conducted considering that the analysis of the strategy should be evaluated periodically. For this work it is important to understand what the impact of applying a COG strategy to an iron ore deposit will be.

It is important to note that most of the available literature on COGO studies application to copper and gold deposits and demostrate that by using COGO they can improve NPV over 10% compared with just using a marginal COG strategy. However, in some deposits this improvement could be affected by the grade distribution, which means that it is important to evaluate the implementations of different COG strategies that take into consideration the grade distribution curves. This is because if the project is a homogeneous ore body in terms of grade distribution, zones with high grades that are the zones where the algorithm of COGO puts its emphasis, are not going to play a big role. This is because the concept behind the optimization of the COG is to bring the high-grade/high-value material to the beginning of the mine life. If there were a limited zone of high grade, the algorithm would be very restricted and may not produce the improvement of NPV necessary to adopt the more sophisticated optimization strategy.

1.3 Research Objectives

The main objective of this research is to review, understand and apply the theory behind COG selection and COGO to an iron ore project. Whittle Software (Version 4.5.3) is used as the platform to interact between the implementation of the COGO algorithm, which is included in the software, and the iron ore deposit. To support this study, the thesis document reviews and analyzes possible methodologies to work with a COG strategy to extract the mineralized ore body, based on the fact that the main objective of the company that owns the deposit is to achieve the highest possible NPV for the project.

The objectives can be summarized as:

1. To review current industrial and best practices in developing a COG strategy, including COGO methods.
2. To analyze the methods reviewed and adapt them for application to the deposit under study, an iron ore deposit with copper and gold by-products.
3. To apply the selected methods in order to develop a series of strategic planning proposals for the project under study and to propose potential improvements to the current strategic plan (the case studies).
4. To present general conclusions about the effectiveness of COG analysis applied to iron ore deposits.

1.4 Methodology

The research presented consists of the application of a COGO strategy to an iron ore deposit called “Dominga”. Dominga is an iron ore deposit, with copper and gold as sub-products. The project is a property of Andesiron, a Chilean company that has carried out the scoping study, prefeasibility study and the feasibility study for this project. The project is composed of two mines (Dominga Norte and Dominga Sur). The deposit hosts more than one rocktype in each of the mines. The different rocktypes included in the block model of Dominga consider different iron, copper and gold recoveries and different processing costs for the rocktypes identified. The iron ore recovery depends on the total iron content (FeT) and the magnetic iron content (FeM).

Andesiron built the block models for Dominga Norte and Dominga Sur and they are available for this study. The work completed for this thesis includes exploration and analysis of the block models looking at the tonnage-grade curves, elements and grades, grade and recoveries distributions, etc. in order to develop a detailed knowledge of the geology of the deposits.

After review of the deposits a case study is developed. The supplied block models are adapted to work with COG and COGO methods in Whittle Software. For this, a new model for iron recoveries has been built and validated. Finally, different options or scenarios to apply COG strategies are developed and implemented using Whittle Software and the results analyzed in order to present conclusions and recommendations.

1.5 Thesis Organization

The following paragraphs are an explanation of each of the chapters included in this work.

Chapter 2: Literature Review

This chapter presents an overview of the concept of COG found in the literature. Definitions and uses of COG are provided. A variety of techniques and algorithms are explained, including COGO.

Chapter 3: Block Model Analysis

This chapter presents the project that is the subject of the thesis research and work, the Dominga project. Analysis of the deposit geology and block models, focusing on grades and recoveries, is presented. A model of constant iron recoveries is built based on the original model, which contained variable iron recoveries.

Chapter 4: Case Study: Dominga Project

This chapter presents the analysis of three different case studies developed to assess different COG/COGO strategies.

Chapter 5: Conclusions and Future Work

This chapter presents conclusions based on the work completed and recommendations that result from the work done.

Appendix A: Basic Statistics FeT, FeM, Cu and Au for Dominga

This appendix presents graphs generated during the statistical analysis of the block model for Dominga Norte and Sur.

Appendix B: Validation of the Recovery Models

This appendix presents graphs generated to support the validation of the recovery models for Dominga Norte and Sur.

Appendix C: Different ways to look for a defined FeT(%) COG

This appendix presents detailed information on the differences between “Cut-off Ore Selection Method” and “Cash Flow Ore Selection Method” used in this report. The Dominga project is used as a case study to determine the different results obtained by applying these methodologies.

Appendix D: Introduction to the Iron Ore Industry

This appendix provides an introduction to key ore and marketing concepts and considerations used in the iron ore industry.

Chapter 2

Literature Review

This chapter reviews the existing literature relating to COG estimation and their uses in mining projects. To define technical concepts related to COG estimation it is important first to define the concept of strategic mine planning and the consequences of applying a COG policy.

2.1 Strategic Mine Planning

Strategic mine planning is the process that is used to build a feasible mine plan that achieves the main purpose, or objective, of the company. This objective can be to maximize the NPV, maximize the cash flow, have as many years of productive life as possible, etc. Strategic mine planning can also be defined as the first stage of a mine plan that will develop realistic and viable strategies of extraction.

The following concepts are the three most common economic criteria that are applied by the mining industry when developing mining company objectives, and also in identifying the main goal of a mine plan during strategic mine planning (Hustrulid & Kuchta, 2006):

a) Maximum present value
b) Maximum total profits
c) Maximum immediate profit

According to Hustrulid and Kuchta, the goal of maximum present value “gives the economic optimum for the mining industry” and the other two objectives are specific cases (using different discount rates) of the first one. According to King (King, 2001), in order to achieve the maximum present value of a project, there are a series of parameters that can be manipulated. The parameters can be divided into two groups. First, there are the uncontrollable parameters that impact the annual cash flow but are not in control of the mining company, for example, the resource grade distribution, tonnage distribution of the deposit, taxes and government royalties. Secondly, there are controllable parameters which impact the NPV (or discounted cash flow methodology to evaluate the effect of the time), which can be modified throughout the mine life, for example mining and production rates, recoveries (using new technologies to recover the metal from the ore) and COG (King, 2001).

2.2 Basic Cut-off Grade Definitions and Strategies

COG is used to separate material that should not be mined, or should be mined and treated as waste, from material that should be mined and processed. According to Kelsey (Kelsey, 1979), Taylor in 1972 defined COG "as any grade that, for any specific reason, is used to separate two sources of action, e.g. to mine or to leave, mill or to dump" (Kelsey, 1979). If the material has impurities and these elements affect the recovery of the main product or the value of the final concentrate, COG can also be defined as the grade that achieves the maximum amount of impurities that a tonne of material can contain if it is sent to the processing plant (Rendu, 2014). COG is a concept that can be defined in many ways depending on what the main purpose of identifying material to process is.

As described, COG is a fundamental factor of the mining process because it can be manipulated and it has a significant impact in reserve calculations, production schedules, estimation of the mine life, and also is a parameter that impacts the NPV achievable during the life of a project.

Using a high COG typically would increase the short-term profitability, and with this increase the NPV of the project, an action referred to as “high-grading” of a deposit. On the other hand, this strategy will reduce the mine life and the job opportunities that help define the social impact of the project. Using a low COG, the general effects would be to increase the undiscounted cash flow, increase the mine life, and increase the amount of material that can be reported as reserves.

As indicated before, there are different definitions of COG and in general they are very similar, however the choice or decision of a COG policy or strategy to be used during exploitation or as a part of a mining study of a deposit is not clear in most mining projects and of course depends on external factors, for example the price of the metal. One question is what action a mining company should take with respect to the COG when the commodity price changes during the life of mine.

Lane in his landmark work proposes that the COG should move in the same direction as the metal price, which means that if the price of a metal decreases then the COG should decrease as well (Lane, 1979). In 2001, King proposed that the answer to the question of what should be done if the price of the metal goes down depends on many factors. These factors are, for example, what material is available to be mined at that moment, the constraints of the mining, milling and smelting processes, and the quantity and grade distribution of remaining material (King, 2001).

In order to achieve the objective of maximizing the NPV of a project, companies use different COG grade strategies. One of the methodologies is to plan to use the same breakeven COG (defined and explained later in this chapter) for all the years of production, changing it only when the price of the metal or recovery of the ore changes (following the formula of the definition of marginal COG). This methodology works in terms that can produce a positive NPV, however it doesn’t necessarily produce the maximum achievable NPV. In 1963, Henning (Kelsey, 1979) was the first to demonstrate that a constant COG is not the correct strategy if the main goal of the company is to maximize the present value of the mining project. He proposed that the maximization of the discounted value of a mine can be achieved by mining high grades at the beginning of the mine life, with a declining COG as the mine life advance.

The following sub-chapters show the theory and basic concepts of COG. First, there is a definition of breakeven grades; second, there is a simple explanation of Lane’s theory and then the basic methods employed when projects contain multiple elements are presented. Finally, an overview of how Whittle Software, used to complete the analysis of the Dominga Project as part of this thesis, implements the concept of COG optimization is presented.

2.3 Breakeven Grades Definitions

Commonly, in open pit mining a COG grade called the “external” or “mining cut-off grade” is used to determine if a block of material should be mined or not, and another different COG called “internal” or “milled cut-off grade” is used to determine if a tonne of material should be milled or taken to the waste dump (Rendu, 2014).

According to Dagdelen (Dagdelen, 1992), the external COG is generally referred to the ultimate pit grade or limit. This COG is sometimes called the breakeven grade because it equates the cost of mining, milling and refining to the value of the block in terms of recovered metal and the selling price.

During the evaluation of final pit limits the destination of the material is either to be mined or left in the ground. Once the decision has been assigned to mine a tonne of material, then the destination for the mined tonne or block must be assigned using the internal COG (Hustrulid & Kuchta, 2006). The internal COG is defined as the breakeven grade that equates cost of milling, refining and marketing to the value of the block in terms of recovered metal and the selling price (Dagdelen, 1992). Because the decision to mine has already been made, the mining cost is ignored in this calculation (unless there is a difference between the cost of mining ore and waste, this can happen for example when the distances of transportation are very different). When discussing breakeven grades it is important to understand if it is the internal or external grade being presented.

The breakeven grade may also be called the minimum COG. It is defined by using only direct costs resulting from mining and processing or mining and wasting a tonne of material at grade "x" in the calculation (Rendu, 2014). Direct costs are the mining cost, the processing cost, refining and selling costs. For this calculation there is no consideration of indirect costs, including the replacement of equipment or the costs of plant expansions, for example. Table 2-1 shows the difference in uses of costs between external and internal COG.

	Breakeven COG	
	External	**Internal**
Direct Costs	Mining	-
	Milling	Milling
	Refining and Selling	Refining and Selling

Table 2-1: Differences in costs used for internal and external COG

It is important to notice that the distribution of tonnes and grades of the deposit are ignored in the calculation of the breakeven COG.

To continue with the definition of breakeven grade, it is necessary to define how material in the ground is valued. As Rendu explains in his book (Rendu, 2014), valuation of one metric tonne of ore is a function of the grade, metallurgical recovery, value of marketable or final product, refining and transportation costs. If one metric tonne of grade "x" is mined and processed, the utility (U_{ore}) is defined as:

Equation 2-1: Utility function for mining and processing a tonne of material

$$U_{ore}(x) = x * r * (V - R) - (M_o + P_o + O_o)$$

where:

$x = average\ grade$

$r = metallurgical\ recovery$

$V = value\ of\ one\ unit\ of\ valuable\ product$

$R = refining\ cost, defined\ as\ costs\ that\ are\ related\ to\ the\ unit\ of\ valuable\ material\ produced$

$M_o = mining\ cost\ per\ metric\ tonne\ of\ ore$

$P_o = processing\ cost\ per\ metric\ tonne\ of\ ore$

$O_o = overhead\ cost\ per\ metric\ tonne\ of\ ore.$

The term "$x * r * (V - R)$" from Equation 2-1 represents the total revenue of mining and processing a tonne of material at grade "x".

If one metric tonne of grade "x" is mined and wasted, the utility (U_{waste}) is defined as:

Equation 2-2: Utility function to mined a tonne of material as waste

$$U_{waste}(x) = -(M_w + P_w + O_w)$$

where:

$M_w = mining\ cost\ per\ metric\ tonne\ of\ waste$

$P_w = processing\ cost\ per\ metric\ tonne\ of\ waste$

$O_w = overhead\ cost\ per\ metric\ tonne\ of\ waste.$

It is possible to have P_w when the dilution affects the mining process or for example, if processing waste is necessary to satisfy environmental regulations. For example there may be a government requirement that the size of the waste dump should not exceed a specific volume per year or during the mine life. After this, the breakeven grade is defined when $U_{ore}(x) = U_{waste}(x)$, which is represented in the following formula:

Equation 2-3: Definition breakeven COG

$$x_c = \frac{(M_o + P_0 + O_o) - (M_w + P_w + O_w)}{r * (V - R)}$$

As explained above, there are two types of COG, external and internal, and the consideration of mining cost defines which grade is calculated. The following sub-chapters discuss in more detail the external and internal COG.

2.3.1 External or Mine Cut-off Grade

This COG is used when it has to be decided whether to leave material in the ground (at no cost) or to mine the material (considering mining costs). Leaving the material in the ground, the utility of one tonne of material is:

Equation 2-4: Utility tonne of waste for external COG (no cost)

$$U_{waste}(x) = 0$$

Therefore, $U_{ore}(x) = U_{waste}(x)$:

Equation 2-5: Breakeven external COG

$$x_c = \frac{(M_o + P_o + O_o)}{[r * (V - R)]}$$

Material below this COG value is treated as waste and left in the ground. This COG separates material that can be mined and processed with a net value or utility greater than or equal to zero. (Hustrulid & Kuchta, 2006)

The Lerchs & Grossmann algorithm (L&G) produces a mathematically optimum solution to the problem of identifying the maximum undiscounted value for an open pit mine (Lerchs & Grossmann, 1964). The objective of this algorithm is to maximize the total profit, which is the total value of material extracted minus total extraction costs and to find an ultimate or final limit pit which is the basis for further analysis including defining the mining sequence and adding consideration for the time-value of cash flows. For this procedure the external COG is used (Lerchs & Grossmann, 1964).

The foregoing external COG calculations do not explicitly consider the cost of waste stripping. If the same metric tonne is exposed to the surface the decision can be made either leave it in the ground or mine it in order to access other material but consider it as waste. (Rendu, 2014). The COG formula should be modified to consider the waste stripping which are the metric tonnes of waste per metric tonne of ore. Assuming that the utility of a tonne of waste left in the ground is null (Equation 2-4), the formulation for including waste stripping costs in the external COG calculation is the following:

Equation 2-6: Utility considering stripping ratio

$$U_{ore}(x) = x * r * (V - R) - (M_o + P_o + O_o) - s * (M_w + P_w + O_w)$$

where:

$s = metric\ tonne\ of\ waste\ per\ metric\ ton\ of\ ore$

$M_w = mining\ cost\ per\ metric\ tonne\ of\ waste$

$P_w = processing\ cost\ per\ metric\ tonne\ of\ waste$

$O_w = overhead\ cost\ per\ metric\ tonne\ of\ waste.$

In strategic mine planning, after applying L&G algorithm to define a pit limit and having used an appropriate external cut-off, the internal COG is applied to define ore for production scheduling. According to Baird & Satchwell (Baird & Satchwell, 1999), it is not necessary to include stripping ratio in the calculation of this internal breakeven COG, because all the blocks are inside of the maximum profit pit determined during optimization of L&G.

2.3.2 Internal or Mill Cut-off Grade

As it was said before, the internal or mill COG is the decision grade applied to blocks that fall inside the optimized pit limit (from L&G) and must be mined as either ore (for processing) or waste (for the dump). The common way to explain this step is to think of a tonne already loaded in the truck and hauled out of the pit, the mining cost is already paid, so the next decision is whether go to the processing plant or go to the waste dump. Material should be processed if its grade is high enough to pay for processing costs even if does not pay for mining costs, since the mining cost is incurred in either case (Rendu, 2014). Mining costs are not considered in the internal cut-off calculation, and there is also an assumption that there are no significant costs in processing waste ($P_w = O_w = 0$).

Equation 2-7: Breakeven internal COG

$$x_c = \frac{(P_o + O_o)}{[r * (V - R)]}$$

2.3.3 Limitations of Breakeven Cut-off Grade Policies

These breakeven COGs (external and internal) are used to achieve the objective of maximizing the undiscounted values in a mining project, and they are normally constant unless the commodity price, or costs or the metallurgical recovery change during the life of mine. As previously indicated, these COGs do not consider the grade and tonnage distribution of the deposit (Dagdelen, 1992). Probably the most important explanation for the widespread use of these breakeven COGs in the industry would be that these optimize the use of the mineral resource of the deposit. That is, they optimize the potential metal recovery by the company by maximizing the undiscounted value of the deposit. They are also simple to understand and implement.

As Baird & Satchwell discuss in the paper "*Application of Economic Parameters and Cutoffs During and After Pit Optimization"* (Baird & Satchwell, 1999), some operations employ a COG above the internal breakeven value during the initial years. In this case, lower grade material is stockpiled until some future date. According to Dagdelen (Dagdelen, 1992), "the concept of using COG higher than breakeven grades during the early years of an operation for a faster recovery of capital investments and using breakeven grades during the later stages of the mine has been practiced in the industry using heuristic NPV optimizations" (Dagdelen, 1992). This is the case in the Dominga project in the prefeasibility stage, where the COG has been assigned after a trade-off study of different COGs searching for the combination of cut-offs that present the highest discounted cash flow. This will be explored more is subsequent chapters.

It is important to note that if a mine is working with marginal or breakeven grades, and the price of the metal goes up for any reason, following the formula of internal COG above, the COG for that element will go down. This effect has an important implication: if the average grade of the metal for that period decreases (because the COG decreases) and if the production rate is at maximum capacity (as is usual), the result of this is that total production of metal in the period decreases because the average grade of the ore in that period decreases. This is a contradiction if the main goal of the company is to maximize the discounted or NPV.

Lane (Lane, 1988) explores in detail the concept of optimum COG policy that maximizes the NPV of annual cash flows coming from a mining project in his book *"The Economic Definition of Ore"*. The following chapter explains in a simplified way the theory that Lane proposed which is the basis for almost all current COG optimization software.

2.4 Lane's Theory

Kenneth F. Lane, a mathematician from Cambridge University, proposed in 1964 an algorithm to determine a COG strategy that maximizes the NPV of a mining project subject or to process capacities constraints for the mine, mill and refinery capacity, each with definable costs (Lane, 1988). He defined a model where mine capacity is the maximum potential rate of mining the deposit, mill capacity is the maximum potential rate of processing ore, and refinery capacity is the maximum rate of production of final concentrate product (subject to marketing constraints), which is basically what occurs in the real world. For the COG optimization model work correctly, capacity constraints must be independent from COG values and also must be constants over time (Abdollahisharif , Bakhtavar , & Anemangely , 2012).

If the COG is too high, much of the mined material will go to the waste dump (assuming that there is no stockpile). If the COG is too low, then the input capacity of the entire mining and processing areas will be fully used, while revenues do not necessarily increase because the average grade from the material entering to the mill would be low which has an impact on the amount of metal produced.

The methodology of COG determination proposed by Lane is based on the fact that either one of those stages is limited and this may limit the entire operation. The theory also takes into account the grade distribution of the deposit and the opportunity cost of mining low-grade ore while high-grade ore is still available in the deposit. This theory determines COG year-by-year or period-by-period (Ataei & Osanloo, 2003). The general idea is to bring the high grade/high value material to the early years and leave the lower grade material to be processed in later years.

As Kelsey explains in his paper (Kelsey, 1979), for each stage defined by Lane in his model (mining, processing or refining) there is a grade at which the cost of extracting the recoverable metal from the ore equals the revenue that can be obtained for that metal (breakeven COG). If the capacity of an operation is limited by one only stage, the breakeven grade for that stage will be the optimum COG for the entire process. When an operation is constrained by more than one stage, the optimum COG may not necessarily be a breakeven grade for the complete process. In that case the balancing COG for each pair of stages need to be considered as well. A balancing grade is that which allows both stages of the pair being considered to achieve maximum physical capacity working together (Kelsey, 1979). The case when more than one process is a constraint is the most common case in mining.

In the paragraph above, there is a concept called balancing grade. To understand what is meant by this concept, it is necessary take a brief look at the definitions of the basic equations proposed by Lane. The following explanation can be found in more detail explained by Kuchta and Hustrulid in their book (Hustrulid & Kuchta, 2006).

The total profit of one tonne of material can be defined:

Equation 2-8: Definition total profit

$$Profit = [Revenue] - [Cost]$$

To determine profit the costs, Capacities and Quantities are defined in Table 2-2.

	Symbols	Definition
Costs	m ($/tonne)	Mining Cost
	c ($/tonne)	Processing Cost
	r ($/per unit of product)	Refining Cost
	f ($/period)	Fixed Cost
Capacities	M (ton/period)	Max. Capacity (Ore + Waste)
	C (ton/period)	Max. Capacity Ore
	R (unit of product/period)	Max. amount of product produced
Quantities	Qm (tonne)	Amount of material to be mined in one period
	Qc (tonne)	Amount of ore sent to processing in one period
	Qr (tonne)	Amount of product produced in one period
	s	Selling Cost of Product
	T (years)	Production Period

Table 2-2: Definition of costs, capacities and quantities

Revenues and Costs can be calculated using the costs, capacities and quantities defined in the table above substituted in the following expression:

Equation 2-9: Profit using costs, capacities and quantities defined from Table 2-2

$$Profit = [sQ_r] - [mQ_m + cQ_c + rQ_r + fT] \Leftrightarrow (s - r)Q_r - cQ_c - mQ_m - fT$$

Lane proposed that if the process is limited by one stage, the optimum COG for the entire process is the breakeven grade for the stage that produces the bottleneck. For example if for a specific case the refining rate (R) is the constraint, then the time required to mine and process a quantity of Q_r of material is: $T = \frac{Q_r}{C}$. Substituting $T = \frac{Q_r}{C}$, in Equation 2-9 defined by profit and then combining terms:

Equation 2-10: Profit not as a function of T

$$Profit = \left(s - r - \frac{f}{R}\right) Q_r - cQ_c - mQ_m$$

Now the profit equation no longer depends on the period because the length of the period is fixed.

To maximize profits the methodology is to take the derivative of Equation 2-10 with respect to the grade g.

Equation 2-11: Profit derivate respect to grade g

$$\frac{d(Profit)}{dg} = \left(s - r - \frac{f}{R}\right) \frac{dQ_r}{dg} - c\frac{dQ_c}{dg} - m\frac{dQ_m}{dg} = 0$$

Where the quantity of material to be mined in that period does not depend of the grade g.

Equation 2-12

$$\frac{dQ_m}{dg} = 0$$

And the amount of product produced in that period can be defined by the quantity of ore sent to processing using the metallurgical recovery from that process (y) and the average grade.

Equation 2-13

$$Q_r = \bar{g} * Q_c * y \iff \frac{dQ_c}{dg} = \frac{1}{\bar{g}y}\frac{Q_r}{dg}$$

Equation 2-14

$$\frac{d(Profit)}{dg} = \left(s - r - \frac{f}{R}\right)\frac{dQ_r}{dg} - \frac{c}{\bar{g}y}\frac{dQ_r}{dg} = 0$$

Equation 2-15

$$\frac{d(Profit)}{dg} = \left(s - r - \frac{f}{R} - \frac{c}{\bar{g}y}\right)\frac{dQ_r}{dg} = 0$$

Therefore, to achieve the requirement that $\frac{d(Profit)}{dg} = 0$, the constant must be equal to 0.

Thus, the cut-off grade, g_r , based in the refining constraint is the value $\bar{g}$, which makes that.

Equation 2-16

$$\left(s - r - \frac{f}{R} - \frac{c}{\bar{g}y}\right) = 0$$

Thus, the g_r is the optimum cut-off grade achievable for the entire process if the refining rate is the constraint.

Equation 2-17

$$g_r = \frac{c}{\left(s - r - \frac{f}{R}\right)y}$$

The same methodology can be applied if the mining rate (M) or the processing rates (P) are the constraint to find the optimum COG for both cases.

Equation 2-18

$$g_m = \frac{c}{y(s - r)}$$

Equation 2-19

$$g_c = \frac{c + \frac{f}{C}}{y(s - r)}$$

These COGs are developed from economic factors and process-limiting constraints, for that reason Lane called them Limiting COGs. These COGs are not necessary the optimum grades. It is possible that the production constraint may be the product of more than one stage. Lane proposed that the COG that achieves the condition of optimum for this case is a grade based on material balance.

Lane used an example to illustrate the case where the system constraint is due to more than one stage. Using a low COG increases the amount of mined material defined as ore, however the average grade of the ore is low, and therefore the metal produced for the quantity of ore is low. If instead a high COG were used, a high mining rate would be required to feed the process with the same tonnage of ore material, however the high average grade of the ore would produce a high production of metal, possibly in excess of the refining capacity. Lane proposed that there is an intermediate COG that can be found at which the capacities between the different parts of the system are fully utilized. These intermediate COGs are called balancing COGs.

To calculate a balancing COG it is necessary to know the distribution of grades of the material mined (tonnage-grade curve and a cumulative grade distribution) (Hustrulid & Kuchta, 2006).

As an example, suppose that the maximum mining capacity of an open pit operation is M, and the maximum processing capacity is C. The proportion of grades of the deposit that exceed a specific grade limit can be described in a graph called Cumulative Grade Distribution (CGD). The idea of using this curve is that these two variables (M and C) will be balanced when they achieve the value of the proportion $C\colon M$, which represents the proportion of ore versus total material mined Using the CGD there must be a point along this curve that the proportion of grades or the mineralized material exactly equals the proportion described before. This proportion is defined as a specific COG called g_{CM}. Figure 2-1 shows a graphic representation of this concept.

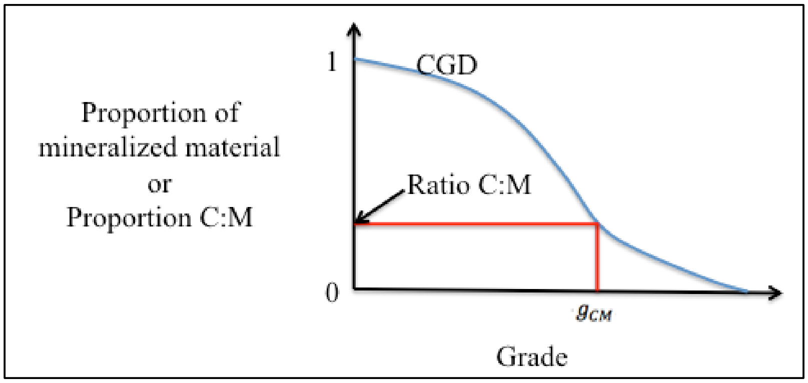

Figure 2-1: CGD curve and balanced COG

This procedure is similar for the other combinations of stage constraints, generating with this the balancing COG for the combinations of Mining-Refining (g_{RM}) and Processing-Refining (g_{CR}) (Lane, 1988). The methodology is independent of prices and costs and is calculated directly from the grade distribution of the deposit, balancing grades by using process capacities.

With this, there are six possible COGs. The objective is to find the COG that maximizes the profits of the entire process. The optimum cut-off for a particular pair of stages is the balancing grade for that pair provided the operation is actually limited by both stages. As stated by Lane, the overall optimum COG for the next unit of mine production is the middle value of the optimum cutoffs for the three pairs of stages. If only one of the stages in the pair is a bottleneck then the optimum cutoff for the pair is the breakeven for the limiting stage.

Lane extended this work to find a COG that maximizes the total profit of the deposit if 2 or more stages are constraining stages. In this approach, Lane tried to maximize the NPV. He introduced the concept of opportunity cost to the calculation. The concept of opportunity cost considers the cost of not receiving the future cash flows (from material with high grades, mined later) due to the limiting capacities from these three stages defined in the model (mining, processing or refining) and instead of processing high-grade material, processing low-grade material. In order to use this concept, he defined a NPV of all the remaining periods, not including the current period. He defined the difference between the present value of the current period and the present value of the remaining periods. The objective is to maximize this difference in every period of the mine life using an iterative process.

Kesley (Kelsey, 1979) defined an opportunity cost as the profit foregone from following one course of action when another would achieve a higher value. He stated that the most important opportunity cost to be considered in calculating COG is the cost of delaying receipts from available high-grade sources in order to mine lower grades. The cutoff grade at any particular time must therefore generate sufficient revenue to offset the cost of this delay. This opportunity cost is included in the breakeven formulae. It is the discount rate applicable to the period of the delay multiplied by the NPV of future cash flows. As the mine ages this opportunity cost will decrease because the value of the remaining operation will decrease. At the limit, the salvage value of the equipment will be just greater than the present value of future cash flows from continuing the operation. The most important result of this declining opportunity cost is that if present value is to be maximized the cutoff grade must generally be reduced over the life of a mine (Kelsey, 1979)

It has been realized that as opposed to constant breakeven cutoff grade, the optimum/dynamic cutoff grades, which change due to the declining effect of NPV during mine life, not only consider the metal price and cash costs of mining, milling, and refining stages, but also take into account the limiting capacities of these stages and grade-tonnage distribution of the deposit (Dagdelen, 1992).

The following sub-chapter introduces methods to work with COG when more than one element present in the deposit.

2.5 Cut-off Grades in Multiple Metal Deposits

According to Rendu (Rendu, 2014), polymetallic or multiple metal deposits are defined as deposits that contain more than one metal of economic value. Lane (Lane, 1988) in his book *"The Economic Definition of Ore"* said that deposits containing more than one metal are usually dealt with by converting all metals to their equivalent in terms of one basic metal. Then any analysis can be conducted exactly as if mineralization consists of a single metal. This is generally referred to as the equivalent grade method.

According to Ataei and Osanloo (Ataei & Osanloo, 2003), the equivalent grades method has some defects, but if the deposit has reasonably stable values, this is there is relatively homogenous grade distribution, this procedure is valid and simplifies the problem. They say "if one of the metals is subject to market limitations, this technique becomes invalid, because, the production in excess of the contracts for that metal cannot be sold and therefore ore cannot be valued as a profit for a specific period". For this reason, the influence of capacities in both plant and market would need to be considered, which invalidates the combined value criterion.

Some methodologies to discriminate between ore and waste in multiple metal deposits are: Net Smelter Revenue Method (Rendu, 2014), Dollar Value Cut-off Approach (mentioned in Ataei & Oslandoo, 2003) and the Golden Search Method (Ataei & Osanloo, 2003).

With the exception of the Golden Search Method, none of the methodologies mentioned above is an optimized technique. The reason is because the mining and mill operation capacity, distribution of grade, and the effect of time on money value are not considered as variables in the calculation of the other methodologies (Ataei & Osanloo, 2003).

Rendu (Rendu, 2014) proposes that COGs in a multiple metal deposit should be calculated by using Net Smelter Revenue methodology because the decision whether one metric ton of material should be wasted or sent to the processing plant can no longer be made on the basis of grade alone. Instead dollar values must be calculated for each possible process, and the cut-off between two processes must be determined or expressed in dollar terms.. After equivalent grade, this is the method most commonly employed in industry.

A brief description of this methodology is explained in this sub-chapter. The complete explanation can be found in Rendu's book.

2.5.1 Net Smelter Return (NSR)

The Net Smelter Return is defined as the return from sales of concentrates, expressed in dollar per metric tonne of ore, excluding mining and processing costs. With this definition, the utility of one tonne of material sent to processing is:

Equation 2-20

$$U_{ore}(x_1, x_2) = NSR_{(x_1,x_2)} - (M_o + P_o + O_o)$$

If the same metric tonne is sent to the waste dump, the corresponding costs are:

Equation 2-21

$$U_{waste} = -(M_w + P_w + O_w)$$

The material should be sent to the processing plant if:

Equation 2-22

$$U_{ore}(x_1, x_2) > U_{waste}$$

Various computer packages are developed based on Lane's theory. This idea was a revolution in the mining world, and most subsequent literature and research names Lane's Theory as the basis to develop strategies to apply in the industry. One of the practical software implementations that include modules based on Lane's theory is Whittle, software created by Jeff Whittle in 1984 under the name of Whittle Programming Pty. Ltd., now marketed by Dassault. Whittle Software includes an algorithm to optimize COG based in Lane's Algorithm.

2.6 Whittle Software: Cut-off Grade Calculation

The determination of COG policy, trying to maximize the NPV, is already used by some in the industry. Whittle optimization software uses the L&G algorithm as first stage of optimization, which gives a set of pit outlines for specified economic conditions, finding the maximum undiscounted cash flow for an open pit mine. These undiscounted value pit outlines are then used to identify the final or ultimate pit as well as the mining sequence. The technique determines discounted values to calculate the NPV of the proposed mining sequence. While the results of the L&G algorithm are mathematically optimal for an undiscounted pit there is no optimal solution to the problem of mine sequencing. Heuristic and semi-automated processes are used.

The techniques that determine the optimum COG policy consider the opportunity cost of not receiving future cash flows earlier during the mine life due to limiting capacities present in the stages of mining, milling, or refining (Lane, 1988), however the methodology described by Lane in his book is complicated even for a single element operation using constant costs, prices and capacities, and does it not work for more complex scenarios. One example is that while optimal COG typically decline in value over time, there may be periods where the COG increases temporarily before again beginning to decline. The decline is not necessarily consistent (Whittle & Whittle, 2007).

Whittle and Whittle (2007) also propose that it is necessary to work with multiple rocktypes, multiple processing methods per rocktype, multiple throughput limits, stockpiling and blending material to reproduce more realistic scenarios, to model real mining operations. When multiple rocktypes and-or processing methods are introduced to the problem it requires a cut-off for each rocktype processing-method combination. The introduction of multiple elements just adds to the number of cut-offs, which must be determined for each year. The practical software implementations available significantly extend the earlier work by Lane and others.

2.6.1 How Whittle Handles Cut-off with Multiple Elements

Whittle handles the selection of COG with multiple elements by providing an "Ore Selection Method". The Ore Selection Method is the methodology that Whittle use to value the block using the specific grades included in each block and the relevant recoveries. This section explains two of the four possible options to determine the destination of a block (ore or waste). The other methods are variants of these two and can be found in detail in the software help (Dassault Systems, 2015).

2.6.1.1 Ore Selection by Cut-off

In cases where there is one payable element (or product) and just one processing method, ore is selected by comparing the grade of the material in the mining block under consideration with pre-calculated processing cut-offs. If the block does not satisfy the COG it is treated as waste. This pre-calculated processing cut-off takes the Equation 2-7 as the basis for the calculation. Assuming that O_o=0 and adding other considerations as follow:

Equation 2-23

$$x_c = \frac{Dilution * P_o * PCAF - Rehab}{[r * (V - R)] - ElementCost}$$

where:

Dilution: Mining Dilution
PCAF: Positional Processing Cost
Rehab: Rehabilitation Cost
ElementCost: Extra Processing Element Cost

If the block has more than one element, Whittle uses an approach that has a similar effect as applying an equivalent COG. The decision is based in Equation 2-24.

Equation 2-24

$$\frac{\sum grade_i}{\sum (cutoff\ grade)_i}$$

If the ratio defined in Equation 2-24 is greater than 1, the material is considered as ore. If the ratio is lower than 1, the material is treated as waste (Dassault Systems, 2015). In the case that Fe and Cu are two elements present in the block, there is a COG for Fe and there is another cut-off for Cu. Figure 2-2 shows a case where the shaded area may include material which is below the COG separately, however, if the analysis were to consider material which gives a positive cash flow using the contribution of both elements the material would become ore.

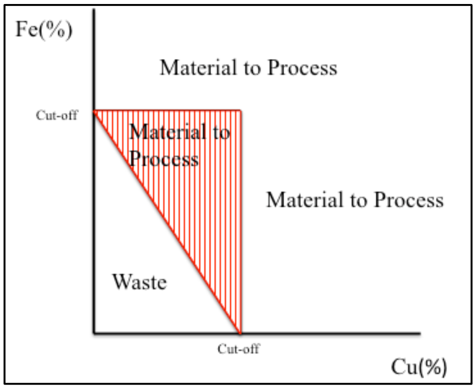

Figure 2-2: Shaded area representing the material below COGs separately

2.6.1.2 Ore Selection by Cash Flow

When ore is selected by cash flow, ore is selected by comparing the cash flow generated by processing the material versus the cash flow generated by mining the material as waste. If the cash flow from processing is higher then the material is treated as ore. Every block is treated as an independent object to maximize the cash flow. This is similar to the net smelter return method described by Rendu (Rendu, 2014) and introduced earlier.

In the case that there is just one element the cash flow and COG methods of ore selection will produce the same result. In the case that there is more than one element (which is usually the case) the effects are very different. Figure 2-3 shows the effect of applying a minimum COG to one of the elements using the Cash Flow Ore Selection Method.

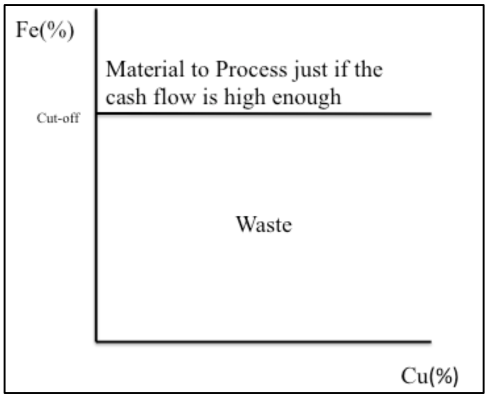

Figure 2-3: Effect of applying a minimum COG to one of the elements using Cash Flow Ore Selection Method

The figure shows that the Fe(%) element has a COG which means that all the material below that COG should be considered as waste and all the material above that COG should be evaluated using the cash flow to decide whether to send the material to the plant or to the waste dump. The Cu(%) grade does not have an impact on the decision of whether the material is ore or waste, however this element can increase the value of the block when calculating its cash flow.

Appendix C presents a detailed example of the impact of the use of these two different methodologies to find a specific COG.

2.6.2 Opportunity Cost Defined by Whittle Software

Whittle software does not directly use Lane's algorithm, however the methodology that the software applies was inspired by Lane's work. Whittle and Wharton (Whittle & Wharton, 1995) proposed the utilization of the idea of *opportunity cost* in COG optimization in monometallic deposits by introducing two costs in addition to the other defined as a cash costs (mining, processing, selling and general and administrative costs). These new costs are named "delay" (Cd) and "change"(Cc) costs.. The sum of Cd and Cc is known as the opportunity cost defined by Lane. (Lane, 1988).

Cd is the cost associated with a delay to process high-grade material by instead processing lower grade material. To calculate the delay cost, it is necessary to know the NPV for the remaining resource, and that value cannot be known without determining the cut-off year by year (or period by period), which again depends on the delay cost. The Cc is the cost associated with the scenario that in the future the sale price of the metal produced by the mine would be lower than today. It is the cost of processing high grades in the future rather than today when the price is higher. The calculation of Cc depends on the NPV for the remaining resources versus the NPV if the mine could process all the remainder material one year from now using all future economic condition. The differences of the NPVs correspond to the estimation of the Cc. If there is no change in the economic parameters in the future, Cc would be 0 (Whittle & Wharton, 1995). Cd and Cc are costs that cannot be known without knowing the cut-offs for the reminder of material in the mine. If Cd is known, based on a mine plan using marginal cut-off for example, this Cd can be optimized each year by trying a series of cut-offs and calculating the cash flow for a year production basis. This requires access to details of the remaining grade distribution. It has little significance when a single cut-off is involved.

2.6.3 Cut-off Optimization Process

The following are the general steps to optimize COG in Whittle: (Gemcom Software, 2005)

1. The first operation is to calculate the marginal COG for each period or year (in an annual mine plan), taking into account any economic circumstances that change with time, and store these cut-offs as a reference set. In most cases these economic circumstances do not change, for example the long-term metal price.
2. Next the marginal cut-offs are found for each element. The software searches for a new COG for the first year *that maximizes the NPV of the whole project.* While the software is doing this, it keeps the cut-offs for the other increments constant. When the program varies the cut-off for the first year, the time considered to mine the remaining material changes related to the original mine plan, and this changes the time at which it starts mining the remaining years' ore (metal). It is here when the delay and change cost appear to build the opportunity cost.
3. Having found the best cut-off for the first increment, the software starts a new search for the best cut-off for the second year and after that at the end of the years of the mine plan.

By changing the cut-offs for the later years there is a change in the NPV, and thus any delay and change costs associated with them, and the cut-off for the first increment is no longer optimal. Consequently, the software goes back to the beginning and optimizes the first increment again. This iterative approach is continued until no further increase in NPV can be obtained. The normal or most common number of passes is 3 or 4 (Gemcom Software, 2005).

Chapter 3

Block Model Analysis

This chapter presents an analysis of the Dominga project block model, supplied by Andesiron. This analysis supports the development of strategic mine plans that explore the application of various COG methods. The COG case study is presented in the next chapter.

3.1 Project Description

3.1.1 Location

The Dominga project is an Iron-Oxide Copper Gold (IOCG) deposit located approximately 70 km north of La Serena and 110 km south of Vallenar, Coquimbo Region (IV Region), Chile, see Figure 3-1.

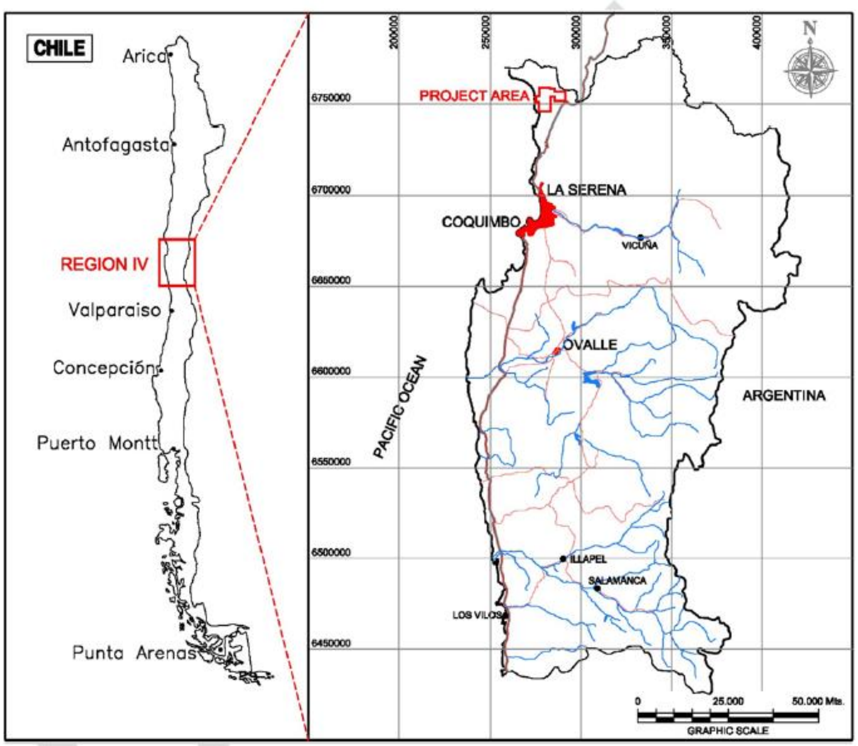

Figure 3-1: Dominga Project location (SRK Consulting (Chile) S.A. , 2013)

Dominga is located in a section of the Coastal Cordillera with elevations between 400m and 600m above sea level.

3.1.2 Project and Regional History

The prefeasibility study of the Dominga project was carried out in 2013. At the time of this thesis, Andesiron is conducting the feasibility study.

The Dominga project is located near other current and past iron ore producers including El Tofo, El Romeral and La Higuera. El Tofo is just a few kilometers to the south of Dominga. El Tofo started industrial scale operation early in the twentieth century, when it supplied high-grade iron ore to the Bethlehem Steel Corporation. Owned by Compañía de Aceros del Pacífico (CAP-CMP) since 1970, it has recently re-started operation. The high grade and very low contaminant ore of El Tofo is used to improve the bulk quality of the iron ore now extracted at El Romeral, another mine owned by CAP-CMP located approximately 20 km to the south of Dominga (SRK Consulting (Chile) S.A. , 2013). According to “Comision Chilena del Cobre” (COCHILCO), in 2008 the reserves of El Tofo are 2 million metric tonnes with an average iron content of 45%, 3.5 million metric tonnes from old stockpiles with a mean grade of 37% of iron content, and 3.1 million metric tons of alluvial resources with a mean grade of 17% of iron content (Comisión Chilena del Cobre (COCHILCO), 2008). Figure 3-2 shows some historic pictures from El Tofo.

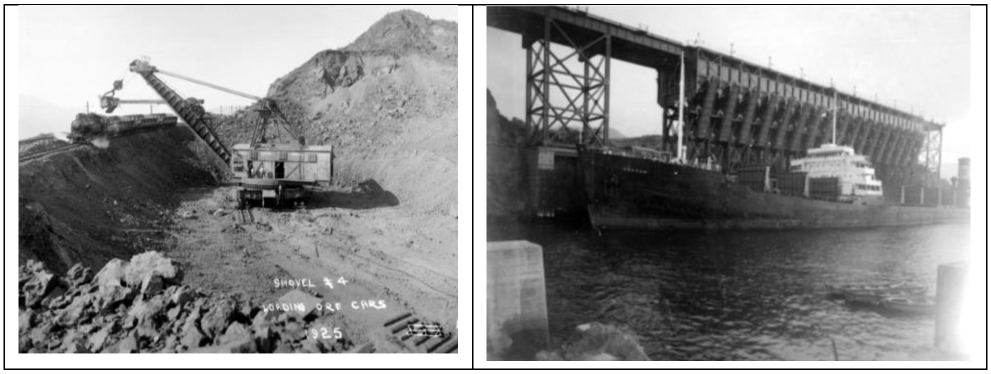

Figure 3-2: Left: Shovel working at El Tofo. Right: Port of El Tofo. (Direccion de Bibliotecas, Archivos y Museos, 2015)

El Romeral is an active mining project operated by CAP-CMP, located 22 kilometers to the northeast of La Serena, IV Region, Chile. It produces fine, lump and pellet feed, for domestic and foreign markets. Table 3-1 shows the characteristics of the product produced by El Romeral.

Product	**Fe% (iron content)**	**Size**	**Production 2014 (kton)**
Lump	61%	from 10mm. to 30 mm	3
Fine	62%	5% max. above 10mm	266
Pellet feed	66%, 67% or 68%	<44 microns	1,229

Table 3-1: Characteristics of the products produced by El Romeral (CAP Mineria) and production 2014 (Compañía Minera de Pacífico S.A., 2014).

3.1.3 Deposit Type

The project contemplates two main iron mineralization zones, Dominga Norte (DN) and Dominga Sur (DS). The two zones are separated by approximately 1 km and have lengths of nearly 2 km and widths of just over 1 km. Figure 3-3 shows a general satellite view of Dominga.

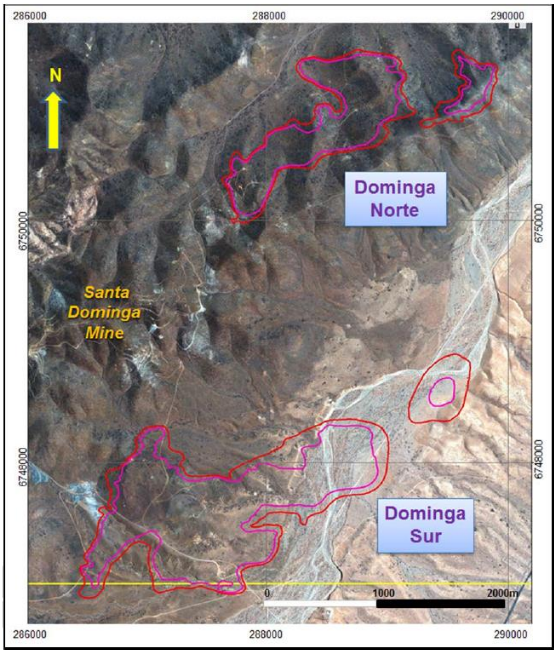

Figure 3-3: Satellite photograph of the deposit, (SRK Consulting (Chile) S.A. , 2013)

According to the feasibility study report (SRK Consulting (Chile) S.A. , 2013), magnetite mineralization and lesser amounts of pyrite-chalcopyrite are the main occurrences in both zones. DN is characterized by E-NE and E-W structural trends with fault-controlled iron-copper (Fe-Cu) mineralization represented by veins, breccias and mantos. At DS there are many outcrops with breccias, intense magnetite replacement and massive magnetite bodies. Copper is subordinate. The DN and DS deposits are characteristic of IOCG deposits. The deposits represent the evolution of a hydrothermal system that has affected the volcano-sedimentary andesitic rocks and to a lesser extent the dacitic and predominantly clastic sedimentary units. The IOCG deposits in Chile are part of a continuum ranging from iron-rich with subordinate copper to copper-rich with subordinate iron. Dominga mineralization is iron-rich with subordinate copper (SRK Consulting (Chile) S.A. , 2013).

3.2 Dominga Norte Block Model Description

Section 3.2.1 describes the block model for Dominga Norte.

3.2.1 Block Model Dimensions

Table 3-2 shows the coordinates of the block model for Dominga Norte.

	Dominga Norte			
Coordinate	**Minimum**	**Maximum**	**Size (m)**	**Numbers of Blocks**
East	287,200	290,000	10	280
North	6,749,500	6,751,800	10	230
Level	-700	710	15	94

Table 3-2: Coordinates block model Dominga Norte, datum PSAD56[1]

3.2.2 Tonnage-Grade Curve

The elements present in the block model are the Total Iron Ore content in percentage (FeT(%)), Magnetic Iron content in percentage (FeM(%)), Copper content in percentage (Cu(%)) and Gold content in parts per million (Au(ppm)). Table 3-3 shows the tonnage-grade values for Measured, Indicated and Inferred Resources for Dominga Norte Project.

Cut-off FeT(%)	Tonnes	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
>0	4,433,850,834	9.9	4.5	0.028	0.009
5	4,366,698,444	10.0	4.5	0.028	0.008
10	1,053,385,099	15.4	8.6	0.047	0.010
15	244,477,622	29.5	20.7	0.105	0.015
20	193,127,030	32.8	23.6	0.118	0.016
25	164,988,185	34.6	25.1	0.124	0.016
30	134,017,910	36.2	26.2	0.128	0.016
35	77,691,449	38.8	27.4	0.136	0.016
40	23,093,969	42.4	28.4	0.153	0.017
45	2,193,053	47.3	28.6	0.153	0.015

Table 3-3: Dominga Norte tonnage-grade table Measured + Indicated + Inferred resources

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[1] Provisional South American Datum 1956

To define reserves, it is important to note that only Measured and Indicated resources are considered, consistent with National Instrument 43-101. The percentage of Measured and Indicated material contained in Dominga Norte is shown in Table 3-4.

Cut-off FeT(%)	**%(Measured+Indicated)**
10	62.6
15	89.7
20	90.5

Table 3-4: Proportion of (Measured+Indicated) resources based on FeT(%)

As can be seen in the table above, for COG of 15%FeT, close to 10% of the resource is inferred.

Table 3-5 shows the Measured and Indicated Resources for Dominga Norte.

Cut-off FeT(%)	**Tonnes**	**FeT (%)**	**FeM (%)**	**Cu (%)**	**Au (ppm)**
>0	2,379,878,644	10.7	5.0	0.034	0.010
5	2,356,490,573	10.8	5.1	0.034	0.010
10	658,958,250	17.4	10.2	0.059	0.012
15	219,199,662	29.8	20.8	0.108	0.015
20	174,774,955	33.1	23.6	0.121	0.016
25	150,467,473	34.8	25.0	0.126	0.016
30	123,788,593	36.3	26.1	0.131	0.016
35	72,730,015	38.9	27.3	0.139	0.016
40	22,494,503	42.4	28.3	0.154	0.017
45	2,176,712	47.4	28.6	0.153	0.015

Table 3-5: Dominga Norte tonnage-grade table Measured + Indicated resources

Note that just Measured and Indicated resources are going to be used for all analysis beyond this point. Figure 3-4 shows the tonnage-grade curve based on Table 3-5.

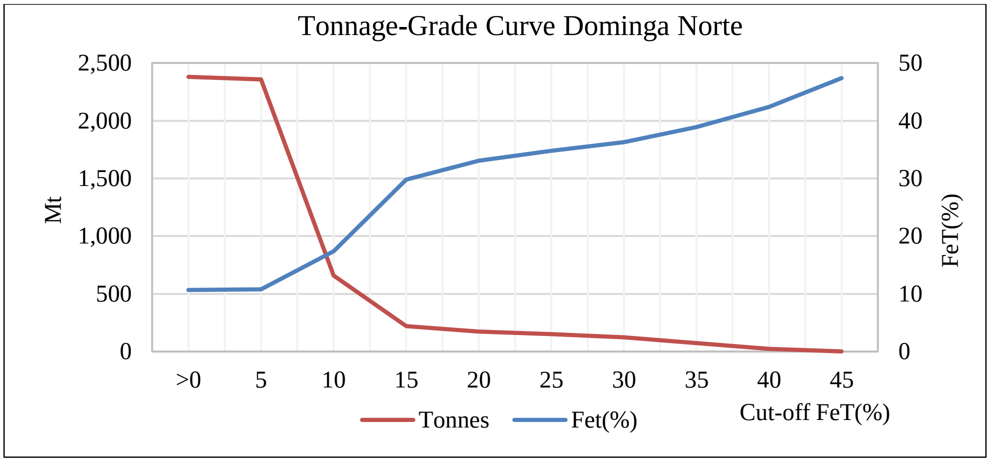


Figure 3-4: Tonnage grade curve Dominga Norte Measured and Indicated resource

3.2.3 Rocktypes

The Dominga Norte block model contains 6 different rocktypes including the code for air (-1). These are presented in Table 3-6.

	Original Code in Block Model
Mineralized Gravel	106
Primary (Fe,Cu)	401
Primary (Fe), Transition (Cu)	402
Transition (Fe,Cu)	403
Oxide (Fe,Cu)	404
Air	-1

Table 3-6: Rocktypes in Dominga Norte block model

For metallurgical reasons presented in the Bridge Engineering Report by Andesiron (Andesiron, 2014), only three of these five rocktypes are considered as possible ore material. These rocktypes are 401-402-403 and are highlighted in the above table.

3.2.4 Basic Statistics

Table 3-7 presents basic statistics for FeT(%)-FeM(%)-Cu(%)-Au(ppm) contained in the three ore rocktypes (401-402-403) for Measured and Indicated resources:

	FeT(%)	FeM(%)	Cu(%)	Au(ppm)
Number of Blocks	548,267	548,267	548,267	548,267
Average Grade	10.34	4.72	0.032	0.009
Minimum Grade	1.87	0	0	0
Maximum Grade	53.89	42.71	2.752	1.757

Table 3-7: Basic statistics for Dominga Norte, Measured and Indicated resources for rocktypes 401-402-403

3.2.4.1 Basic Statistics by Rocktype

Table 3-8 shows the number of blocks, average, minimum and maximum grades for rocktypes 401, 402 and 403 in Dominga Norte.

Rocktype		FeT(%)	FeM(%)	Cu(%)	Au(ppm)
401	Number of Blocks	457,537	457,537	457,537	457,537
	Average Grade	10.25	5	0.031	0.009
	Minimum Grade	1.87	0.02	0	0
	Maximum Grade	51.67	42.72	2.752	1.757
402	Number of Blocks	27,323	27,323	27,323	27,323
	Average Grade	10.93	4.92	0.037	0.009
	Minimum Grade	3.02	0.03	0	0
	Maximum Grade	48.52	40.91	1.385	0.551
403	Number of Blocks	40,784	40,784	40,784	40,784
	Average Grade	10.69	2.79	0.039	0.01
	Minimum Grade	3.13	0.02	0	0
	Maximum Grade	53.88	26.34	1.368	0.523

Table 3-8: Basic Statistics, Measured and Indicated resources, rocktype 401-402-403, Dominga Norte considering FeT(%)>0

From Table 3-8, rocktype 401 represents 87% of the ore blocks, 402 represents 5%, and 403 represents 8%. The maximum grade of FeT(%), 53.9%, is associated with rocktype 403. The average grade of FeT(%) is similar for the 3 rocktypes. For FeM(%), rocktype 403 has a considerably lower average grade, which corresponds to a Transitional material. The maximum FeM(%) grade corresponds to rocktype 401. Figures 3-5 through 3-7 show a histogram and logprobability (log-prob) curve for FeT(%) for rocktypes 401-402-403. The graphs for the other elements can be found in Appendix A.

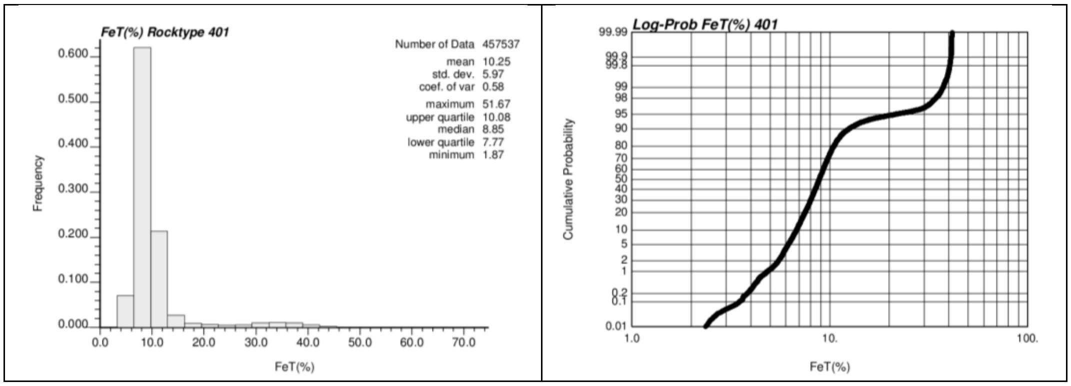


Figure 3-5: Left: Histogram for FeT(%) for rocktype 401, Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Norte

Graphs for rocktype 402 are shown in Figure 3-6.

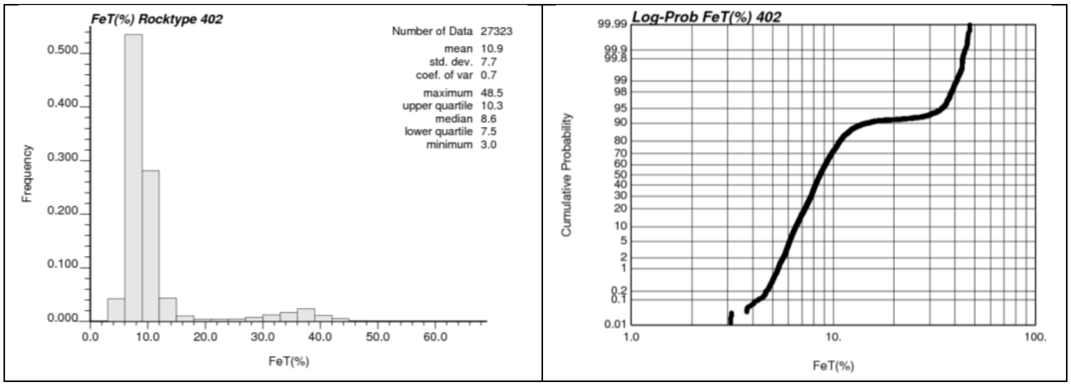


Figure 3-6: Left: Histogram for FeT(%) for rocktype 402, Right: Log-prob Graph rocktype 402, Measured and Indicated resources, Dominga Norte

Graphs for rocktype 403 are in Figure 3-7.

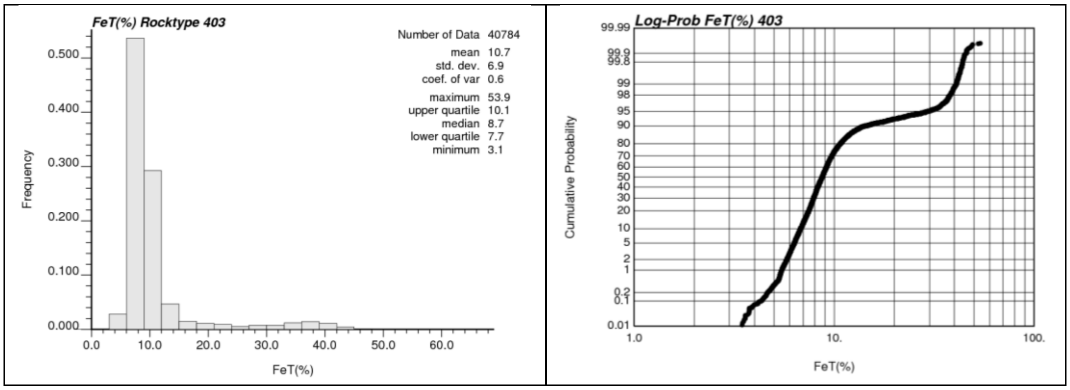


Figure 3-7: Left: Histogram for FeT(%) for rocktype 403, Right: Log-prob Graph rocktype 403, Measured and Indicated resources, Dominga Norte

From the figures above, the log-prob graph shows that 3 different populations of iron grades exist within the rocktypes 401, 402 and 403, which are shown in Table 3-9.

Rocktype					
401		**402**		**403**	
Population	**Range FeT**	**Population**	**Range FeT**	**Population**	**Range FeT**
1	0%-12%	1	0%-13%	1	0%-13%
2	12%-31%	2	13%-32%	2	13%-32%
3	31%-100%	3	32%-100%	3	32%-100%

Table 3-9: Graph FeT(%) population rocktype 401-402-403, Dominga Norte

These populations are important and will be used for further block model analysis related to transformation of a model with variable recoveries to a model with constant recoveries.

3.2.5 Metallurgical Recovery

The recoveries associated with the ore rocktypes (401, 402, 403) are shown in Table 3-10.

	Recovery (%)		
Code	**FeT(%)**	**Cu(%)**	**Au(ppm)**
401	see Equation A	75	60
402	see Equation A	75	60
403	see Equation B	50	0

Table 3-10: Recoveries for FeT(%), Cu(%) and Au(ppm) in Dominga Norte

where Equation A:

$$FeT\ Recovery\ = 8 * \frac{FeT(\%) - FeM(\%)}{FeT(\%)} + \ 99 * \frac{FeM(\%)}{FeT(\%)}$$

and Equation B:

$$FeT\ Recovery\ = 24 * \frac{FeT(\%) - FeM(\%)}{FeT(\%)} + \ 95 * \frac{FeM(\%)}{FeT(\%)}$$

where:

$FeT(\%)$ = Total iron content in percentage

$FeM(\%)$ = Magnetic iron content in percentage.

Equations A and B are dependent on two variables. For rocktypes 401 and 402 recoveries for Cu(%) and Au(%) are constants (75% and 60% respectively). For rocktype 403, Cu(%) recovery is 50%.

Figures 3-8 through 3-10 show a histogram and log-prob curve for the recovery for rocktypes 401-402-403.

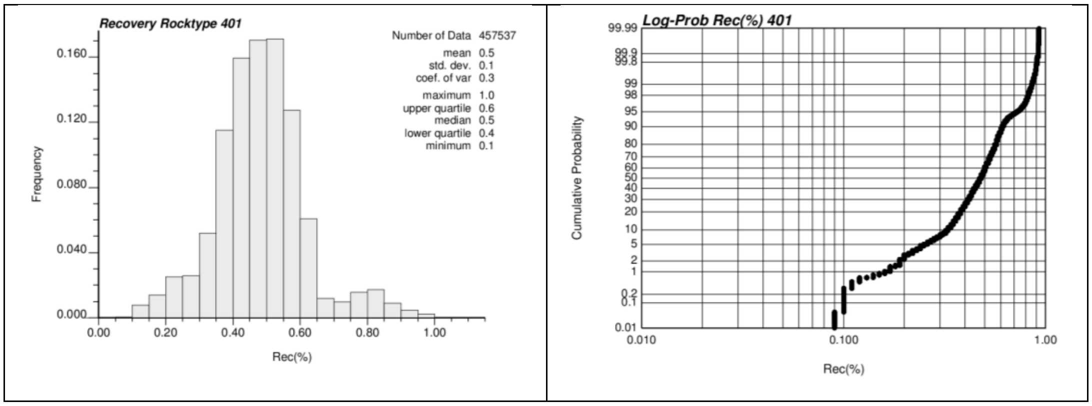


Figure 3-8: Left: Histogram for recovery for rocktype 401, Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Norte

It can be seen in the graph above and also can be deduced from Equation A, the lowest recovery value (0.1), is achieved when magnetic iron content is very low. The histogram shows a mean value of 50% recovery for iron and has a Gaussian distribution. The log-prob graph shows that 3 different populations of recoveries exist for rocktype 401 which are indicated in the Table 3-11.

For rocktype 402, the graphs are:

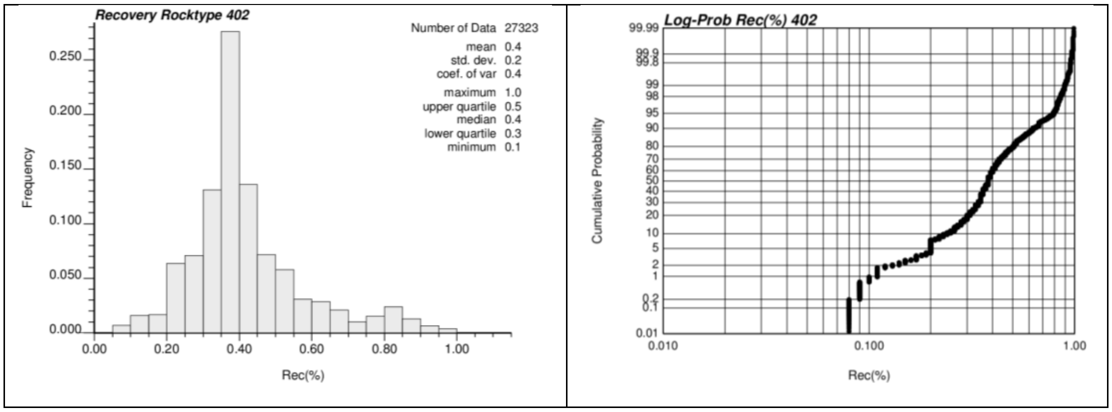


Figure 3-9: Left: Histogram for Recovery for rocktype 402, Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Norte

The histogram shows a mean value of 40% recovery for iron with a Gaussian distribution. The log-prob graph shows that 3 different populations of recoveries exist for rocktype 402 which are shown in the Table 3-11.

For rocktype 403, the graphs are:

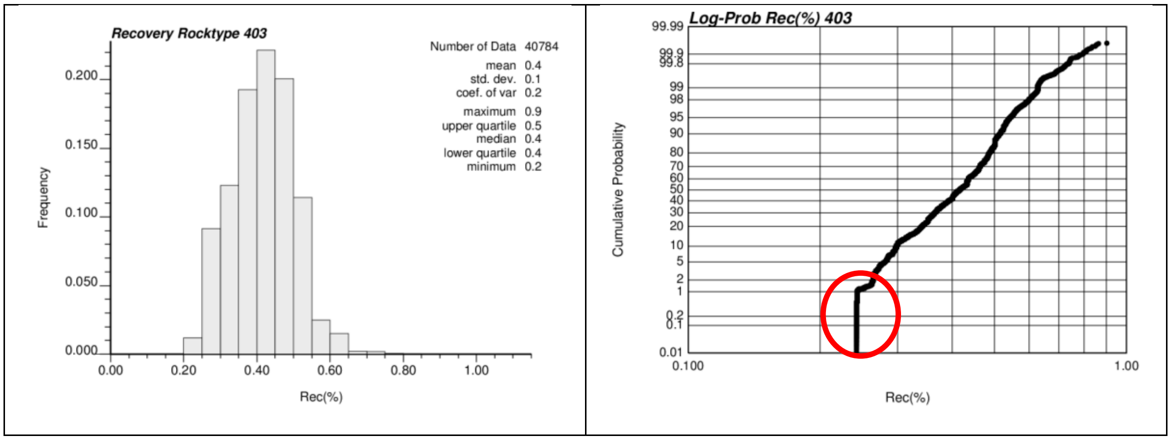


Figure 3-10: Left: Histogram for recovery for rocktype 403, Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte

The histogram shows a mean value of 40% recovery for total iron and a Gaussian distribution. The log-prob graph shows that one recovery population exists. The red circle shows a constant recovery of 24% that is related to low grades of magnetic iron (FeM(%) < 0.037).

Table 3-11 presents all the populations that were defined in the graphs above.

Rocktype					
401		**402**		**403**	
Population	Range Recovery	**Population**	Range Recovery	**Population**	Range Recovery
1	0%-32%	1	0%-40%	1	0%-100%
2	32%-70%	2	40%-80%		
3	70%-100%	3	80%-100%		

Table 3-11: Graph Recovery% population rocktype 401-402-403, Dominga Norte

3.3 **Dominga Sur Block Model Description**

The following section describes the block model for Dominga Sur.

3.3.1 Block Model Dimensions

Table 3-12 shows the coordinates of the block model for Dominga Sur:

	Dominga Sur			
Coordinate	**Minimum**	**Maximum**	**Size (m)**	**Number of blocks**
East	286,000	290,000	10	400
North	6,746,510	6,749,500	10	299
Level	-700	710	15	94

Table 3-12: Coordinates block model Dominga Sur, datum PSAD56

3.3.2 Tonnage-Grade Curve

Table 3-13 shows the tonnage-grade values for Measured, Indicated and Inferred resources for Dominga Sur.

Cut-off FeT(%)	Tonnes	FeT(%)	FeM(%)	Cu(%)	Au(ppm)
0	10,482,663,286	11.77	6.32	0.041	0.009
5	10,450,249,976	11.79	6.34	0.041	0.009
10	4,967,282,439	15.65	9.31	0.056	0.011
15	1,794,891,498	22.43	14.50	0.068	0.012
20	922,015,477	27.40	18.43	0.073	0.013
25	577,021,375	30.43	20.89	0.076	0.013
30	265,937,474	33.87	22.78	0.078	0.013
35	70,730,639	38.75	24.00	0.080	0.014
40	17,243,763	44.83	23.83	0.072	0.013
45	6,426,480	49.69	28.26	0.061	0.014
50	2,334,192	53.71	29.01	0.044	0.011

Table 3-13: Dominga Sur Tonnage-Grade Measured + Indicated + Inferred resources

As with Dominga Norte, only Measured and Indicated materials will be used in estimating reserves. The proportion of Measured and Indicated material at different cut-off grades is shown in Table 3-14.

Cut-off FeT(%)	**%(Measured+Indicated)**
10	51.2
15	66.5
20	70.4
25	71.7

Table 3-14: Proportion of (Measured+Indicated) resources based in FeT(%)

As can be seen in Table 3-14, for a cut-off grade of 15%, 33.5% of the resources are Inferred.

Table 3-15 shows the Measured and Indicated Resources for Dominga Sur.

Cut-off FeT(%)	**Tonnes**	**FeT(%)**	**FeM(%)**	**Cu(%)**	**Au(ppm)**
0	4,223,267,876	13.52	7.54	0.044	0.010
5	4,202,363,993	13.57	7.57	0.044	0.010
10	2,545,450,739	17.06	10.24	0.054	0.011
15	1,194,468,683	22.82	14.47	0.065	0.012
20	649,500,959	27.52	17.78	0.071	0.012
25	413,452,161	30.49	19.95	0.073	0.012
30	187,264,098	34.12	21.61	0.073	0.012
35	53,049,892	39.23	22.64	0.077	0.013
40	15,665,821	44.86	23.13	0.074	0.014
45	5,794,631	49.76	26.56	0.063	0.015
50	2,318,373	53.71	28.97	0.044	0.011

Table 3-15: Dominga Sur Tonnage-Grade Measured + Indicated resources

Dominga Sur mineralization extends into a CAP-owned property. In Figure 3-11, the property line is represented by the yellow (North coordinate= 6,747,000). In this thesis, all the material falling inside the CAP property is considered as waste (grades of the blocks set as 0).

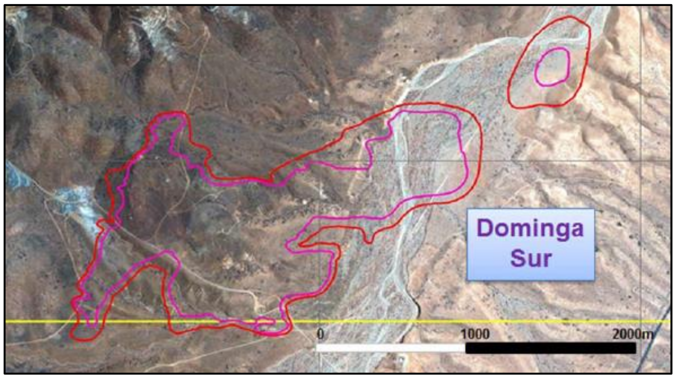


Figure 3-11: Dominga-CAP property line (in yellow) to the south of Dominga Sur

Table 3-16 shows the tonnage-grade curve of Measured and Indicated resources inside the Dominga property boundary.

Cut-off FeT(%)	Tonnes	FeT(%)	FeM(%)	Cu(%)	Au(ppm)
0	4,184,542,889	13.38	7.47	0.043	0.010
5	4,164,089,382	13.43	7.50	0.043	0.010
10	2,516,930,214	16.85	10.14	0.053	0.011
15	1,178,566,141	22.50	14.31	0.064	0.012
20	641,137,928	27.15	17.60	0.070	0.012
25	408,001,976	30.06	19.72	0.071	0.012
30	183,790,299	33.47	21.30	0.071	0.012
35	51,865,765	38.31	22.31	0.076	0.013
40	15,150,280	43.29	22.46	0.074	0.013
45	5,421,392	46.56	25.02	0.062	0.014

Table 3-16: Dominga Sur Tonnage-Grade Measured + Indicated resources, considering material inside CAP property as waste.

The material inside the CAP property is treated as waste.

Measured and Indicated resources, not considering the grades of material inside CAP property, are going to be used for Dominga Sur for all the analysis beyond this point. Figure 3-12 shows the tonnage-grade curve from Table 3-16.

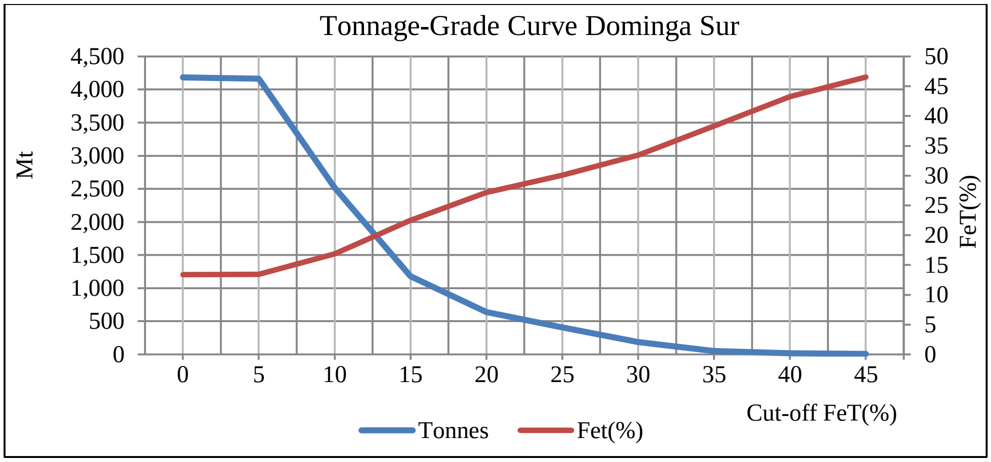


Figure 3-12: Tonnage grade curve Dominga Sur Measured and Indicated resource

For a cut-off of 35%FeT there are just 51Mt of material. The tonnage curve show that approximately 50% of the tonnage is below 12%FeT.

3.3.3 Rocktypes

The Dominga Sur block model contains seven different rocktypes including the code for air (-1). Table 3-17 shows rocktypes included in the Dominga Sur Block Model.

	Original Code in Block Model
Mineralized Gravel	106
Gravel	107
Primary (Fe,Cu)	401
Primary (Fe), Transition (Cu)	402
Transition (Fe,Cu)	403
Oxide (Fe,Cu)	404
Air	-1

Table 3-17: Rocktypes in Dominga Sur block model

As with Dominga Norte, only three of these rocktypes are considered as ore types: 401-402-403.

3.3.4 Basic Statistics

Table 3-18 shows the basic grade statistics for FeT(%)-FeM(%)-Cu(%)-Au(ppm) of these 3 ore rocktypes (401-402-403) for Measured and Indicated resources falling within the Dominga property and for Measured and Indicated resources:

	FeT(%)	**FeM(%)**	**Cu(%)**	**Au(ppm)**
Number of Blocks	828,221	828,221	828,221	828,221
Average Grade	13.35	8.06	0.044	0.010
Minimum Grade	0.35	0.07	0	0
Maximum Grade	62.77	61.12	1.799	1.279

Table 3-18: Basic statistics for Dominga Sur, Measured and Indicated resources for rocktypes 401-402-403 not considering CAP

There are 828,221 blocks containing measured or indicated resources for rocktypes 401-402-403. The minimum iron grade is 0.35% and the maximum is 62.77%. Some blocks contain no copper and/or gold.

3.3.4.1 Basic Statistics by Rocktype

Table 3-19 shows the number of blocks, average, minimum and maximum grades for rocktypes 401, 402 and 403 in Dominga Sur.

Rocktype		**FeT(%)**	**FeM(%)**	**Cu(%)**	**Au(ppm)**
401	Number of Blocks	745,305	745,305	745,305	745,305
	Average Grade	12.99	8.19	0.043	0.01
	Minimum Grade	0.35	0.16	0	0
	Maximum Grade	62.77	61.12	1.799	1.279
402	Number of Blocks	22,260	22,260	22,260	22,260
	Average Grade	15.87	9.97	0.046	0.01
	Minimum Grade	5.11	0.93	0.005	0
	Maximum Grade	49.95	42.23	0.549	0.41
403	Number of Blocks	60,656	60,656	60,656	60,656
	Average Grade	16.85	5.75	0.051	0.01
	Minimum Grade	4.75	0.07	0.004	0
	Maximum Grade	59.23	28.95	0.663	0.419

Table 3-19: Basic statistics for Dominga Sur by rocktype

Figures 3-13 through 3-15 show a histogram and log-prob curve for the total iron for rocktypes 401-402-403. The graphs for the other elements can be found in Appendix A.

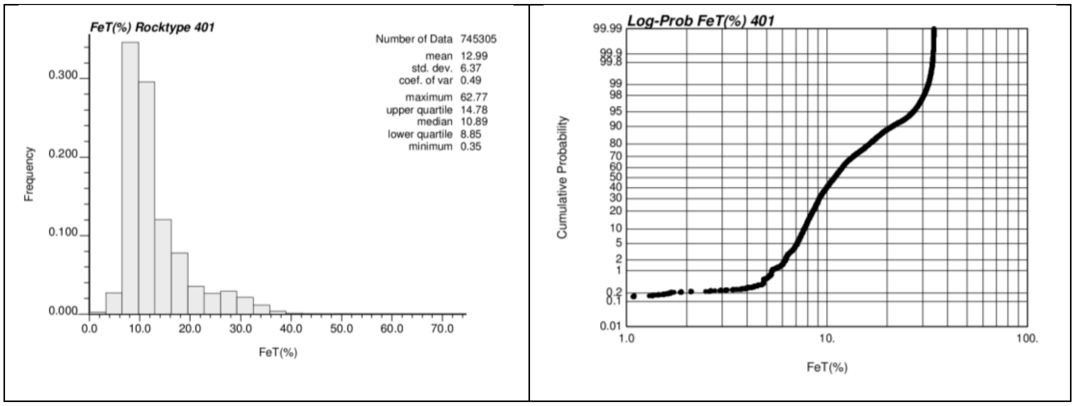


Figure 3-13: Left: Histogram for recovery for rocktype 401, Right: Log-prob graph rocktype 401, Measured and Indicated Resources, Dominga Sur, considering material inside CAP property as Waste.

The histogram shows a mean value of 12.9% for FeT. The log-prob graph shows that three different populations of iron content exist inside rocktype 401 which are shown in Table 3-20:

For rocktype 402, the graphs are:

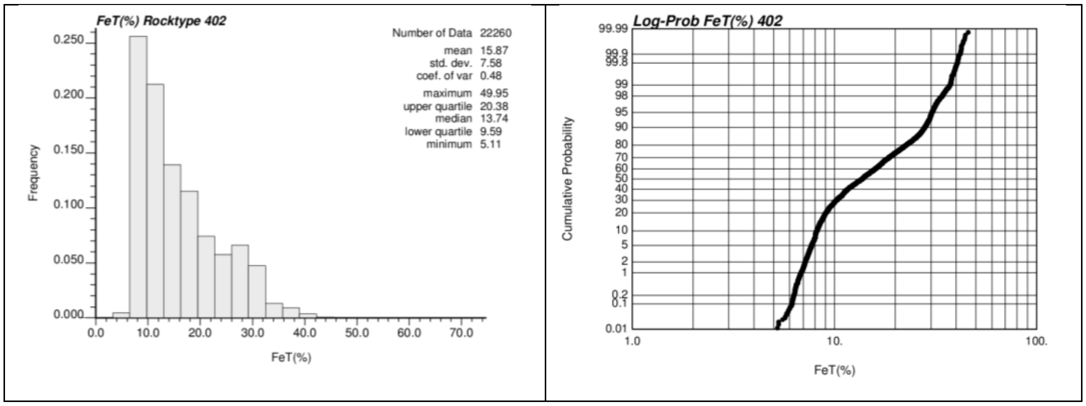


Figure 3-14: Left: Histogram for recovery for rocktype 402, Right: Log-prob graph rocktype 402, Measured and Indicated Resources, Dominga Sur, considering material inside CAP property as waste.

The histogram shows a mean value of 15.9% for total iron. The log-prob graph shows that three different populations of iron content exist inside rocktype 402 which are shown in Table 3-20.

For rocktype 403, the graphs are:

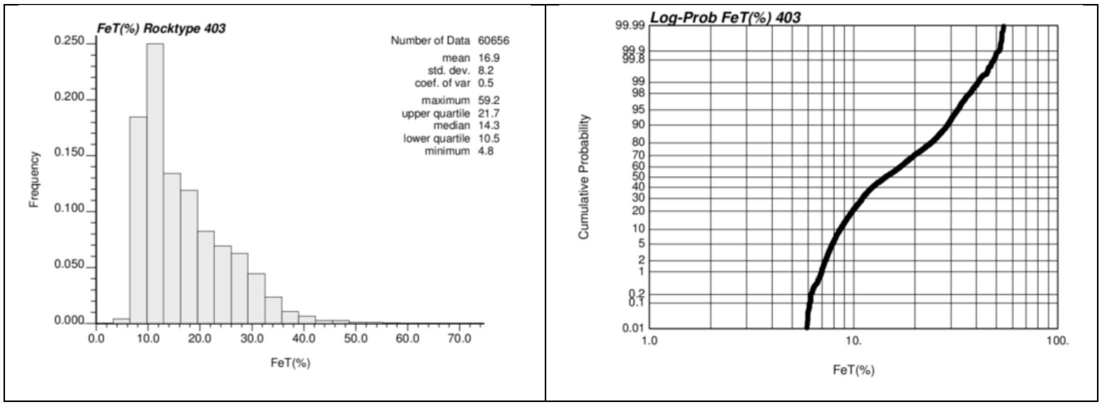


Figure 3-15: Left: Histogram for recovery for rocktype 403, Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Sur, considering material inside CAP property as waste.

The histogram in Figure 3-15 shows a mean value of 16.85% total iron. The log-prob graph shows that 3 different populations of FeT(%) grades exist for rocktype 403. However, for this particular rocktype, there is a constraint on recoverable magnetic iron. If the block has less than 8% magnetic iron (FeM(%)), the iron is not recoverable. This is a constraint that should be taken into account when developing the mine plan. For this reason, the block model has been modified with the grades of iron and magnetic iron for blocks that have less than 8% FeM being zeroed (just for rocktype 403). However, the grades of copper and gold have not been modified. If the block contains copper and gold grades that pay for the mining and processing cost, the block should be considered as ore. Figure 3-16 shows the basic statistics for the rocktype 403 after removing iron grades in blocks with less than 8% magnetic iron.

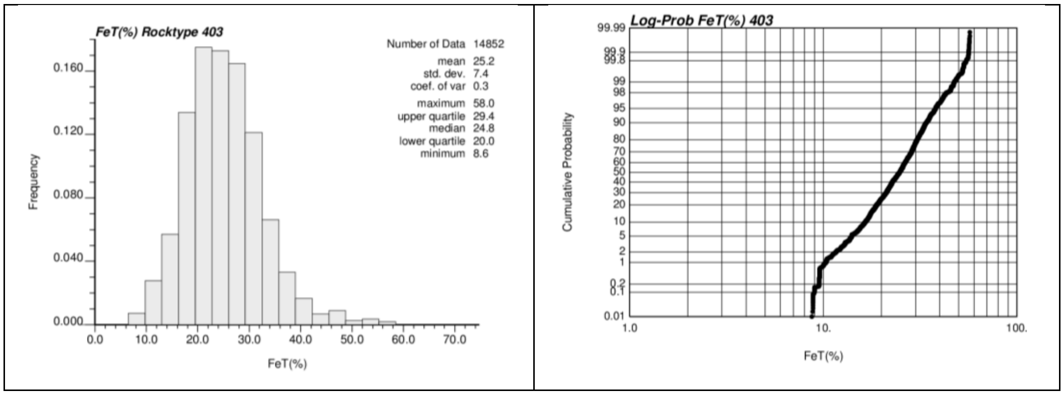


Figure 3-16: Left: Histogram for recovery for rocktype 403, Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Sur, considering material inside CAP property as waste and not considering iron grades which contain less than 8% of magnetic iron.

From the figures above, the log-prob graph shows that different populations of iron grades exist within rocktypes 401, 402 and for 403, which are shown in Table 3-20.

Rocktype					
401		**402**		**403**	
Population	**Range FeT**	**Population**	**Range FeT**	**Population**	**Range FeT**
1	0%-13%	1	0%-9%	1	0%-100%
2	13%-27%	2	9%-28%		
3	27%-100%	3	28%-100%		

Table 3-20: Graph FeT(%) population rocktype 401-402-403, Dominga Sur

As noted, blocks of rocktype 403 with less than 8% FeM are assumed to have zero iron content but maintain their copper and gold grades. This is important when applying Cut-off Ore Selection Method in Whittle, and is necessary to ensure a correct analysis.

3.3.5 Metallurgical Recovery

The Dominga Sur block model contains seven different rocktypes including the code for air (-1) as shown in Table 3-17. The recoveries for FeT(%), Cu(%) and Au(ppm) are the same for Dominga Norte and Dominga Sur shown in the Table 3-10.

Figure 3-17 through 3-19 show a histogram and log-prob curve for the recovery for FeT(%) for rocktypes 401-402-403 from Equations A and B.

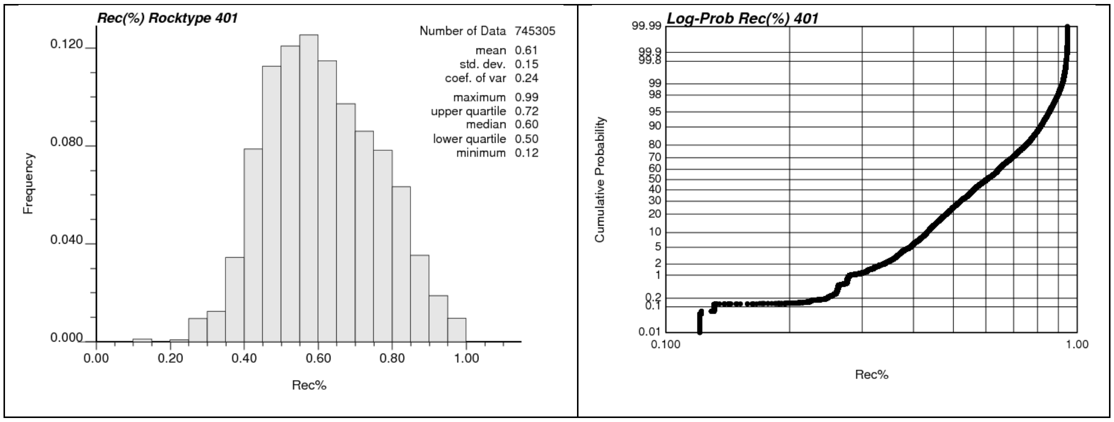


Figure 3-17: Recovery for rocktype 401 Dominga Sur, Measured and Indicated resources, No CAP, FeT>0%

It can be seen in the graph above, and also can be deduced from the Equation A, the lowest recovery value is 12%. The histogram shows a mean value of 61% recovery for FeT. The log-prob graph shows that 3 different populations of recoveries exist for rocktype 401.

For rocktype 402, the graphs are the following.

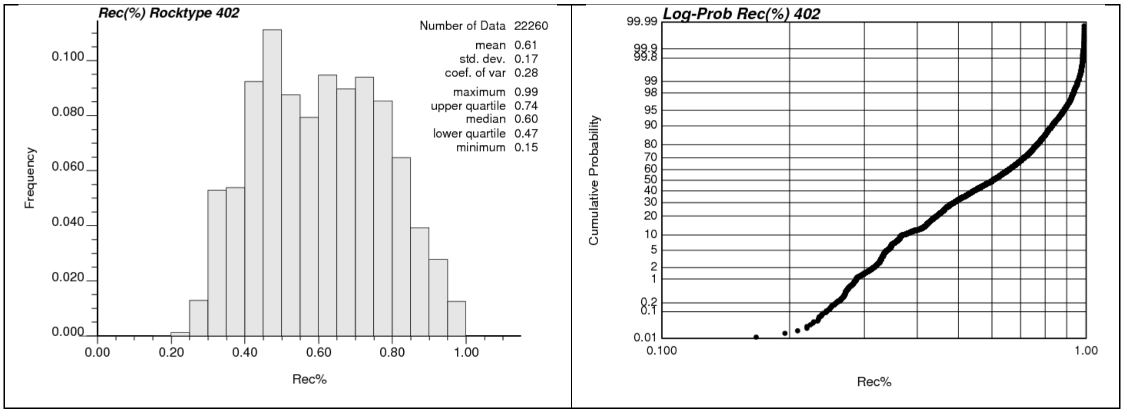


Figure 3-18: Recovery for rocktype 402 Dominga Sur, Measured and Indicated resources, No CAP, FeT>0%

As can be seen in the graph above, and also can be deduced from the Equation A, the lowest recovery value is 15%. The histogram shows a mean value of 61% recovery for FeT(%). The log-prob graph shows that 2 different populations of recoveries exist for rocktype 402.

For rocktype 403, the graphs are the following (considering only FeT(%) which has greater than 8% FeM).

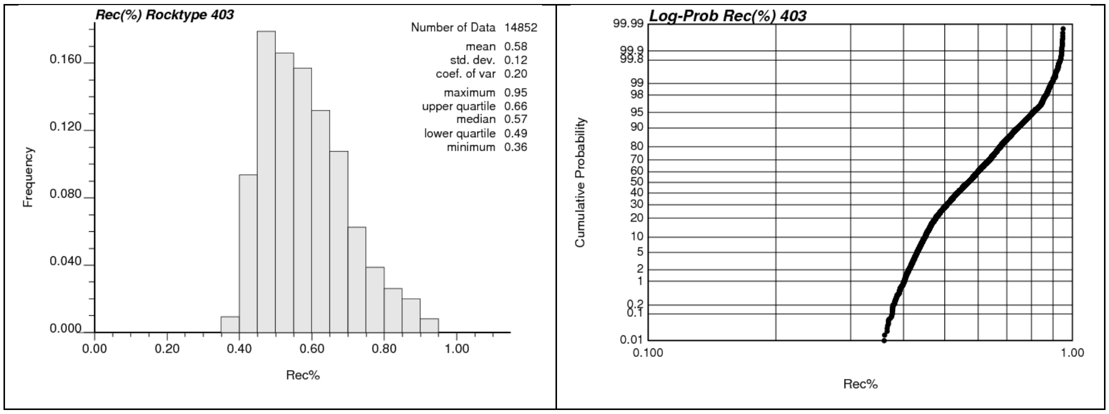


Figure 3-19: Recovery for rocktype 403 Dominga Sur, Measured and Indicated resources, No CAP, FeT>0%, No FeM<8%

As can be seen in Figure 3-19, and also can be deduced from the Equation B, the lowest recovery value is 36%. The histogram shows a mean value of 58% recovery for FeT(%). The log-prob graph shows that 3 populations of recoveries exist for rocktype 403. Table 3-21 presents all the populations defined in the graphs above.

Rocktype					
401		**402**		**403**	
Population	**Range Recovery**	**Population**	**Range Recovery**	**Population**	**Range Recovery**
1	0-0.33	1	0-0.8	1	0-0.49
2	0.33-0.83	2	0.8-1	2	0.49-0.83
3	0.83-1			3	0.83-1

Table 3-21: Graph recovery(%) population rocktype 401-402-403, Dominga Sur

3.4 From Variable Recovery Model to Constant Recovery Model

In order to use COGO in Whittle Software, it is necessary to have constant recoveries. This is not the case for the Dominga project, where iron (the main product) has variable recoveries. This is because the calculation of the COG is a function of the recovery, and the software cannot apply COGO to a variable recovery that is function of two variables (FeT(%) and FeM(%)). For this reason it is necessary to transform the recovery model from variable to constant. This problem can be solved in many ways. In this thesis three methods are analyzed and one of them is selected for further development work.

1. ***Base Case:*** Original block model rocktypes using variable recovery for iron. Equation A and B are used to determine iron recovery which means that is a model based on variable recoveries.
2. ***Model 1: Rocktype Populations based on Recovery Distribution***: The first procedure is to split the rocktype population based on the iron recovery population inside the rocktype. After this, calculate the mean recovery for each population and use that value for recovery.
3. ***Model 2: Rocktype Populations based on Total Iron (FeT) Distribution***: The second procedure is to split the rocktype based on the iron content then calculate the recovery for each population and then calculate the mean recovery.
4. ***Model 3: Rocktype Populations based on FeM/FeT Distribution***: The third procedure is to split the rocktype based on the ratio FeM/FeT then calculate the recovery for each population and then calculate the mean recovery.

3.4.1 Dominga Norte

3.4.1.1 Model 1: Rocktype Populations Based on Recovery Distribution

Table 3-22 shows each rocktype with a separate sub-rocktype associated to the recovery distribution ranges obtained in Section 3.3. The right side of the table presents the recovery associated with each sub-rocktype.

Rocktype	Population	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
401	1	4011	>0%-32%	42,185	0.24
	2	4012	>32%-70%	388,870	0.48
	3	4013	>70%-100%	26,482	0.81
Rocktype	Population	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
402	1	4021	>0%-40%	16,460	0.32
	2	4022	>40%-80%	9,622	0.52
	3	4023	>80%-100%	1,241	0.86
Rocktype	Population	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
403	1	4031	>0%-100%	40,784	0.42

Table 3-22: Average recovery from rocktype populations based in recovery distribution

The average recovery for sub-rocktype 4031 should not consider blocks FeM(%) with grades less than 8%. If this constraint is considered in the calculation of the mean recovery, the mean recovery value changes to the following for the rocktype 403 (see Table 3-23).

Rocktype	Population	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
403	1	4031	>0%-100%	40,784	0.52

Table 3-23: Average recovery from rocktype populations based in recovery distribution, not considering blocks with less than 8% FeM

3.4.1.2 Model 2: Rocktype Populations Based on Iron Grade Distribution

Table 3-24 shows every rocktype with a separate sub-rocktype associated with the total iron grade distribution ranges obtained above in this thesis. The right side of the table presents the recovery associated with each sub-rocktype.

Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT(%) Recovery
401	1	4011	>0%-12%	404,957	0.45
	2	4012	>12%-31%	36,569	0.62
	3	4013	>31%-100%	16,011	0.80
Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT(%) Recovery
402	1	4021	>0%-13%	24,123	0.37
	2	4022	>13%-32%	1,518	0.62
	3	4023	>32%-100%	1,682	0.78
Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT(%) Recovery
403	1	4031	>0%-13%	35,989	0.41
	2	4032	>13%-32%	2,992	0.45
	3	4033	>32%-100%	1,803	0.45

Table 3-24: Average recovery from rocktype populations based on iron grade distribution

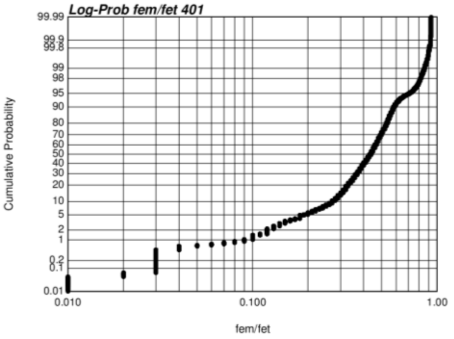
The average recoveries for sub-rocktype 4031 correspond to not considering blocks with grades of FeM(%) less than 8%. If this constraint is considered in the calculation of the mean recovery, this value changes for rock type 403 (see Table 3-25). Using the FeM>8% processing constraint, population 4031 doesn't have any processable blocks because all the blocks in this population have FeM < 8%.

Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT Recovery
403	2	4032	>13%-32%	2,992	0.57
	3	4033	>32%-100%	1,803	0.50

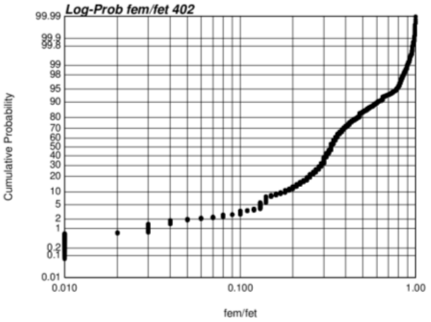
Table 3-25: Average recovery from rocktype populations based on iron grade distribution, not considering blocks with less than 8% FeM

3.4.1.3 Model 3: Rocktype Populations Based on FeM/FeT distribution

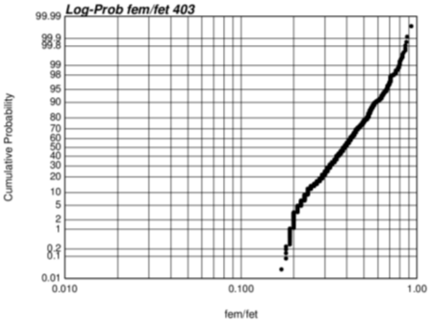
Table 3-26 shows every rocktype with a separate sub-rocktype associated with the FeM/FeT ranges obtained with the following log-prob graphs. The right side of the table presents the recovery associated with each sub-rocktype.



Population	Range FeM/FeT
1	0%-0.3%
2	0.3%-0.7%
3	0.7%-1%



Population	Range FeM/FeT
1	0%-0.3%
2	0.3%-0.8%
3	0.8%-1%



Population	Range FeM/FeT
1	0%-0.25%
2	0.25%-1%

Table 3-26: Graphs Log-prob ratio FeM/FeT for rocktypes 401-402-402. Rocktype 403 FeM/FeT considering only blocks with FeM > 8%

Table 3-27 shows the mean recoveries associated with the exercise before:

Rocktype	Population	Sub-Rocktype	Range FeM/FeT	Mean Recovery
401	1	4011	0%-0.3%	0.28
	2	4012	0.3%-0.7%	0.49
	3	4013	0.7%-1%	0.82
Rocktype	Population	Sub-Rocktype	Range FeM/FeT	Mean Recovery
402	1	4021	0%-0.3%	0.28
	2	4022	0.3%-0.8%	0.47
	3	4023	0.8%-1%	0.87
Rocktype	Population	Sub-Rocktype	Range FeM/FeT	Mean Recovery
403	1	4031	0%-0.25%	0.35
	2	4032	0.25%-1%	0.48

Table 3-27: Average recovery from rocktype populations based on FeM/FeT distribution

The mean recovery for sub-rocktype 4031 should not consider blocks with grades for FeM less than 8%. If this constraint is considered in the calculation of the mean recovery, this value changes to the following for the rocktype 403 (see Table 3-28).

Rocktype	Population	Sub-Rocktype	Range FeM/FeT	Mean Recovery
403	1	4031	0%-0.25%	0.40
	2	4032	0.25%-1%	0.55

Table 3-28: Average recovery from rocktype populations based on FeM/FeT distribution, not considering blocks with less than 8% FeM

To assess the impact of the various recovery models, a Lerchs & Grossman (L&G) pit limit optimization will be completed. The model results will be compared using the outcomes of L&G based on Ore Tonnes, Waste Tonnes and Strip Ratios produced by the models. The economic parameters used for this exercise are described in Table 4-1.

3.4.1.4 Validation of the Recovery Models

One of these previous models of recovery must be selected to continue with COGO. The selection and validation of the model consists of analyzing the output values of the L&G pit limit analysis for the three different constant recovery models and comparing it with the output of using original variable recovery model. As stated, the parameters used as inputs to the L&G study are the defined in Table 4-1. The comparison of the model is based in the output of the L&G pit limit analysis. The "Ore Selection Method" selected in the software (Whittle) is "Cash Flow".

Figure 3-20 shows the ore tonnes for each of the three models obtained from L&G.

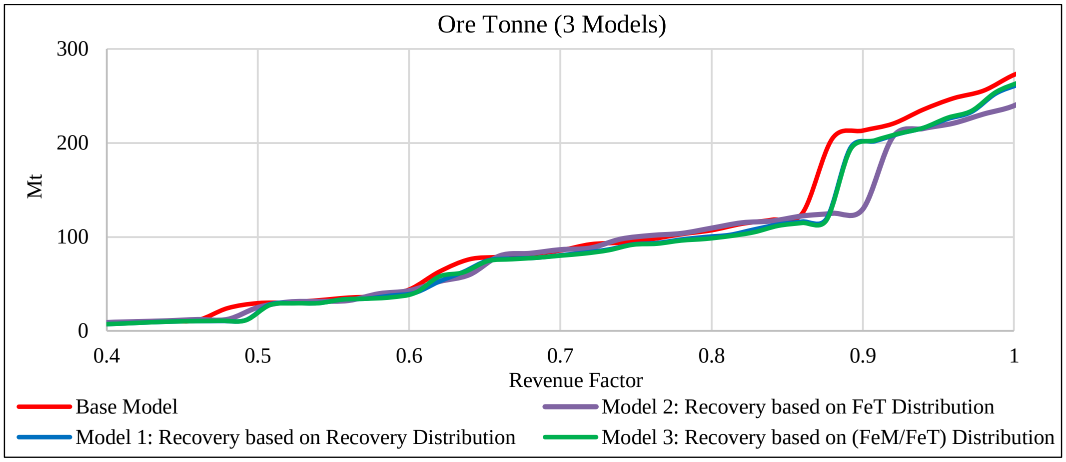


Figure 3-20: Ore tonnes from three different recovery models

As can be seen in the graph above, the relation between the Base Model and the other three models is very similar in terms of ore tonnes, however Model 2 presents greater accuracy close to the revenue factor 0.7-0.85 ranges. The graphs for Rock Tonnage, Strip Ratio, and FeT(%) iron grade for this validation can be found in Appendix B.

Table 3-29 shows a comparison of Rock Tonnes, Ore Tonnes and Strip Ratio generated for these 3 models for Revenue Factor = 0.7 (To see complete outputs, see Appendix B)

Model	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT(%)	FeM(%)	Cu(%)	Au(ppm)
Base Model	0.7	470,299,829	85,701,618	4.49	31.8	23.1	0.149	0.020
Model 1	0.7	451,354,070	80,639,841	4.60	32.6	23.6	0.150	0.020
Model 2	0.7	453,319,677	86,557,877	4.24	31.2	22.3	0.148	0.020
Model 3	0.7	451,314,075	80,165,967	4.63	32.7	23.7	0.150	0.020

Table 3-29: L&G Outputs of three models for revenue factor 0.7

For Dominga Norte, recovery Model 2 (Model based on FeT distribution) has been chosen for further analysis. The reason is because between revenues factors 0.5 to 0.85 the model reproduces very closely the Base Model. The range between these two revenue factors is most likely to yield the final pit limit for Dominga Norte.

3.4.2 Dominga Sur

As with the Dominga Norte model presented in the previous section, in order to work using the cut-off grade optimization algorithms in Whittle Software it is necessary to have constant recoveries. This is because the calculation of the COG is a function of the recovery, and the software is not able to work based on a variable recovery that is function of two variables (in this case variables FeT(%) and FeM(%)). For Dominga Sur only Models 1 and 2 are going to be analyzed based on the results obtained for Dominga Norte.

As was said before, for this exercise potential ore material inside the CAP property boundary is considered and treated as waste.

3.4.2.1 Model 1: Rocktype Populations Based on Recovery Distribution

Table 3-30 shows every rocktype with a separate sub-rocktype associated with the recovery distribution ranges obtained above in this thesis. The last column on the right of the table presents the recovery associated with each sub-rocktype.

Population	Rocktype	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
1	401	4011	0-0.33	13,768	0.28
2		4012	0.33-0.83	668,225	0.59
3		4013	0.83-1	63,312	0.89
Population	Rocktype	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
1	402	4021	0-0.8	19,044	0.56
2		4022	0.8-1	3,216	0.87
Population	Rocktype	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
1	403	4031	0-0.49	37,602	0.41
2		4032	0.49-0.83	22,266	0.59
3		4033	0.83-1	788	0.88

Table 3-30: Average recovery from rocktype populations based on recovery distribution

The mean recovery for sub-rocktype 4031, 4032 and 4033 should not consider blocks with grades for FeM less than 8%. If this constraint is considered in the calculation of the mean recovery, this value changes as is shown in the following table for the rocktype 403 (see Table 3-31).

Population	Rocktype	Sub-Rocktype	Range Recovery	Number of Blocks	Mean Recovery
1	403	4031	0-0.49	3,693	0.45
2		4032	0.49-0.83	10,566	0.61
3		4033	0.83-1	593	0.87

Table 3-31: Average recovery from rocktype populations based on recovery distribution, not considering blocks with less than 8% FeM

3.4.2.2 Model 2: Rocktype Populations Based on Iron Grade Distribution

Table 3-32 shows every rocktype with a separate sub-rocktype associated with the total iron grade distribution ranges obtained above in this thesis. The right side of the table presents the recovery associated to each sub-rocktype.

Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT(%) Recovery
401	1	4011	>0%-13%	500,824	0.56
	2	4012	>13%-27%	200,547	0.7
	3	4013	>27%-100%	43,934	0.81
Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT(%) Recovery
402	1	4021	>0%-9%	4,311	0.46
	2	4022	>9%-28%	15,728	0.62
	3	4023	>28%-100%	2,221	0.77
Rocktype	Population	Sub-Rocktype	Range FeT	Number of Blocks	Mean FeT(%) Recovery
403	1	4031	>0%-100%	14,852	0.58

Table 3-32: Average recovery from rocktype populations based on iron grade distribution

3.4.2.3 Validation of the Recovery Models

We have to choose one of these two recovery models for the COGO analysis for Dominga Sur. The validation of the model consists of analyzing the output of an L&G pit optimization for the two different constant recovery models and comparing with the output using the original variable recovery model.

The parameters used as inputs to the L&G study are the defined in Table 4-1. The comparison of the models is based in the output of the L&G pit limit analysis. The “Ore Selection Method” used in the software is by “Cash Flow”. Figure 3-21 shows the Ore Tonnes relation between these 2 models obtained from L&G.

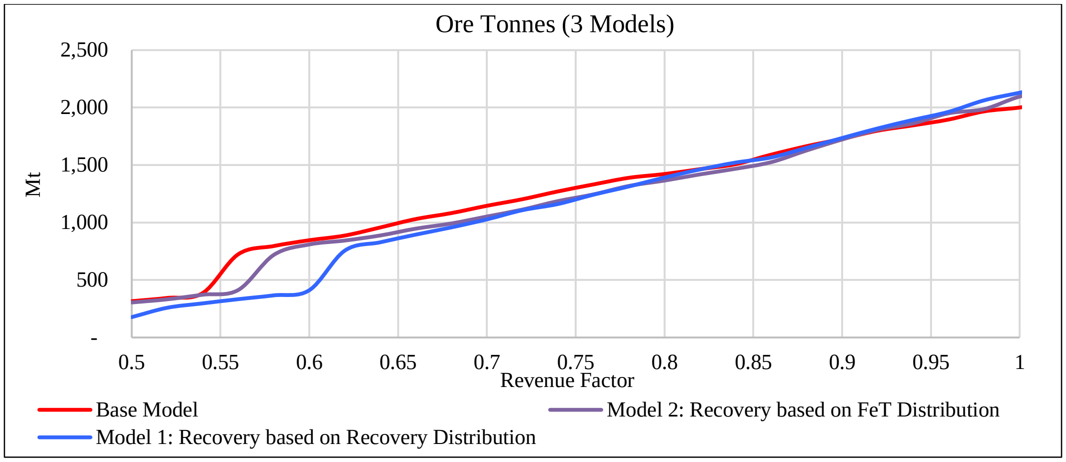


Figure 3-21: Ore tonne from 2 different recovery models

For Dominga Sur, the model chosen to continue with the COG analysis is the model based on FeT Distribution (Model 2) as shown in Table 3-33.

Model	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT(%)	FeM(%)	Cu(%)	Au(ppm)
Base Model	0.6	1,954,694,565	845,785,287	1.31	22.0	16.1	0.067	0.013
Model 1	0.6	828,656,526	410,769,426	1.02	23.5	16.9	0.070	0.013
Model 2	0.6	1,904,316,182	808,931,091	1.35	22.4	16.1	0.068	0.013

Table 3-33: Ore tonnes from 2 different recovery models

There is a significant difference in rock tonnes and ore tonnes from the Base Model to Model 1 for a revenue factor 0.6. For this reason the model chosen for Dominga Sur is the model based on FeT distribution (Model 2)

The graphs for Rock Tonnage, Strip Ratio, and FeT(%) iron grade for this validation can be found in Appendix B.

Chapter 4

Case Study: Dominga Project

This chapter presents a case study of the Dominga project. The goal of the case study is to explore opportunities for improvement to the planning work completed for the prefeasibility study for the Dominga project. The analysis considers three different scenarios (or cases) using different cut-offs methodologies to build a strategic mine plan for the project. The scenarios consider different approaches to cut-off grade strategy development. These scenarios do not result in detailed long-range plans, rather they show the effect of using the COGO. The analysis is completed using Whittle Software.

4.1 Mining Methods

The present chapter shows different strategies for applying COG in the Dominga project. These cases show the impact on the discounted cash flow generated for each strategy based on the same economic parameters. The main purpose of this section is to demonstrate the impact of various strategic planning decisions. Detailed mine plans are not developed.

4.1.1 Economic Parameters

Table 4-1 shows the economic parameters used in this report. These parameters are the same as those used in the Bridge Engineering Study by Andesiron (2014), with exception of the price for pellet feed and the processing cost for FeT(%) in Dominga Norte.

		March2015
Description	**Unit**	**Value**
Price Fe (Port Chile FOB)	US$/t pellet feed	80
Cu Price	US$/lb	3
Au Price	US$/oz	1,000
Grade Fe Concentrate	%	65
Grade Cu concentrate	%	22
Mine cost	US$/t Material	1.65
Process Fe cost Norte	US$/t Ore	7.2
Process Fe cost Sur	US$/t Ore	6.2
Process Cu Cost	US$/t Ore	0.5
Filter Plant cost	US$/t Conc	0.9
Transportation Cost to port (Pellet Feed)	US$/t Conc	2
Port cost	US$/t Conc	0.5
Transportation Cost to Paipote (Cu Concentrate)	US$/t Conc	28
TC (Cu)	US$/t Conc	80
RC (Cu)	US$/lb	0.08
G&A	US$/t Conc	2.6

Table 4-1: Economic parameters for Dominga Project

The discounted rate used in this exercise in 8% (Value used in Bridge Engineering (Andesiron, 2014)). When a stockpile is included in the mine plan, a re-handling cost of 0.50US$/tonne is used.

There is an additional cost associated with the mining cost which is an additional 0.10US$/tonne to each block above the level 305 in Dominga Norte and level 206 for Dominga Sur. Below these levels, the additional mining cost is 0.15US$/tonne for both mines. These levels were chosen in the Prefeasibility Study of Dominga and correspond to the ramp to exit in both open pits. There is a metallurgical restriction in which there is no recoverable iron for rocktype 403 for FeM grades of 8% or less (Value used in Bridge Engineering (Andesiron, 2014)). For all the following cases, rocktype 403 material for Dominga Norte and Dominga Sur is modified eliminating all the grades of FeT(%) that have less than 8% magnetic iron (FeM(%)).

4.1.2 Pit Optimization and Mine Plans

Whittle 4.5.3 pit optimizations were carried out on Dominga Norte and Dominga Sur using the economic parameters indicated above in Table 4-1. Strategic mine schedules are built using the Milawa Algorithm[2] in Whittle Software. All the following scenarios consider a processing rate of 95ktpd (Value used in Bridge Engineering (Andesiron, 2014)). A mine life approximately of 30 years is targeted. Another consideration is that the original block model for Dominga Norte and Sur has been reblocked from 10m x 10m x15m to 60m x 60m x 15m in order to reduce software processing times.

The first scenario, called CASE1, evaluates the block model of Dominga Norte and Sur using marginal COG but considering the application of the COGO algorithm present in Whittle Software. This scenario considers the application of the “Cash Flow” Ore Selection Method

The second scenario, called CASE2, evaluates the block model using a defined COG[3] for FeT(%) in both mines. These COGs are chosen using an exercise explained in Section 4.1.2.2.1. This scenario considers the application of the “Cut-off” ore selection method to achieve more control over which element(s) are used to define the cut-off. In Section 4.1.2.2.2 the same exercise is developed to find a defined COG but this time using the “Cash Flow” ore selection method. An

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[2] Algorithm for schedule optimization developed by Whittle Software. The idea is to find what should be taken from each bench to maximize NPV.

[3] Defined COG: Use a constant FeT(%) COG above the marginal FeT(%) COG

outcome of the mine plan based on this COG is presented (Appendix C presents a complete analysis of how to choose a defined COG using different strategies).

The third scenario, called CASE3, evaluates the block model of Dominga Norte and Sur without a defined COG for FeT(%), but considering the application of the COGO algorithm present in Whittle Software. This scenario considers the application of the “Cut-off” Ore Selection Method (versus “Cash Flow” used in CASE1). For this case the mining rate is changed to analyze the full potential impact of the algorithm. At the end of this case, capital expenditure is included in the algorithm to analyze the effect produced on the NPV of the project.

4.1.2.1 CASE 1

The first scenario evaluates the block model of Dominga Norte and Sur not using a defined cut-off grade for FeT(%) but considering the application of the COGO. The actual value (or cash flow) produced by a block is calculated and used to classify it as ore or waste.

The principal inputs for this case are:

- Maximum Mining Rate=100Mtpa, Processing Rate =95ktpd
- Life of mine approximately 30 years
- Use of Marginal COG
- COGO is applied
- This case corresponds to use Cash Flow Ore Selection Method
- Use of a Stockpile when COGO is used

4.1.2.1.1 Final Pit Limit Analysis

In this case, the selection of the ultimate pit is based on Cash Flow discounted value. There is no defined COG to find the final pit, which means that the algorithm L&G works with the marginal COG. Also, Dominga Norte and Dominga Sur are considered as a "multi-mine", where blocks from either deposit can be mined at any time.

Figure 4-1 shows a pit by pit graph produced by the pit limit analysis (PLA) considering Dominga Norte and Sur as a multi-mine.

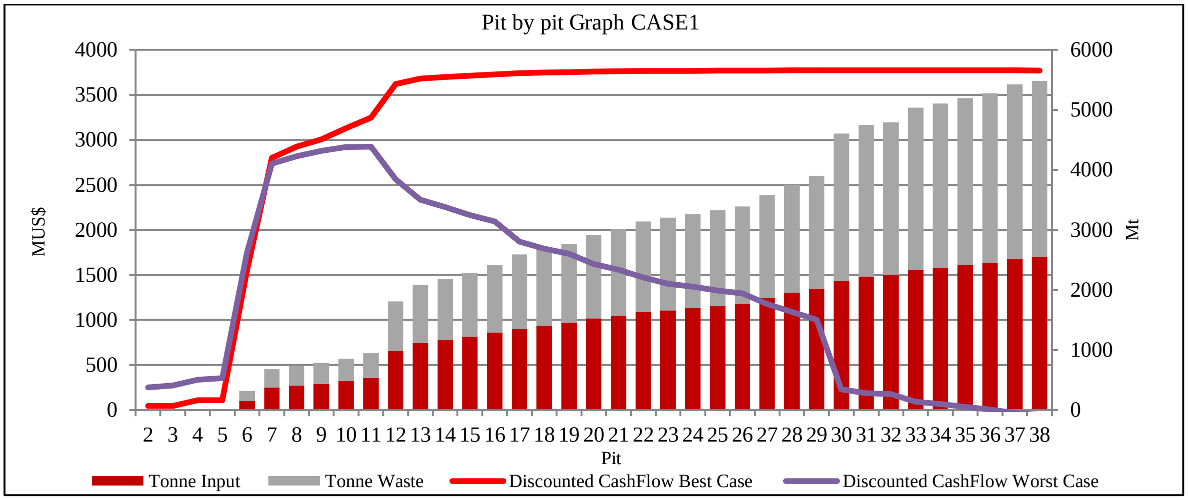

Figure 4-1: Pit by pit graph CASE1

Based on the requirement to have a mine life of 30 years, we have chosen pit number 12 as a final pit, which corresponds to a revenue factor[4] 0.58 as shown in Table 4-2.

Final Pit	CashFlow BestCase MUS$discounted	Mt Input	Mt Waste	Strip Ratio	Mine Life	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
12	3,743	981	830	0.8	31	20.1	14.0	0.064	0.012

Table 4-2: Outcome final pit Dominga Norte and Sur for CASE1

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[4] Pit parameterization method used for generating Life-of-Mine plans "A range of factor is applied to the block revenue to alter its value in consecutive L&G optimization runs" (Whittle D. , 2011)

Figure 4-2 shows the pit by pit graph from the PLA treating the Dominga project as multi-mine project. In this case the cash flow contributions of the two deposits (Norte and Sur) are presented individually and in total.

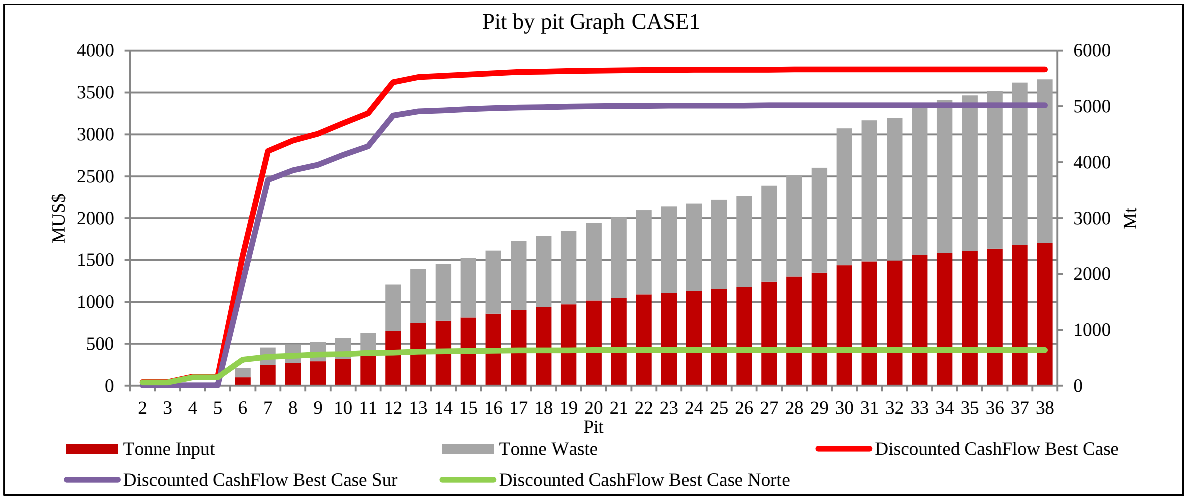

Figure 4-2: Pit by pit graph CASE1 for Dominga Norte and Sur separetly

The red line shows the total discounted cash flow for every pit achievable for the best case of mining that material. The purple and green lines represent the contribution of Dominga Sur and Dominga Norte respectively. Table 4-3 shows the outcome for pit number 12 for Dominga Norte and Sur.

Mine	Final Pit	CashFlow BestCase MUS$disc	Mt Input	Mt Waste	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
Dominga Norte	12	402	34	81	2.4	30.1	20.6	0.129	0.017
Dominga Sur	12	3,341	947	749	0.8	19.8	13.8	0.061	0.012
Norte + Sur		3,743	981	830	0.8	20.1	14.0	0.064	0.012

Table 4-3: Outcome final pit Dominga Norte and Sur separately for CASE1

In this exercise, the selection of pushbacks is a function of the tonnage and they are not necessarily operative. The objective of this work is to compare different methodologies of evaluation using COG, not to complete detailed mine planning. From Table 4-3, it is important to notice that the material considered as ore in Dominga Norte is just 34Mt. This is less than 1 year of mill feed at the assumed processing rate (95ktpd). The total amount of ore in this case is 981Mt which produces discounted cash flow of MUS$3,743 for the best case scenario

4.1.2.1.2 Strategic Mine Plan CASE1

The strategic mine plans were built using the Milawa NPV algorithm. Figure 4-3 shows a strategic mine plan for the Dominga project after applying COGO:

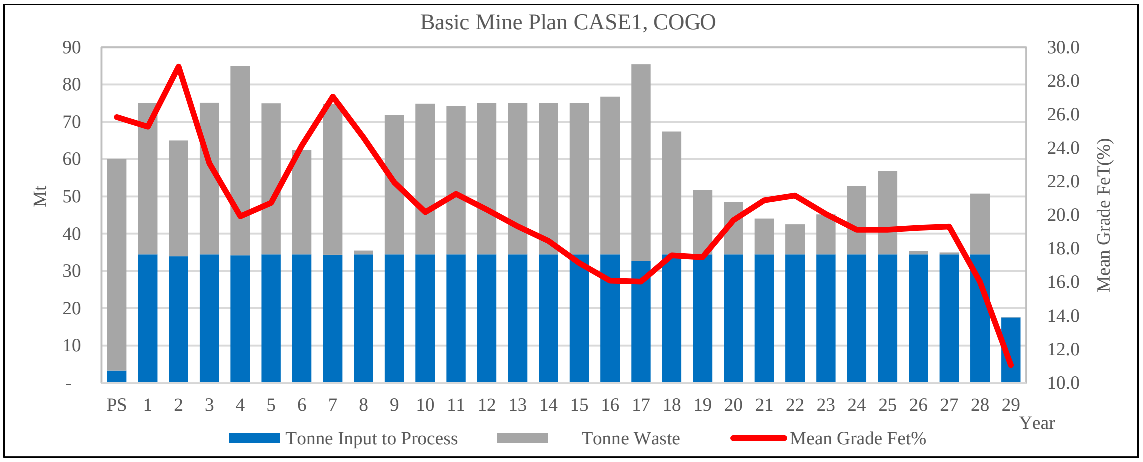

Figure 4-3: Strategic mine plan for the Dominga project after applying COGO

The mining/movement of material is not constant which is not a problem if the main objective is to produce the highest discounted cash flow. Figure 4-4 corresponds to the ore sent to the mill from Dominga Norte and Sur mines and from the stockpile (purple bar):

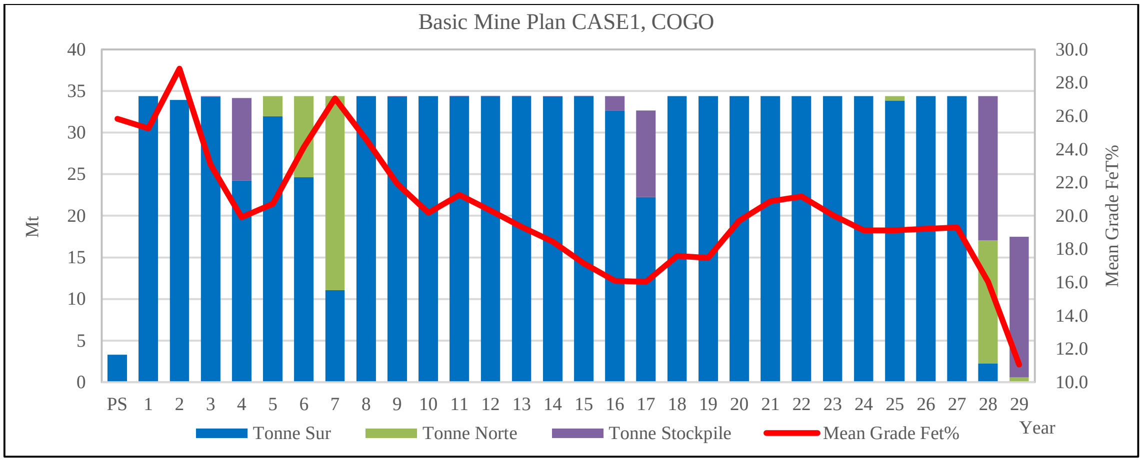

Figure 4-4: Strategic mine plan for the Dominga project after applying COGO and stockpile

The figure above shows that Dominga Norte is mined between years 5-7, not again until year 28. Table 4-4 shows the differences between the 2 mine plans generated, the first is using marginal COG and the second is applying the COGO for CASE1.

	CASE1 (Marginal COG)	CASE1 (COGO)
Ore (Mt)	990	924
Stockpile (from stockpile to process) (Mt)	-	57
Waste (Mt)	849	857
Total (Mt)	1,839	1,839
General Strip Ratio	0.86	0.87
Discounted CashFlow (US$)	3,746	3,819
Life of Mine (years)	30.0	29.5

Table 4-4: Comparison using marginal COG and using COGO for CASE1

In this case, the improvement of using a marginal COG and use a COGO is an increment of 2% in the discounted cash flow generated for the mine plan. The increment is not considered a significant improvement to the discounted cash flow even though it is 73MUS$. Figure 4-5 shows the average grade of iron before and after applying COGO:

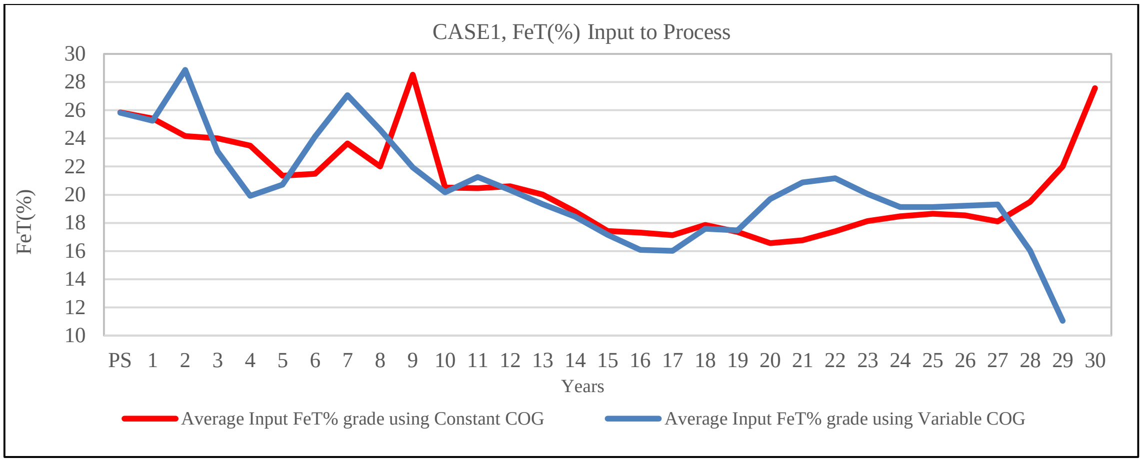

Figure 4-5: Average annual grades indicated by using a defined COG and COGO for CASE1

The mean grade for both methodologies is similar throughout the mine life. At the end of the mine life, the mean grade using COGO is lower than the other case because of the use of stockpiled material. The impact of use COGO should be that at the beginning of the mine life, the mean grades of FeT(%) should be higher than not using COGO. This happened in years 2 and 7, but in year 4 the optimized grade is lower than the mean grade using marginal COG. The methodology is not working as anticipated because the distribution of grades in the deposit is relatively homogeneous. If there is not enough variability of grades in the deposit, the algorithm does not produce significant results. The algorithm functions by focusing on milling high grades (or high value material) at the beginning of the mine life and deferring the lower grade materials to the end of mine life.

4.1.2.2 CASE 2

For this case, a defined COG is used instead of a marginal COG. Two different exercises are shown. The first one is using the “Ore Selection Method” based on cut-off (applied in Whittle). The reason for this is that using this ore selection method there is more control over the elements used in calculating the cut-off. For this case the grades of FeT(%) and Cu(%) are used. The second exercise is using the “Ore Selection Method” based on cash flow (applied in Whittle)

The principal inputs for this case are:

- Maximum Mining Rate=100Mtpa, Processing Rate =95ktpd.
- Life of mine approximately 30 years
- Defined COG (not using marginal COG)
- COGO is applied
- Use of a Stockpile when COGO is used

4.1.2.2.1 CASE 2 Using Cut-off Ore Selection Method

In this case, the selection of the ultimate pit is based on a cash flow discounted value. Also, the Norte and Sur deposits are considered as a multi-mine, where material can be mined from either pit at any time to maximize NPV.

4.1.2.2.1.1 Defined COG

Marginal COGs are not used for this case. Instead of the marginal COG, a search of the optimal COG has been made to use as the defined COG. This search consists of the evaluation of the best case discounted cash flow generated for Dominga project using different combinations of FeT grades between Dominga Norte and Dominga Sur. The rates of mining and processing are 100Mtpa/95ktpd respectively. Table 4-5 shows the results of this exercise, with changing grades for both Dominga Norte (DN) and Dominga Sur (DS). For example, the first combination 9DN-9DS means that there is a cut-off 9%FeT for Dominga Norte and 9%FeT for Dominga Sur. In this case FeT(%) is going to be used to search for the defined COG. Cu(%) and Au(ppm) are not going to be considered because the main product is iron concentrate.

FeT(%) Cut-off Combination	**Cut-off Best Case Multi-mine (US$)**	**FeT(%) Cut-off Combination**	**Cut-off Best Case Multi-mine (US$)**
No Cutoff	3,772,372,477	11DN-12DS	3,859,518,915
9DN-9DS	3,772,372,477	12DN-13DS	3,879,767,165
10DN-10DS	3,784,980,014	16DN-16DS	2,958,024,860
9DN-12DS	3,859,518,915	17DN-17DS	3,969,305,255
9DN-13DS	3,879,767,165	18DN-18DS	3,958,864,463
12DN-12DS	3,859,518,915	19DN-19DS	3,969,560,307
12DN-16DS	3,957,726,409	20DN-20DS	4,069,377,466
13DN-13DS	3,879,733,886	17DN-18DS	3,959,482,155
14DN-15DS	3,915,848,952	16DN-17DS	3,970,030,093
15DN-15DS	3,916,541,654	15DN-17DS	3,970,345,458
10DN-12DS	3,859,518,915	14DN-17DS	3,969,969,312

Table 4-5: Defined FeT(%) COG using Cut-off Ore Selection Method

The COG considers a defined FeT(%) COG for Dominga Norte and Dominga Sur, which is 15%FeT and 17%FeT respectively. These COG are used for this case. The value 20DN-20DS is not considered because is a high cut-off for this deposit decreasing the reserves.

Different combinations of defined COG can be obtained depending on the Ore Selection Method and the elements considered. The differences are explained in Appendix C.

4.1.2.2.1.2 Final Pit Limit Analysis

Figure 4-6 shows the pit by pit graph for CASE2:

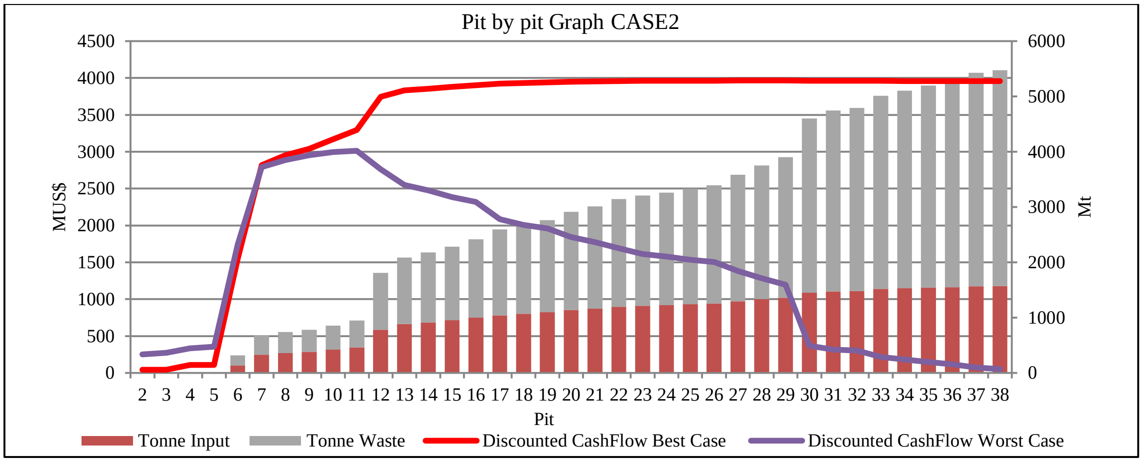

Figure 4-6: Pit by pit graph CASE2

Based on the requirement to have a mine life of approximately 30 years (for this case has been chosen a mine of life of 30.9 years) pit number 13 is selected as the final pit limit, which corresponds to a revenue factor 0.60 (see Table 4-6):

Final Pit	CashFlow BestCase MUS$disc	Mt Input	Mt Waste	Strip Ratio	Mine Life	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
13	3,833	901	1,185	1.3	31	22.2	15.8	0.071	0.013

Table 4-6: Outputs CASE2 for final pit

In this exercise, the selection of pushbacks is a function of the tonnage (or mine life) and they are not necessarily operative. The objective of this work is to compare different methodologies of evaluation using COG, not to complete detailed mine planning.

Figure 4-7 shows the pit by pit graph of the CASE2 from the PLA treating the Dominga project as multi-mine project. In this case the cash flow contributions of the two deposits (Norte and Sur) are presented individually and in total.

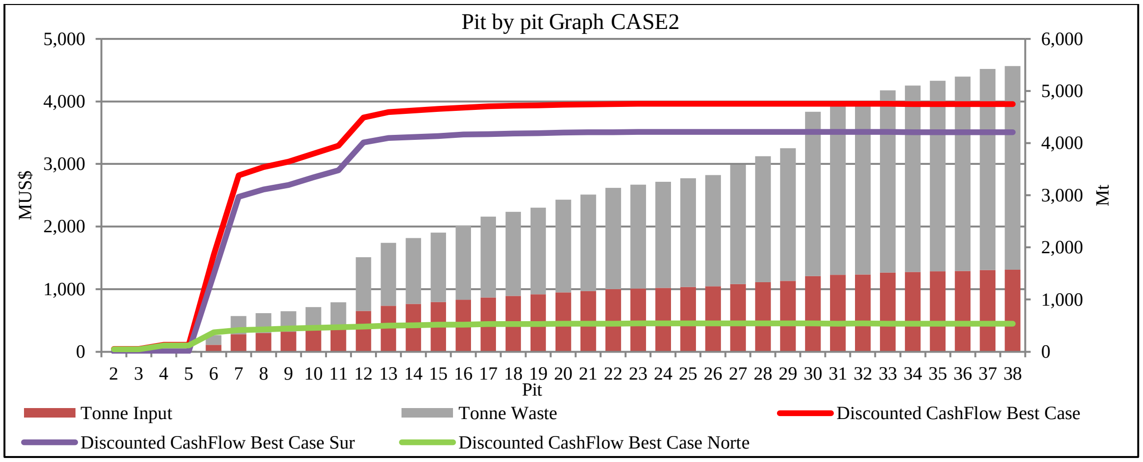

Figure 4-7: Pit by pit graph CASE2 for Dominga Norte and Sur separately

The red line shows the total discounted cash flow for every pit achievable for the best case mining sequence. The purple and green lines represent the contribution of Dominga Sur and Dominga Norte respectively. Table 4-7 shows the mine plan performance data for final pits chosen.

Mine	Final Pit	CashFlow BestCase MUS$disc	Mt Input	Mt Waste	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
Dominga Norte	13	419	46	136	3.0	30.3	21.2	0.127	0.016
Dominga Sur	13	3,414	855	1,049	1.2	21.8	15.6	0.068	0.013
Norte + Sur		3,833	901	1,185	1.3	22.2	15.8	0.071	0.013

Table 4-7: Outcome final pit Dominga Norte and Sur separately for CASE2

Increasing the COG from marginal to defined ones, the amount of ore from Dominga Norte increases and the amount of ore from Dominga Sur decreases if we compare with CASE1 (Table 4-3). The total amount of ore (901Mt) is lower than the total amount of ore for CASE1 (981Mt) after applying COGO.

4.1.2.2.1.3 Marginal Cut-off Grades

Marginal COG for each rocktype is calculated for the software based on all the economic parameters (Appendix C present the formula and the variables used for the calculation of the marginal COG in Whittle). In this case the “Ore Selection Method” is by cut-off (explained in more detail in the Literature Review) to classify material as ore or waste. The raised cut-off is applied by the software by calculating in this case the marginal COG for FeT(%) and Cu(%). These two elements are considered because the first one is the main product and the second one is the sub-product, gold is not considered in terms this type of decision.

The marginal COG for FeT(%) for every rocktype is shown in Tables 4-8 and 4-9.

Dominga Sur		
Rocktype	**DefinedCOG**	**MarginalCOG**
	FeT(%)	FeT(%)
401	17	9.7
4012	17	7.8
4013	17	6.7
402	17	11.8
4022	17	8.8
4023	17	7.1
403	17	9.4

Table 4-8: Marginal and defined COG Sur

Dominga Norte		
Rocktype	**DefinedCOG**	**MarginalCOG**
	FeT(%)	FeT(%)
401	15	14.05
4012	15	10.20
4013	15	7.91
402	15	17.09
4022	15	10.20
4023	15	8.11
403	15	11.10
4032	15	11.10
4033	15	12.65

Table 4-9: Marginal and defined COG Norte

The marginal COG for Dominga Sur is lower than the COG defined and used in this exercise. In Dominga Norte the same occurs with exception of one rocktype (402), which has a marginal COG higher than the defined grade (15%).

4.1.2.2.1.4 Strategic Mine Plan Case2

Figure 4-8 shows a basic mine plan for Dominga Project using the defined COG grade for FeT(%).

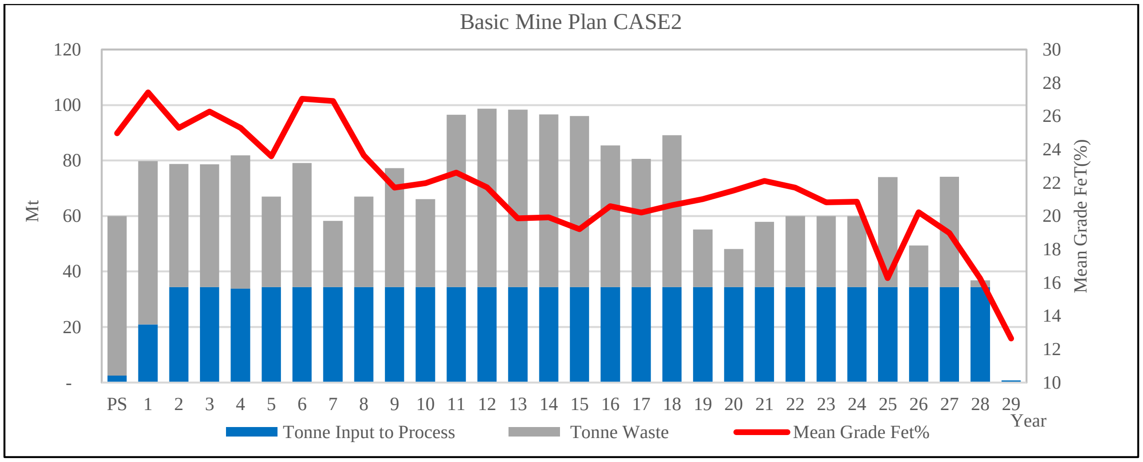

Figure 4-8: Strategic mine plan for the Dominga project using a defined COG

The mine plan above shows a maximum mining rate of 100Mtpa for years 12 to 15. The red line shows the average grade of iron feed from the mine to the mill. As can be seen in the figure above, the red line (average grade) decreases from the early years to the end of the mine life. The discounted cash flow for this mine plan is MUS$3,999 (Table 4-10). Figure 4-9 shows the ore sent to the mill. This material is a combination of the mines Dominga Norte and Sur, and stockpiled ore. The red line represents the average grade to the mill, which has some small differences from the curve representing direct mine feed to the mill only.

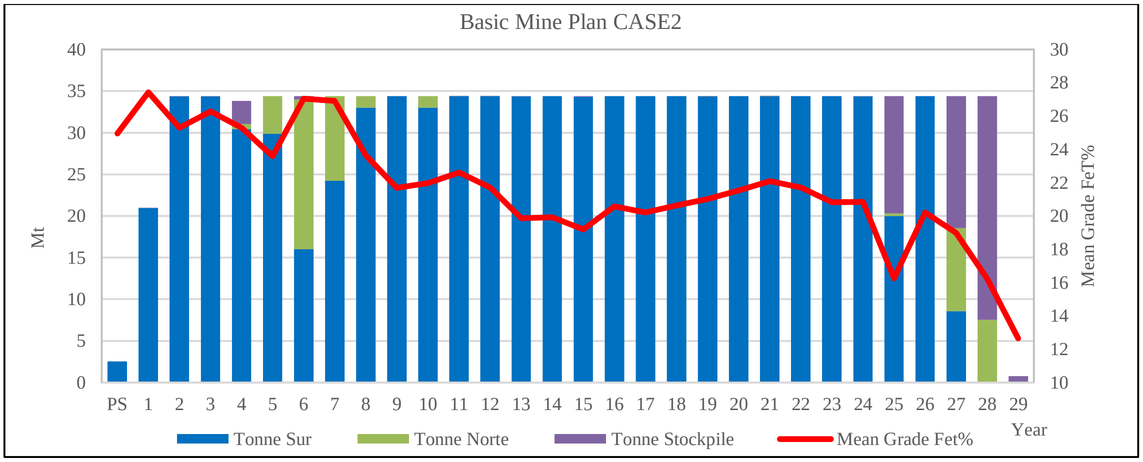

Figure 4-9: Strategic mine plan for the Dominga project using a defined COG. Ore sent to the mill.

From Figure 4-9, it can be seen that the amount of ore feed to the mill is constant for all the years of production. The next step in this case is to apply the COGO to this mine plan. All the parameters used in this case including stockpile use, the defined COG, mining and processing rates are held constant.

Figure 4-10 shows a simple graph trying to explain the effect to apply a COGO above a defined COG.

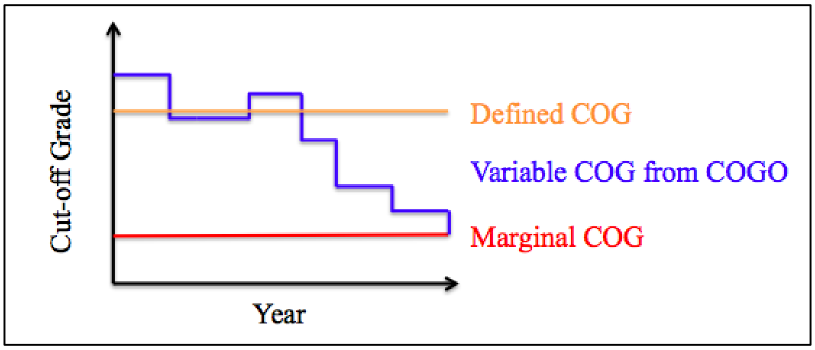

Figure 4-10: Simplified effect of applying different COG

In Figure 4-10, the red line represents a marginal COG of a particular deposit. The blue line represents the COG if a COGO algorithm is applied to the deposit. In this case the COG is variable and the effect is to have high COG early in the mine life and at the end achieve the marginal COG. If a defined COG, orange line, is applied then the effect of the COGO depends on the grade distribution of the deposit. It is for this reason that the algorithm does not achieve significant results if it is applied above a defined COG in Dominga project.

Figure 4-11 shows the mine plan after applying COGO. It is important to notice that the algorithm does not perform properly. This is because one of the results of applying a defined COG is to reduce variability of the ore grades. If the ore grades don't have enough variability, the algorithm of COGO, which tries to bring the high grade material to the beginning of the mine life, is not able to prioritize high-grade material achieving an important improvement of the discounted value.

Figure 4-11 shows the strategic mine plan from CASE2 after applying COGO.

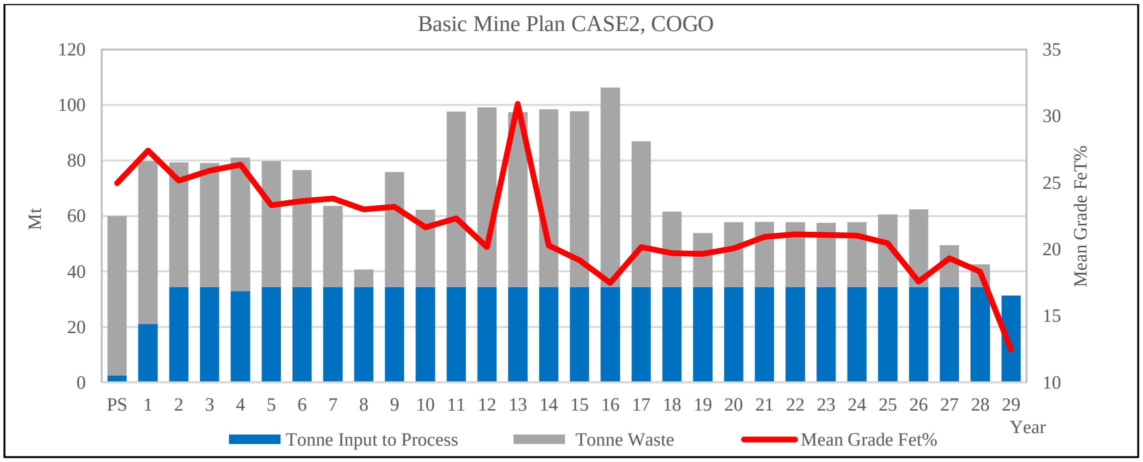

Figure 4-11: Strategic mine plan for the Dominga project using a defined COG above a defined COG

Figure 4-12 shows the mine plan of the material sent to the mill, generated after applying COGO.

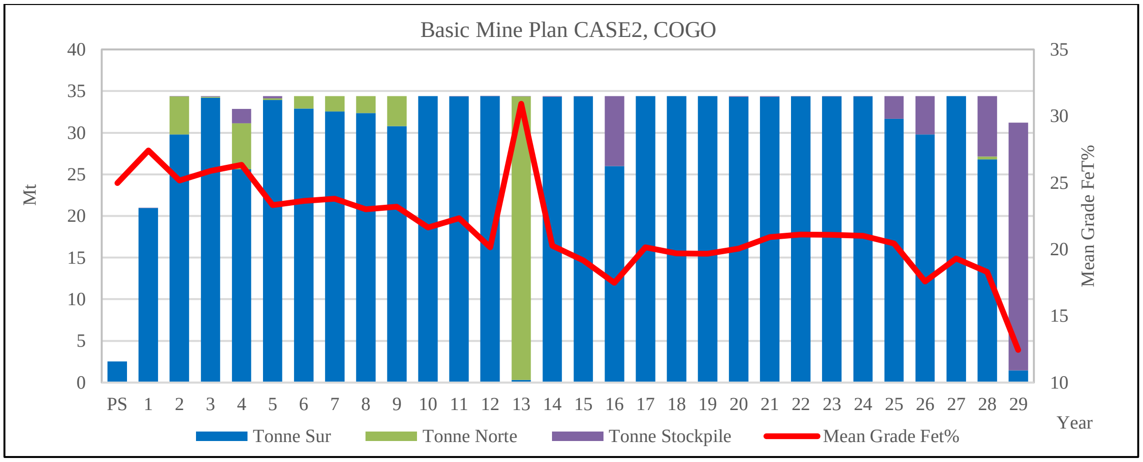

Figure 4-12: Strategic mine plan for material sent to the mill for the Dominga project using COGO above a defined COG

From Figure 4-12, the feed to the mill is similar to the mine plan from Figure 4-9. The results show that there is no improvement in the discounted cash flow generated for this mine plan after applying COGO. The reason for this is that defined high COGs are used as basis of the mine plan; optimization works best when the selection of COG is not pre-restricted.

Table 4-10 shows the values from applying and not applying the COGO:

	CASE2 (Defined COG)	CASE2 (COGO)
Ore (Mt)	891	927
Stockpile (from stockpile to process) (Mt)	61	55
Waste (Mt)	1,159	1,130
Total (Mt)	2,111	2,112
Strip Ratio	1.3	1.22
Discounted CashFlow (MUS$)	3,999	3,961
Life of Mine (years)	29	30

Table 4-10: Comparison using defined COG and using COGO for CASE2 (Cut-off ore selection method)

The reason why there is an increment in the total amount of ore can be explained because the algorithm is not able to take advantage of grade variability, as was explained before. The other reason is because as is shown in Figure 4-13, the average grade between years 5 and 8 after applying COGO is lower when not using COGO. This reduces metal production and cash flow in those years. Figure 4-13 shows the average annual grades indicated by using a defined COG and COGO.

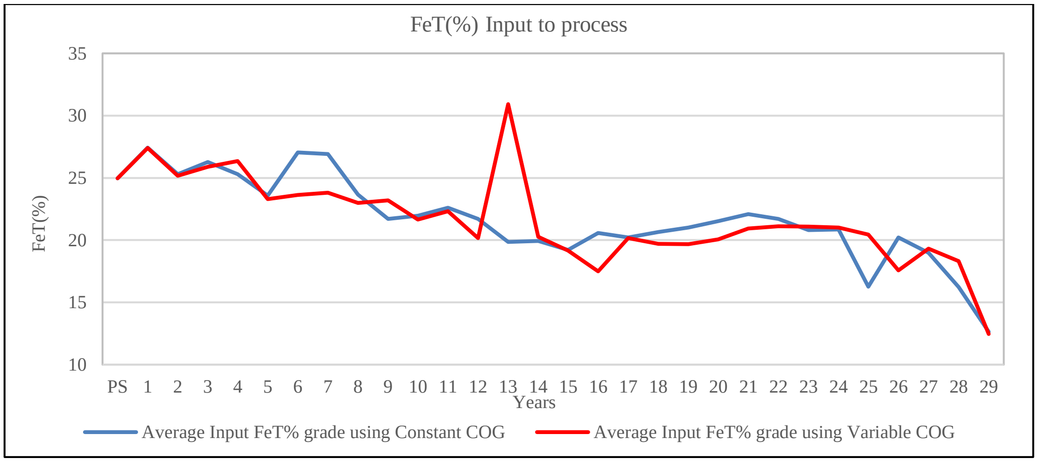

Figure 4-13: Average annual grades indicated by using a defined COG and a COGO

Figure 4-14 shows the effect of applying the optimization for sub-rocktype 4012 in Dominga Sur.

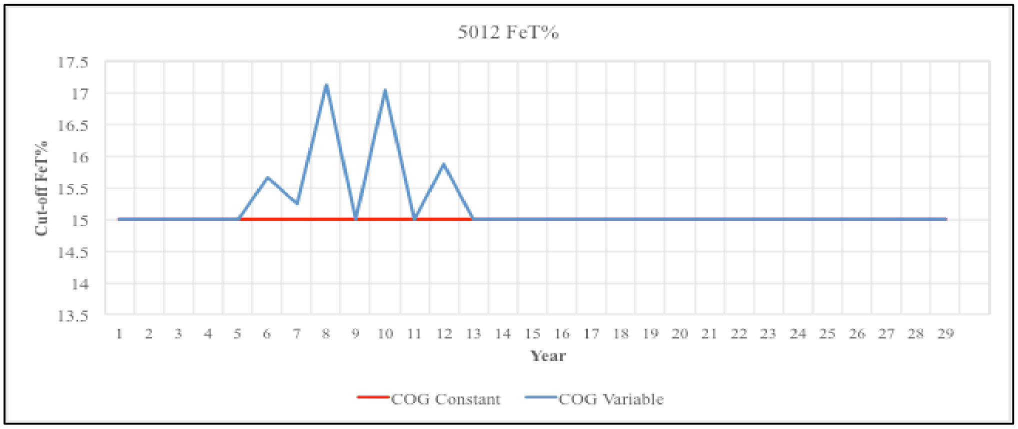

Figure 4-14: Effect COGO for FeT(%) for sub-rocktype 4012 in Dominga Sur.

The red line represents the defined COG, which in this sub-rocktype from Dominga Norte is 15%FeT. As can be seen in the figure above, the variable COG has a peak of 17%FeT. The optimization produces the same effect in every rocktype involved in the process.

4.1.2.2.2 CASE 2 Using Cash Flow Ore Selection Method

In this case, the selection of the ultimate pit is based on a cash flow discounted value rather than a defined COG. The Norte and Sur deposits are considered as a multi-mine, where material can be mined from either pit at any time to maximize NPV.

4.1.2.2.2.1 Defined COG

This section reproduces similar analysis to section 4.1.2.2.1.1. The objective is to search for the optimal COG and use the optimal COG as the defined cut-off rather than a marginal COG. This search consists of the evaluation of the best case discounted cash flow generated for Dominga project using different combinations of grades between Dominga Norte and Dominga Sur. The rates of mining and processing are 100Mtpa/95ktpd respectively. The cash flow selection method is used in this analysis.

Table 4-11 shows the result of this exercise, with different combinations of FeT(%) COG for both Dominga Norte (DN) and Dominga Sur (DS).

FeT(%) Cut-off Combination	**Cut-off Best Case Multi-mine (US$)**	**FeT(%) Cut-off Combination**	**Cut-off Best Case Multi-mine (US$)**
No Cutoff	3,772,471,047	11DN-12DS	3,940,504,205
9DN-9DS	3,846,935,758	12DN-13DS	4,070,177,640
10DN-10DS	3,888,264,673	16DN-16DS	3,840,109,838
9DN-12DS	3,943,382,739	17DN-17DS	3,687,645,263
9DN-13DS	4,076,209,556	18DN-18DS	3,501,916,913
12DN-12DS	3,973,723,802	19DN-19DS	3,334,718,134
12DN-16DS	3,855,224,467	20DN-20DS	3,169,951,538
13DN-13DS	4,065,855,568	17DN-18DS	3,502,363,781
14DN-15DS	3,949,326,407	16DN-17DS	3,689,005,253
15DN-15DS	3,946,386,124	15DN-17DS	3,691,601,188
10DN-12DS	3,942,095,168	14DN-17DS	3,694,543,971

Table 4-11: Defined FeT(%) COG using the cash flow ore selection method

The COG considers a defined FeT(%) COG for Dominga Norte and Dominga Sur, which is 9%FeT and 13%FeT respectively. There is a difference of COG between using the cut-off or Cash Flow Ore Selection Methods. While the COG defined using a Cut-off Ore Selection Method is 15%FeT for Dominga Norte and 17%FeT for Dominga Sur, using the cash flow selection method it is 9%FeT for Dominga Norte and 13%FeT for Dominga Sur.

4.1.2.2.2.2 Final Pit Limit Analysis

Based on the requirement to have a mine life of approximately 30 years (for this case the mine life is 29.7 years) pit number 14 is selected as the final pit limit, which corresponds to a revenue factor 0.62. Table 4-12 shows the mine plan performance data for final pits chosen.

Mine	Final Pit	CashFlow BestCase MUS$disc	Mt Input	Mt Waste	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
Dominga Norte	14	432	51	162	3.1	30.3	21.2	0.018	0.015
Dominga Sur	14	3,531	813	1,153	1.4	22.6	16.3	0.064	0.012
Norte + Sur		3,964	864	1,315	1.5				

Table 4-12: Outcome final pit Dominga Norte and Sur separately for CASE2, using cash flow ore selection method

4.1.2.2.2.3 Strategic Mine Plan CASE2

The objective of this section is to show the effect of using a different Ore Selection Method than was used in Section 4.1.2.2.1.4 on the outcomes from a mine plan (see Table 4-13).

	CASE2 (Defined COG)
Ore (Mt)	873
Stockpile (from stockpile to process) (Mt)	-
Waste (Mt)	1,335
Total (Mt)	2,208
Strip Ratio	1.53
Discounted CashFlow (MUS$)	4,050
Life of Mine (years)	27

Table 4-13: Outcome from the mine plan using a defined COG for CASE2 (Cash Flow Ore Selection Method)

For this case (using Cash flow ore selection method) it is not practical to apply COGO because of the computational time necessary to run the algorithm.

4.1.2.3 CASE 3

The third scenario evaluates the block model of Dominga Norte and Sur without a defined COG for FeT, but considering the application of the COGO algorithm present in Whittle Software. This scenario considers the application of the “Cut-off” Ore Selection Method (versus “Cash Flow” used in CASE1). For this case the mining rate is changed to analyze the full potential impact of the algorithm.

The principal inputs for this case are:

- Maximum Mining Rate=100Mtpa, Processing Rate =95ktpd.
- Life of mine approximately 30 years
- Marginal COG are used
- COGO is applied
- Use of a Stockpile when COGO is used
- This case corresponds to use Cut-off Ore Selection Method.

In Whittle, when ore selection is by cut-off, ore is selected by comparing the grades of the material with pre-calculated marginal cut-offs. If it does not satisfy the calculated cut-offs, it is treated as waste. If there is more than one element for each block, which is the case for Dominga where iron, copper and gold are all present, Whittle works using the concept of equivalent grades. Whittle initially calculates cut-offs to maximize the cash flow, not the discounted cash flow, when the cut-off selection method is used.

4.1.2.3.1 Final Pit Limit Analysis

In this case, the selection of the ultimate pit is based on the discounted cash flow value. There is no defined COG to define the final pit, which means that the algorithm works with the marginal COG. Figure 4-15 shows the pit by pit graph generated when treating the Dominga Project as a multi-mine (i.e., Norte and Sur as independent mining pits):

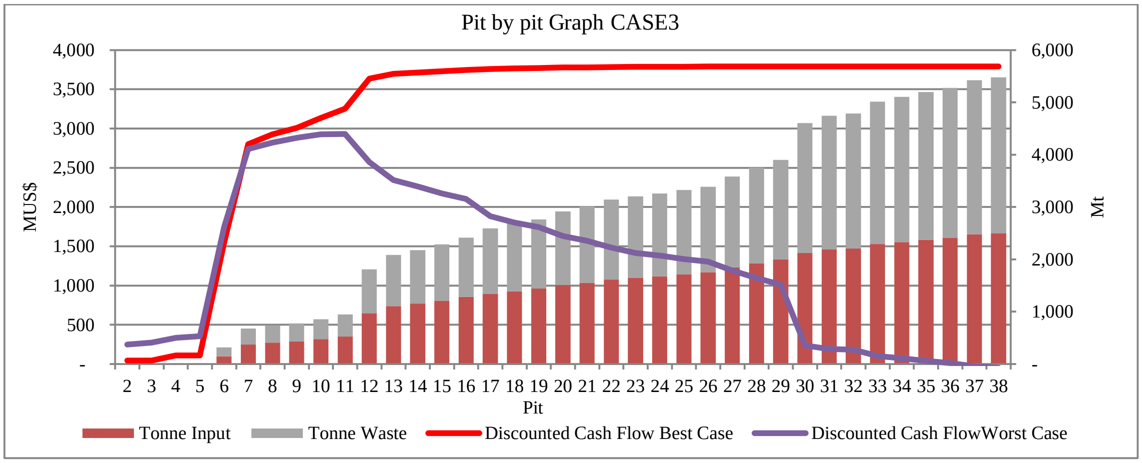

Figure 4-15: Pit by pit graph CASE3

Based on the requirement to have a mine life of approximately 30 years pit 12 is identified as the final pit limit, which corresponds to a revenue factor 0.58. Table 4-14 shows the values for the final pit chosen.

Final Pit	CashFlow BestCase MUS$disc	Mt Input	Mt Waste	Strip Ratio	Mine Life(y)	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
12	3,635	973	838	0.9	32	20.2	14.13	0.064	0.012

Table 4-14: Outputs CASE3 for final pit as multi-mine

The concept mentioned before is the key feature of the "Multi-mine" option in Whittle. When using the multi-mine option a different final pit can be defined for each mine pit, different pushbacks can be selected between mine pits, and the constraints for the Milawa algorithm and mining limits can be different in the different mine pits. For this exercise, the final pit would be the same for each mine but the pushbacks are chosen separately.

Figure 4-16 shows the pit by pit graph produced by treating the Dominga project as multi-mine project.

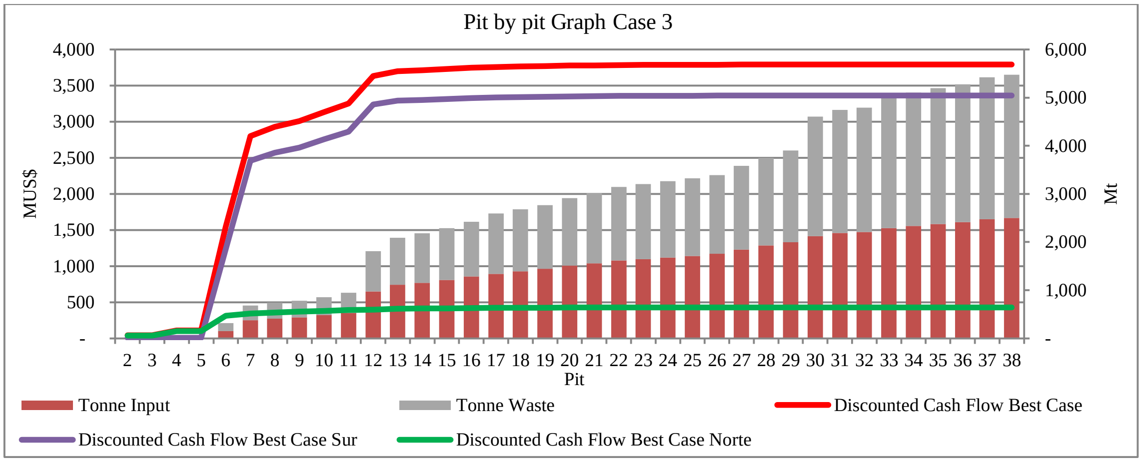

Figure 4-16: Pit by pit graph CASE3 for Dominga Norte and Sur separately

The red line shows the total discounted cash flow for every pit achievable for the best case of mining that material. The purple and green lines represent the contribution of Dominga Sur and Dominga Norte respectively.

Table 4-15 shows the mine planning results for pit number 12 (the final pit limit) for Dominga Norte and Sur.

Mine	Final Pit	CashFlow BestCase MUS$disc	Mt Input	Mt Waste	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
Dominga Norte	12	397	33	81	2.4	30.3	20.8	0.130	0.017
Dominga Sur	12	3,238	939	757	0.8	19.9	13.9	0.061	0.012
Norte + Sur		3,635	972	838	0.9	20.2	14.1	0.064	0.012

Table 4-15: Outputs CASE3 for Final Pit as multi-mine separately

From Table 4-15, it is important to note that the material considered as ore in Dominga is 972Mt with a mean grade of 20.2% FeT. Dominga Norte contributes just 33Mt of this total. This is less than 1 year of processing at the defined rate. For the Bridge Engineering Study (Andesiron, 2014), the price of pellet feed was set at 101US$/tonne pellet feed in comparison with the

80US$/tonne pellet feed used in this study. The quantity of resources inside the final pit in Dominga Norte for the Bridge Engineering was close to 200Mt. The difference in ore feed from Dominga Norte can be mostly explained by the use of a lower pellet feet price in this study. This has reduced ore feed and increased waste stripping in the pit. In this new price scenario (80US$/tonne pellet feed) there is no reason to mine a big part of Dominga Norte. This has a significant impact on the economics of the project.

In this exercise, the selection of pushbacks is a function of the tonnage and they are not necessarily operative. Using the module "Multi-mine" in Whittle, pushback selection can now be completed for each deposit using pits 12 as the final pit limits.

4.1.2.3.2 Strategic Mine Plan "1", CASE3

This mine plan was built using the Milawa NPV algorithm. The following graph shows a strategic mine plan for the Dominga Project. As generated, year five has reduced ore feed to the mill, however this material can be added from other periods in a more detailed stage of mine planning. This example used is to show the impact of using or not using COGO. Figure 4-17 shows the strategic mine plan for the Dominga project.

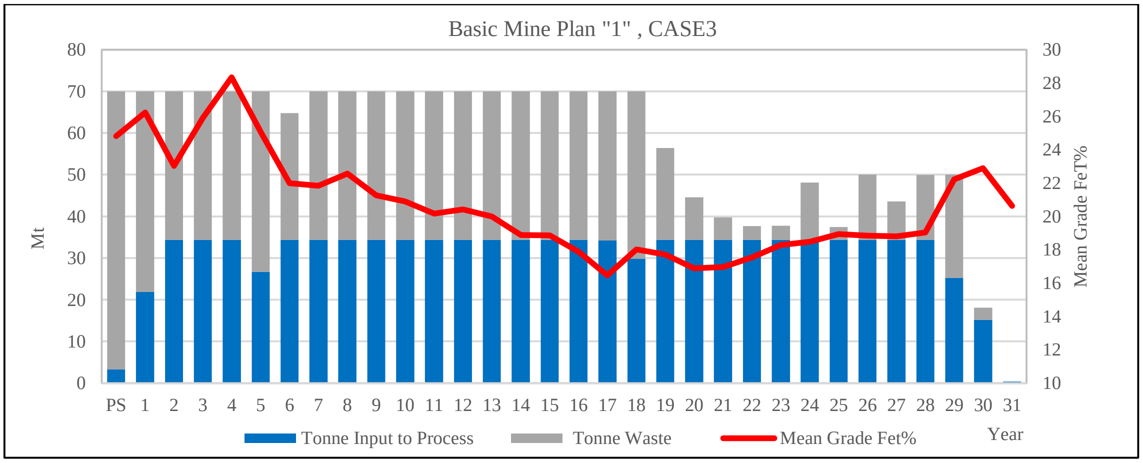

Figure 4-17: Strategic mine plan for the Dominga project using marginal COG, Mine Plan "1", CASE3

The mine plan considers 30 years of production. The maximum mining rate is 70Mtpa, which is achieved from pre-stripping to year 18, after that the quantity of waste material mined is reduced. Stockpiling is not considered in this case because using marginal COG does not leave resources to send to the stockpile. All the material below the COG is sent to the waste dump or to the stockpile if the material may generate revenue, and for this specific case the COG is the marginal grade.

After building a base strategic mine plan, the next step is to apply COGO. In order to do this, a stockpile is included using a re-handling cost of 0.50US$/tonne. Figure 4-18 shows the mine plan generated after COGO.

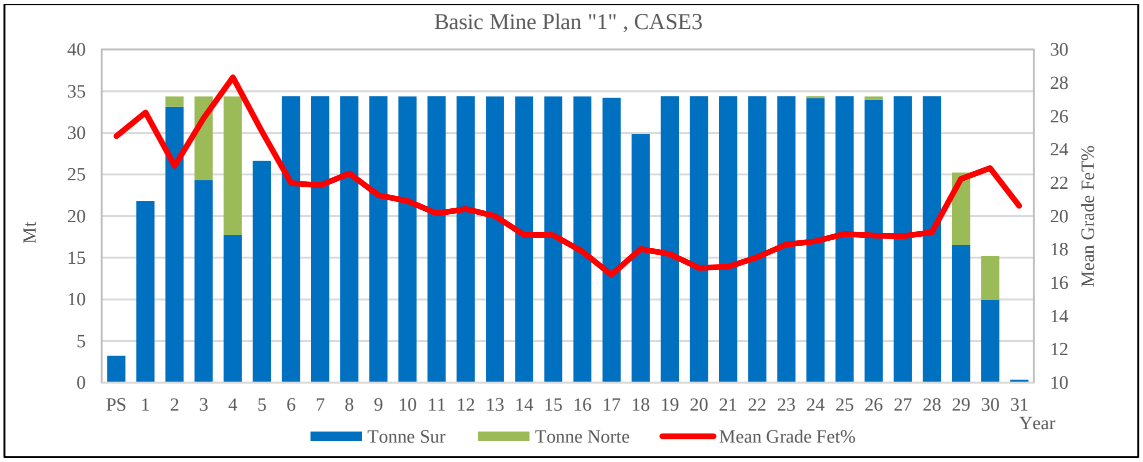

Figure 4-18: Strategic mine plan for the Dominga project using marginal COG, Mine Plan "1", CASE3

In this strategic mine plan, there is a reduction in ore material in year 18. This is not an issue for this study because the discounted cash flow generated in this year has a limited impact on the total discounted cash flow (or NPV). For the purpose of the case study this variation is acceptable as it could be addressed in detailed planning. Table 4-16 shows the differences between the 2 mine plans generated by applying the COGO.

	CASE3, MinePlan”1”	CASE3, MinePlan”1” (COGO)
Ore (Mt)	982	867
Stockpile (from stockpile to process) (Mt)	-	42
Waste (Mt)	857	927
Total (Mt)	1,839	1,839
Strip Ratio	0.87	1.02
Discounted CashFlow (MUS$)	3,655	3,719
Life of Mine (years)	31.0	28.6

Table 4-16: Comparison using defined COG and using COGO for CASE3, Mine Plan “1”

The discounted cash flow generated for CASE3 without COGO is MUS$3,655 versus MUS$3,719 using the optimization. This is a 2% increase in discounted cash flow using a COG strategy. The amount of ore has been reduced from 982Mt to 909Mt (Ore+Stockpile). This may conflict with company objectives is to increase the tonnes of reserves, however if the main goal of the company is to increase NPV (increase the discounted cash flow), this optimization improves that amount and is a valid strategy.

Figure 4-19 shows the average grade for both cases:

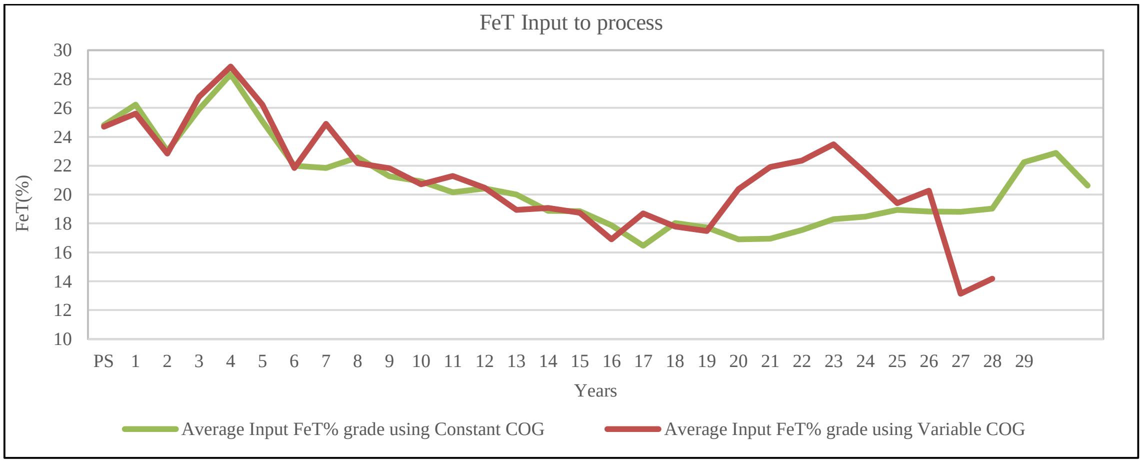

Figure 4-19: Average annual grades indicated by using a defined COG and a COGO

The mean grades for each period for both methodologies are similar in that the average grade declines over the mine life. The COGO algorithm does not produce large changes in average grades throughout the mine life and this can be explained because the block model, or the deposit, is highly homogeneous in terms of iron grades. This means there is limited opportunity to exploit the mining of high grades early in the mine life to improve cash flow. In the later part of the mine life the graph shows that the COGO was able to increase COG to improve the economics of the project. However, because this occurs well into the mine life the impact on discounted value is limited.

Figure 4-20 shows the effect of applying the optimization for rocktype 4012 in Dominga Sur.

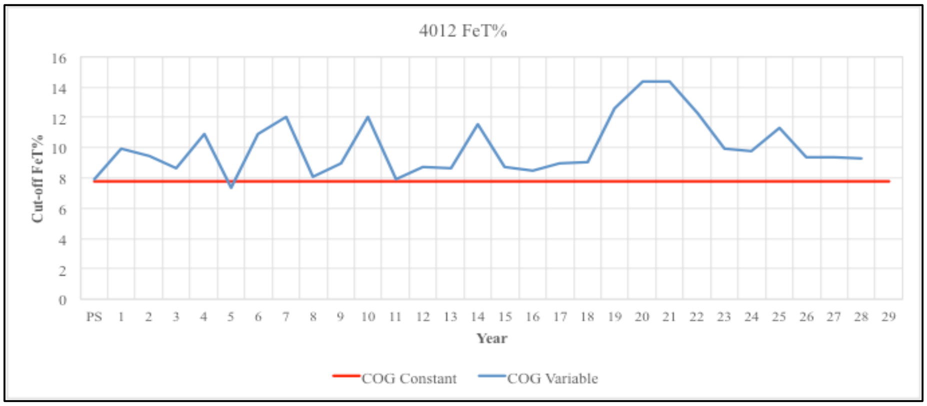

Figure 4-20: Effect in FeT(%) grade of applying the optimization for rocktype 4012 in Dominga Sur

The red line represents the marginal COG calculated by Whittle that in this rocktype is 7.8%FeT. As can be seen in the figure above, the variable COG has a peak of 14%FeT for the years between 19 and 22. The optimization produces the same effect for every rocktype involved in the process.

4.1.2.3.3 Strategic Mine Plan “2”, CASE3

This mine plan was built using the Milawa NPV algorithm, in this mine plan the maximum mining rate achievable is increased to 100Mtpa instead of 70Mtpa form the case Mine Plan “1”. This example is to show the impact of COGO and increasing the mining rate from 70Mtpa to 100Mtpa. Figure 4-21 shows the strategic mine plan for Dominga project:

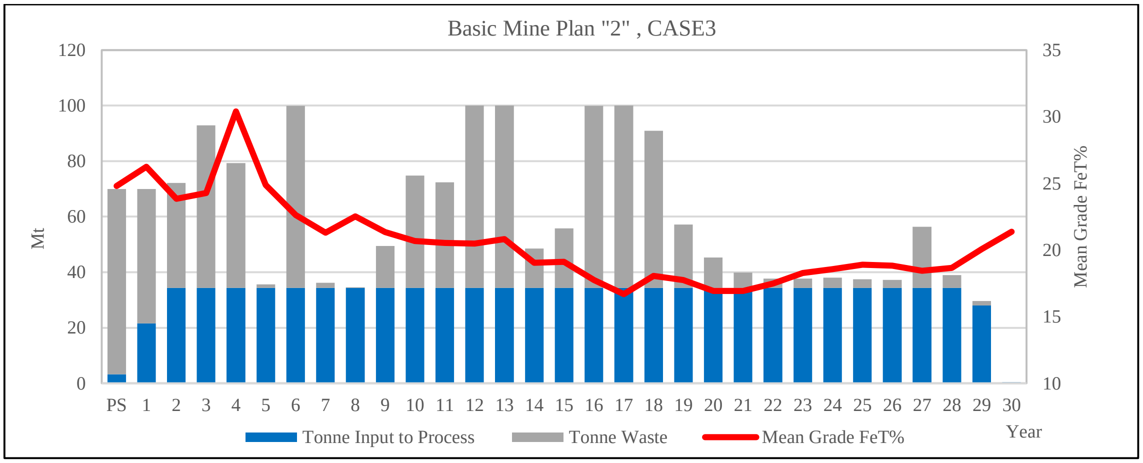

Figure 4-21: Strategic mine plan for the Dominga project using marginal COG, Mine Plan “2”, CASE3

In this example (see Figure 4-22), the amount of material sent to the mill is constant from year 2 until the end of the mine life. The movement of waste material is not constant and the mine life is almost 30 years.

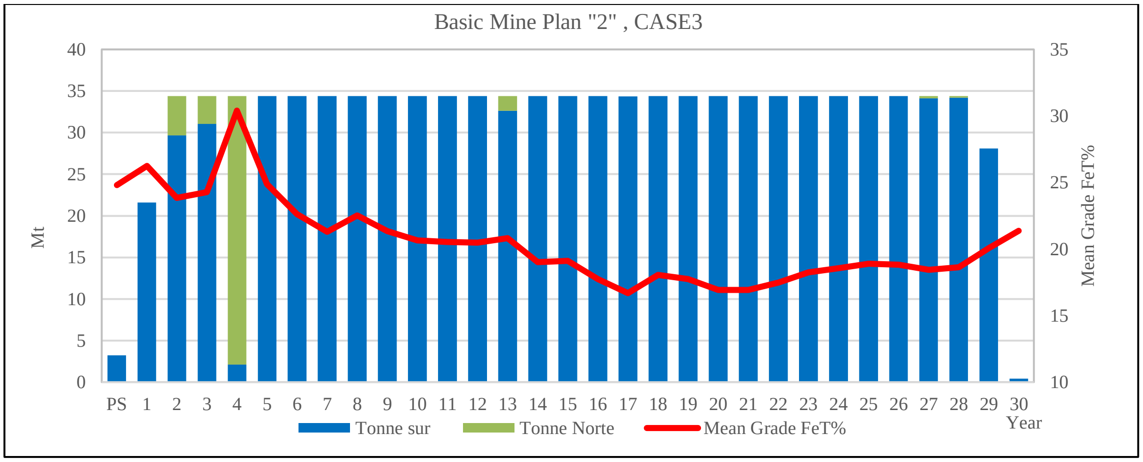

Figure 4-22: Strategic mine plan for the Dominga project using marginal COG, Mine Plan “2”, CASE3

The material from Dominga Norte is sent to the mill in the early years of the mine life. There is no material to stockpile because marginal cut-off grade is used.

Applying the COGO to the mine plan, there is a change in the mine life from 30 years to 24 years as shown in Figure 4-23.

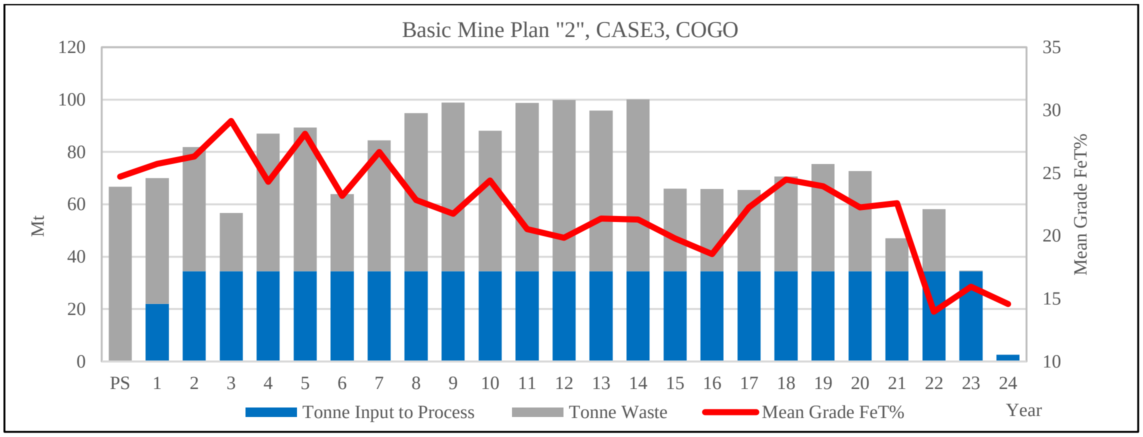

Figure 4-23: Strategic mine plan for the Dominga project using marginal COG, Mine Plan “2”, CASE3

The movement of material is more consistent throughout the mine life. Figure 4-24 shows that the impact to applying COGO is that the ore from Dominga Norte is not concentrated solely in the early years. Also, material from the stockpile is included or sent to the mill at the end of the mine life.

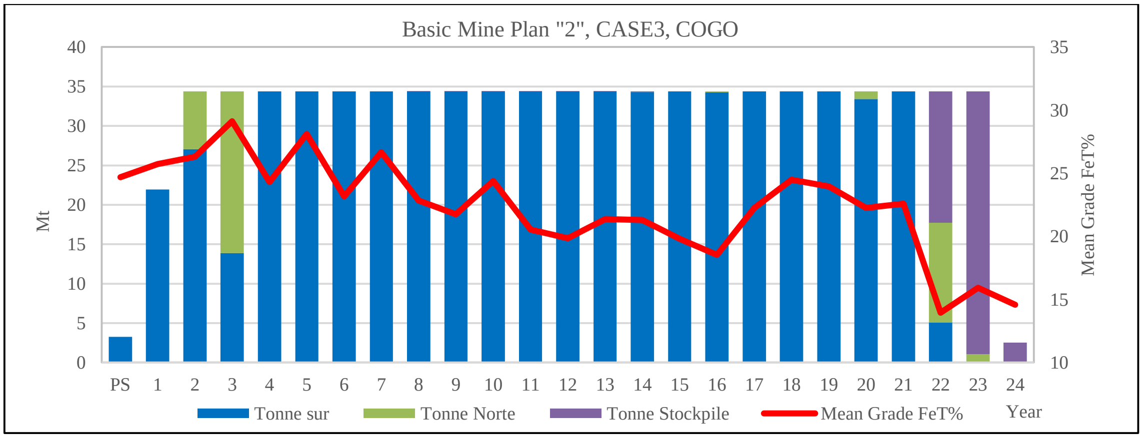

Figure 4-24: Strategic mine plan for the Dominga project using marginal COG, Mine Plan “2”, CASE3

Table 4-17 shows the mine plan statistics from applying and not applying the COGO.

	Case3 MinePlan"2"	Case3, MinePlan"2" (Cut-off Optimization)
Ore (Mt)	982	732
Stockpile (from stockpile to process) (Mt)	-	53
Waste (Mt)	857	1055
Total (Mt)	1,839	1,839
Strip Ratio	0.87	1.34
Discounted CashFlow (MUS$)	3,766	3,885
Life of Mine (years)	30	24

Table 4-17: Comparison using defined COG and using COGO for CASE3, Mine Plan "2"

The discounted cash flow generated for the CASE3 MinePlan"2" not using COGO is MUS$3,766 meanwhile using COGO it is MUS$3,885. This is a 3% improvement using a COGO strategy. The amount of ore has been reduced from 982Mt to 785Mt.

Figure 4-25 represents the mean grades from the two mine plans. The red line is for a variable COG strategy and most of the periods at the beginning of the mine life have a higher COG than with the constant COG strategy.

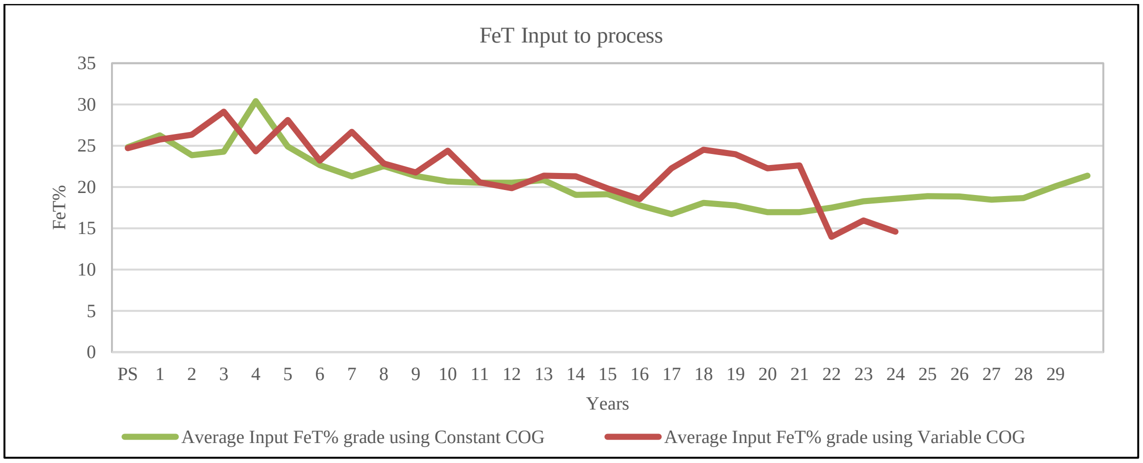

Figure 4-25: Average annual grades indicated by using a defined COG and a COGO

The 3% improvement in discounted project value, while desirable, is not as large as the improvement indicated in some of the literature. This can be explained because although higher grade material is advanced to earlier years of the mine life the increase in average grade is still small. The deposit is fairly homogeneous in terms of grade. Although there is a significant improvement in the average grade in the later years of the plan when applying the variable COG, the use of discounting reduces the impact of these years in terms of their present (or discounted) value.

4.1.2.3.3.1 Mine Plan "2" Considering Capital Expenditure

The objective of this sub-section is to apply the capital expenditure to the economics of the mine plan "2" for Dominga project and observe the effect that it has on the NPV generated for that mine plan when a COGO is applied (see Table 4-18). The capital expenditure (CAPEX) used in this case is MUS$2.500.

	CASE3 MinePlan"2"	CASE3, MinePlan"2" (COGO)
Ore (Mt)	982	759
Stockpile (from stockpile to process) (Mt)	-	55
Waste (Mt)	857	1,024
Total (Mt)	1,839	1,838
Strip Ratio	0.87	1.34
Net Present Value (MUS$)	1,270	1,376
Internal Rate of Return (%)	13.1	13.6
Life of Mine (years)	30	25

Table 4-18: Net present value comparison using defined COG and using COGO for CASE3, Mine Plan "2", considering capital expenditure

The same economic parameters defined in the Section 4.1.1 are used in this case where the differences between the discounted cash flow generated from using and not using COGO is 3%. In this case, where the NPV is taken into account to measure the difference, the improvement of NPV is from MUS$1,270 from the case using marginal COG to MUS$1,376 from the COGO.

This corresponds to an 8% of improvement in the NPV of the project. The internal rate of return is almost the same for both cases, which is 13%. The life of mine has been significantly impacted, dropping from 30 to 25 years of production.

4.1.3 Summary Results

Table 4-19 presents a summary from the CASE1, CASE2 and CASE3.

	CASE1		**CASE2**			**CASE3**			
	Marginal COG	COGO	Cut-off Ore Selection Method		Cashflow Ore Selection method	MinePlan”1”		MinePlan”2”	
			Defined COG	COGO above Defined COG	Defined COG	Marginal COG	COGO	Marginal COG	COGO
Ore (Mt)	990	924	891	927	873	982	867	982	732
Stockpile (from stockpile to process) (Mt)	-	57	61	55	-	-	42	-	53
Waste (Mt)	849	857	1,159	1,130	1,335	857	927	857	1055
Total (Mt)	1,839	1,839	2,111	2,112	2,208	1,839	1,839	1,839	1,839
General Strip Ratio	0.86	0.87	1.3	1.22	1.53	0.87	1.02	0.87	1.34
Discounted CashFlow (US$)	3,746	3,819	3,999	3,961	4,050	3,655	3,719	3,766	3,885
Life of Mine (years)	30	29.5	29	30	27	31	28.6	30	24
CODIFICATION[5]	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***

Table 4-19: Summary for CASE1, CASE2 and CASE3

Columns B-D-G-I represent the mine plans after applying COGO.

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[5] The last row of the Table 4-19 presents a codification created to simplify the comments related with every column of this table

Figure presents a Discounted cash flow summary from the CASE1, CASE2 and CASE3.

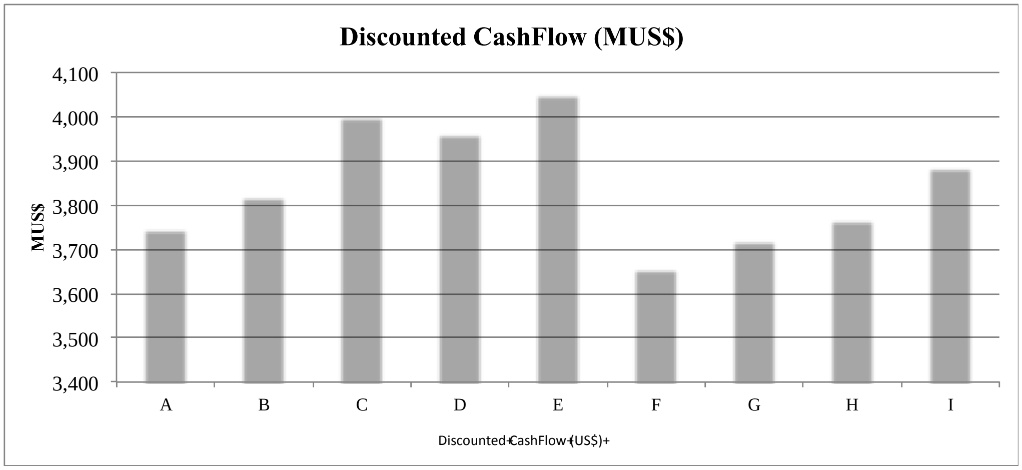

Figure 4-26: Discounted Cash Flow summary for CASE1, CASE2 and CASE3

For CASE1, the increment in the discounted value applying COGO is 2%. Considering discounted cash flow as a basis for comparing the three cases presented in Chapter 4, it is important to notice that the COGO does not produce a big impact in terms of adding value to the discounted project value.

For CASE2, “Cash Flow” Ore Selection Method using a defined COG is the methodology that produces the highest discounted cashflow.

From Table 4-19, for CASE2 and CASE3, applying a constant COG for the entire life of mine as is shown in the CASE2, has a similar impact as if COGO is applied.

The case that produces the highest impact in terms of discounted cashflow after applying COGO is the CASE3, Mine Plan”2”, where the increment is 3.16%. The case that produces the lowest impact in the discounted cashflow after apply COGO is the CASE3, Mine Plan “2”, where the increment is 1.75%.

Chapter 5

Conclusions and Recommendations

It is clear that the definition of the cut-off grades used as strategy is a fundamental stage of the mining process. The results of the case study presented in this thesis allow general conclusions to be drawn about the usefulness of various COG strategies for the Dominga project. Some of these conclusions could also be relevant when planning a COG strategy for other deposits similar to Dominga where the grade distribution is fairly homogeneous or also where multiple elements are present (in the Dominga project the main element is FeT which has a homogeneous distribution, and produces Cu and Au concentrate as a sub-product).

The use of both defined COG strategy and COGO produce improved discounted cashflow results when compared to the marginal COG case. This was true for all of the approaches investigated. It is clear that the marginal strategy often employed in industry is not a suitable approach where the objective of the project is to maximize NPV.

5.1 Research achievement

The objective of this thesis is not to present a detailed mine plan using a COGO strategy. The objective is to analyze the effect of the use of different methodologies of COG in the Dominga project. For this reason three cases were developed using different COG methodologies.

A review of industrial practices in COG strategies was described. A wide range of literature was reviewed and analyzed. Methodologies of marginal COG, defined COG and COGO were developed and applied for Dominga project. Finally conclusions were developed.

5.2 Conclusions

The following conclusions can be drawn for the Dominga project analysis.

1. The benefit of the use of defined COG and COGO strategies over the use of a marginal COG in improved discounted cashflow is demonstrated (see Table 4-19). The improvements in the discounted cashflow using COGO over marginal COG ranged from 1.8% (CASE3 Mine Plan"1") to 3.2% (CASE3 Mine Plan"2").

   These results are not as dramatic as some of the results presented in the literature, most likely explained by the narrow grade distribution typical of this type of deposit, but they still are an improvement.

2. For the Dominga project, the use of a defined COG strategy generally produced similar results to applying a COGO above a marginal or defined COG. It is obvious that while it is easy to implement, the marginal grade approach should not be used even where the grade distribution is fairly homogeneous. The use of a defined FeT(%) COG is therefore an acceptable practice to work with, however it requires a knowledgeable individual to conduct the analysis.

   Because the iron grade and tonnage distribution of the deposit affects the COGO algorithm (see Figure 3-4, 3-12 and Appendix A, where the tonnage-grade curves and the histograms are shown) the results of applying COGO in this deposit are similar to applying a defined COG.

3. Using the “Cut-off” Ore Selection Method and considering FeT(%) and Cu(%) and Au(ppm) as elements to calculate cut-offs, the defined FeT(%) COGs selected were 15% for Dominga Norte and 17% for Dominga Sur (see CASE 2). Applying COGO above the defined COGs, the results are that the mine plan produces a lower discounted value. The conclusion can be drawn that application of the COGO method in a mine plan which already has a well-defined COG (15%DN-17%DS) will not improve the discounted value in Dominga project. The optimization algorithm may not be able to function properly when the constraint of defined COGs is introduced.

4. For the Dominga project the “Cash Flow” ore selection method in Whittle produced the greatest discounted cashflow (see Table 4-19, row E) taking into consideration the same economic parameters and the same mine plan inputs were used for all the cases.

   The improvement of the discounted cashflow was, however, associated with a high strip ratio, the most waste mined, and a reduction in ore tonnes compared to the marginal CASE1, reducing the mine life by 3 years. Some of these impacts may not be acceptable and are of questionable validity depending on what is the defined objective of the company.

   The “Cash Flow” Ore Selection Method is similar in function to the NSR method of evaluating blocks proposed by Rendu, in terms that the value of the block is evaluated considering the full range of value adding and destroying (e.g. impurities) elements in a block, rather than the grade of just the primary element (see Appendix C). With the

Dominga project the algorithm could include the additional value contributed by copper and gold when determining whether or not to process a block.

5. To work using COGO in Whittle Software it is necessary that the recoveries of the different rocktypes in the model should be constant value or a function of one variable. In the case of the Dominga project, the recoveries are a function of two variables and for this reason it is necessary to build models with constant recoveries. This is not a favorable scenario in the sense that increasing the number of rocktypes to have the required format for recoveries would increase the time and the complexity of the exercise.

6. Computing power was a limiting factor in the types of analysis and level of detail that could be performed for the Dominga project, which is a large and complex deposit. In particular, the size of each block had to be modified and also because the time required to apply COGO to a "CashFlow" Ore Selection Method was unknown (the analysis could not be completed within the timeframe of the thesis). Although the more advanced COG strategies require greater knowledge and increased work the increase in NPV is worth the additional costs.

The following general conclusions may also be drawn from the work completed for this thesis and are applicable to similar deposits.

7. The COG method that produces the highest discounted cashflow may impact other project parameters, such as mine life, total tonnes mined, strip ratio, stockpile utilization, etc.

For a sustainability point of view, it is important to consider the regulatory and social acceptance before any strategy is implemented. For this reason additional costs of reclamation for the extra waste material should be considered. These types of factors are not possible to include in the current methods and software and the decision making process must therefore still rely on human judgment.

8. The improvement of the discounted value in deposits where the grade distribution is relatively concentrated is probably not as significant as when there is a wide variation in grades. However, it was shown that defined COG and COGO strategies still produced improvements in discounted value if they are applied above a marginal COG strategy. Marginal strategies are sub-optimal and should not be used.

9. The use of the “Cash Flow” Ore Selection Method in Whittle, or an NSR approach as described by Rendu, will most likely produce a superior discounted value. This is because this method allows blocks with high by-product values to be categorized as ore, even if the primary metal content is low. Although not an issue in the Dominga project, the method also allows for negative values to be assigned to undesirable included materials. The cash flow method eliminates the problems associated with equivalent grade approaches identified in the literature review.

10. The use of COG and COGO optimization routines in Whittle remains limited by computer processing power, in some cases requiring simplifications to be made to the

block model. A skilled user can reduce the impact of these, but an understanding of these limitations is important.

5.3 Recommendations

For the Dominga project it is recommended that:

1. The recovery model used in this document was a simplification of the problem presented for the utilization of variable recoveries in the application of the COGO methodology in Whittle. For this reason it is recommended to study in more detail the concept to build a recovery model. This would enable applying COGO during the time of the mine life to evaluate different options for improvement.

2. As is more common in the mining industry, the deposits are close to human communities. This is the case in the Dominga project that is surrounded by small communities. Considering conclusion 7, before any COG strategy is chosen, a potential improvement related to the consideration of reclamation costs should be studied, building a model that considers the reclamation cost in the calculation of the COG.

3. One of the reasons the COGO does not generate an improvement of the discounted value above 10%, is because there is a concentration of the grades of the principal element. Considering conclusions, one possible future area of study is to apply COGO to the Dominga project based in Cu(%) as a principal element. That is to consider the copper grade distribution rather than the iron distribution.

4. Considering conclusion 4, the next step is to apply COGO to a different combination of defined FeT(%) COG to analyze the effect of using lower cut-offs in the achievement of a more significant increase in the discounted value.

5. It is interesting to review the analysis of Appendix C, where different alternatives to define a COG are evaluated using “Cut-off” and “Cash Flow” Ore Selection Methods. It is recommended that a more exhaustive analysis considering the different shapes of the pits generated by Whittle should be done.

Chapter 6

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Appendix A

Basic Statistics FeT, FeM, Cu and Au for Dominga

The following figures show basic statistics for FeT, FeM, Cu and Au for Dominga Norte for rocktypes 401-402 and 403.

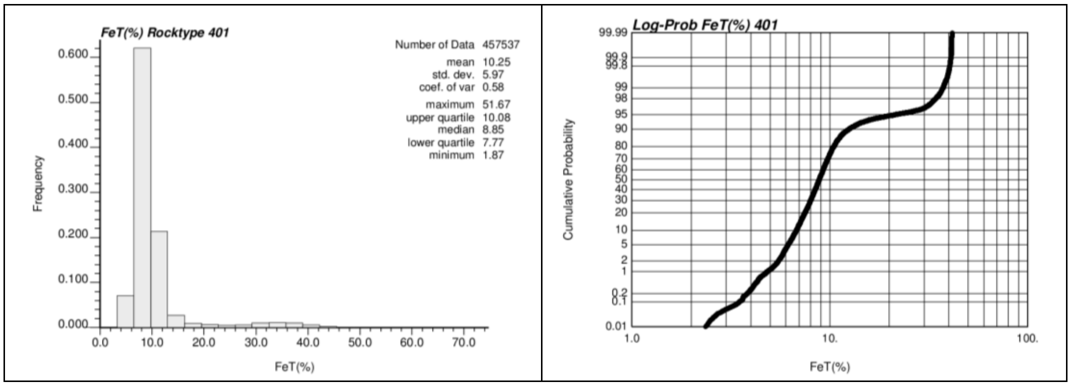

Figure Appendix 1: Left: Histogram for FeT(%) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Norte

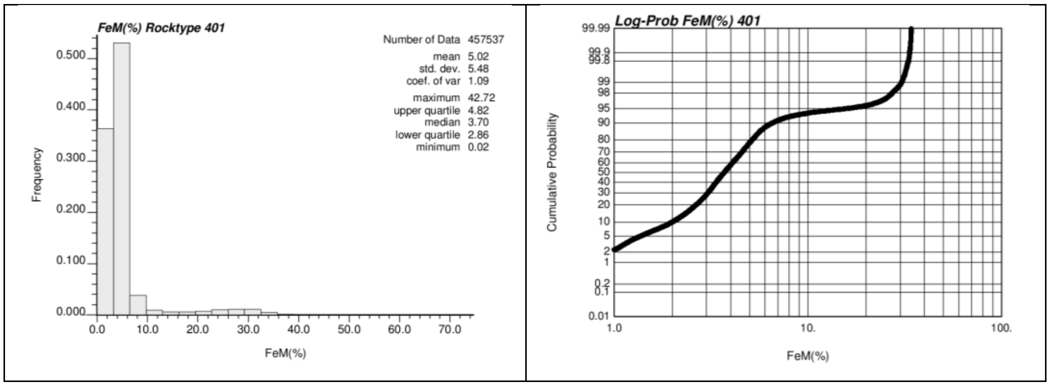

Figure Appendix 2: Left: Histogram for FeM(%) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Norte

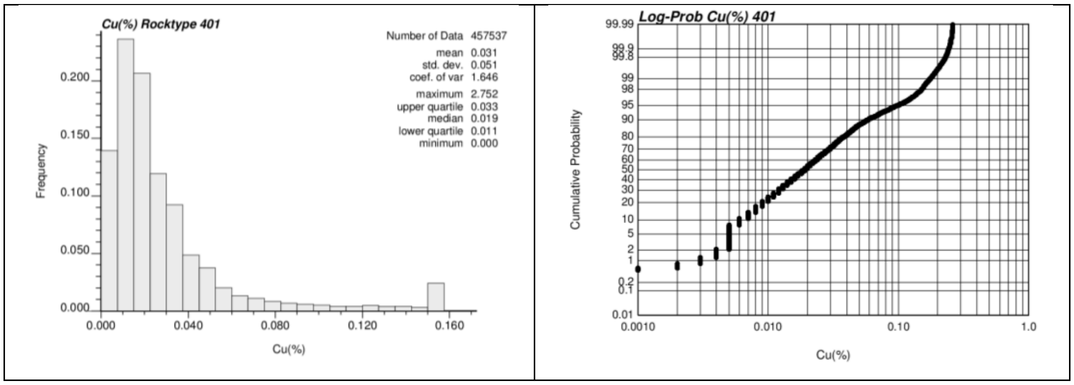

Figure Appendix 3: Left: Histogram for Cu(%) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Norte

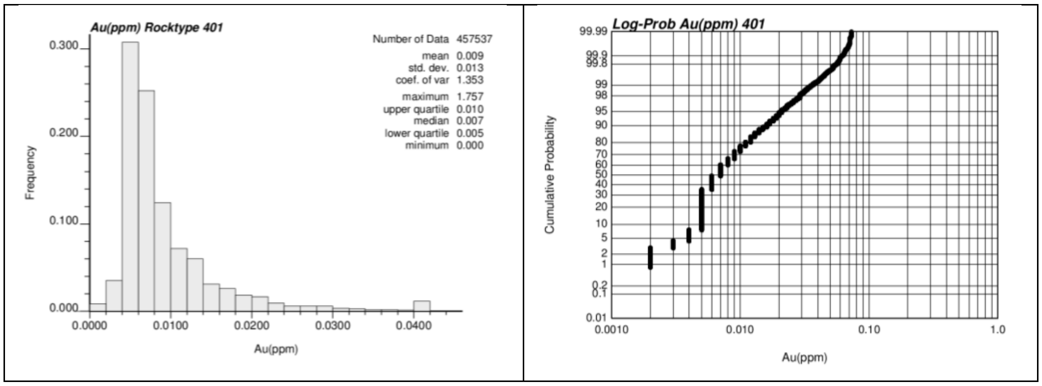

Figure Appendix 4: Left: Histogram for Au(ppm) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Norte

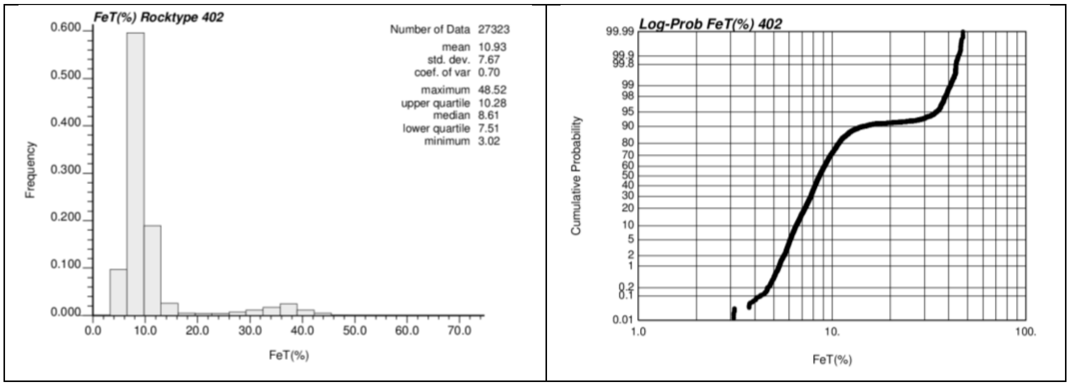

Figure Appendix 5: Left: Histogram for FeT(%) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Norte

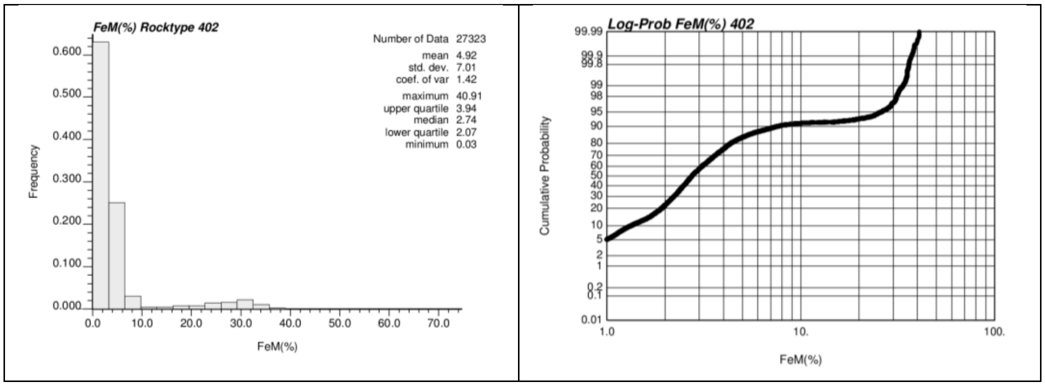

Figure Appendix 6: Left: Histogram for FeM(%) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Norte

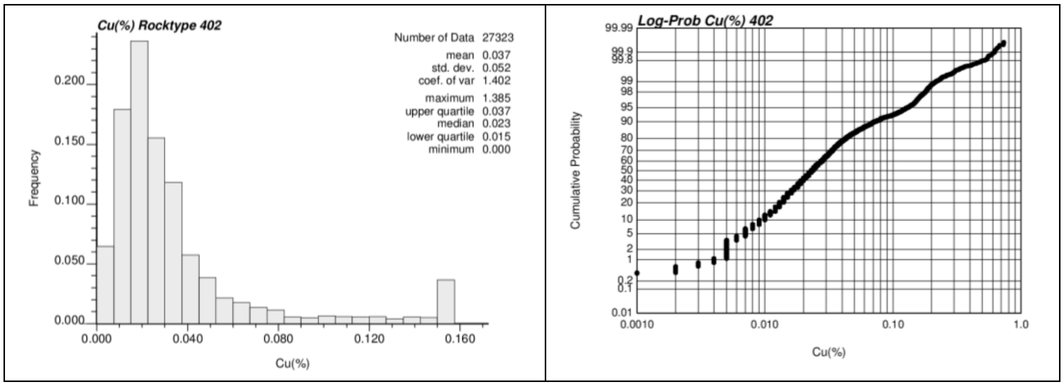

Figure Appendix 7: Left: Histogram for Cu(%) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Norte

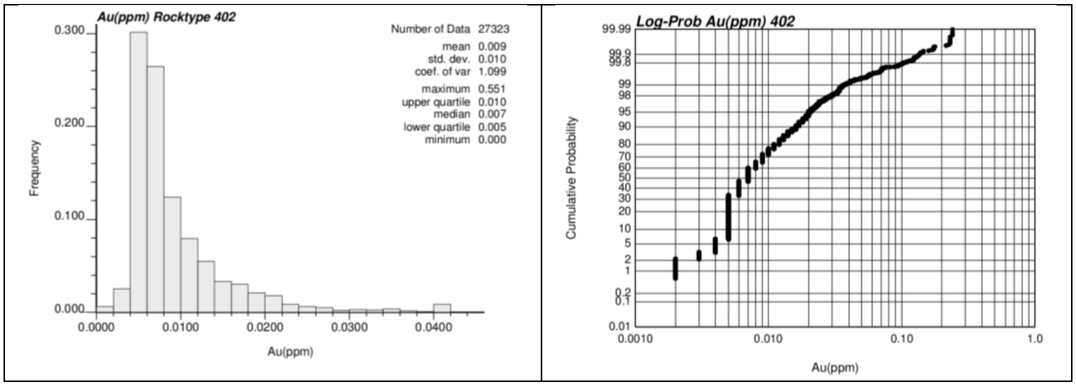

Figure Appendix 8: Left: Histogram for Au(ppm) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Norte

The following figures show basic statistic for FeT and FeM for Dominga Norte and rocktype 403 not considering the grade of FeT that has less than 8%FeM.

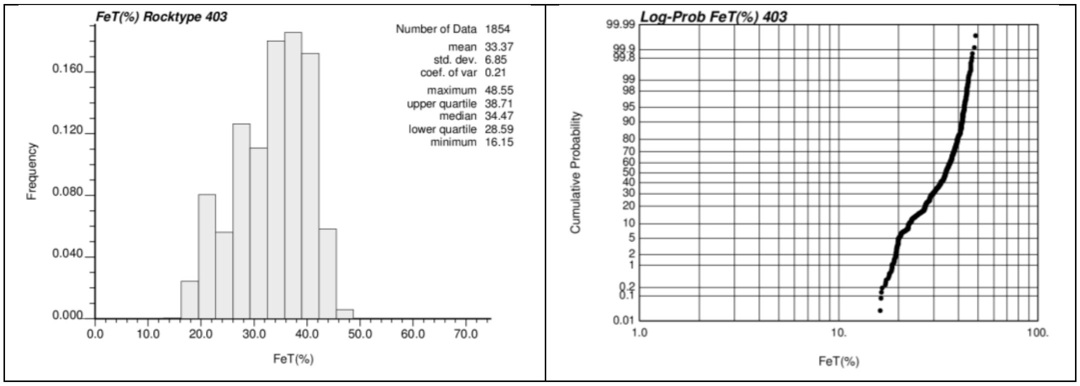

Figure Appendix 9: Histogram for FeT(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte not considering blocks with less than 8%FeM

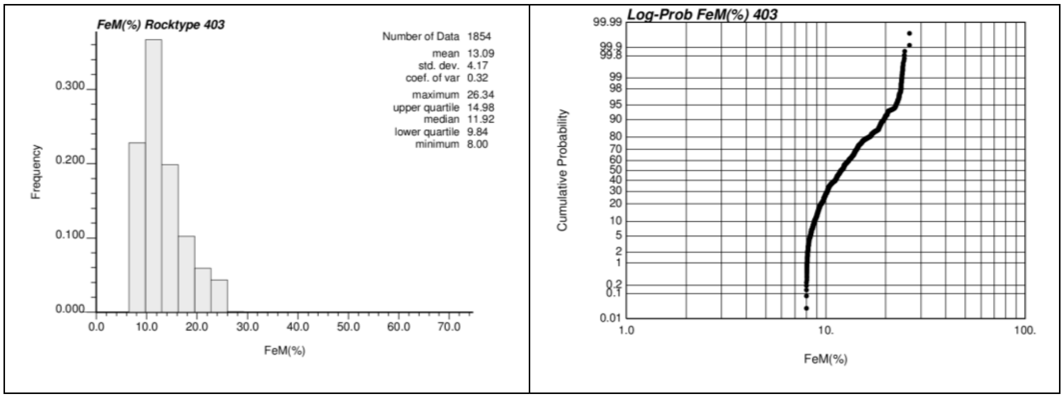

Figure Appendix 10: Histogram for FeM(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte not considering blocks with less than 8%FeM

The following figures show basic statistic for FeT, FeM, Cu and Au for Dominga Norte and rocktype 403 considering the grade of FeT that has less than 8%FeM.

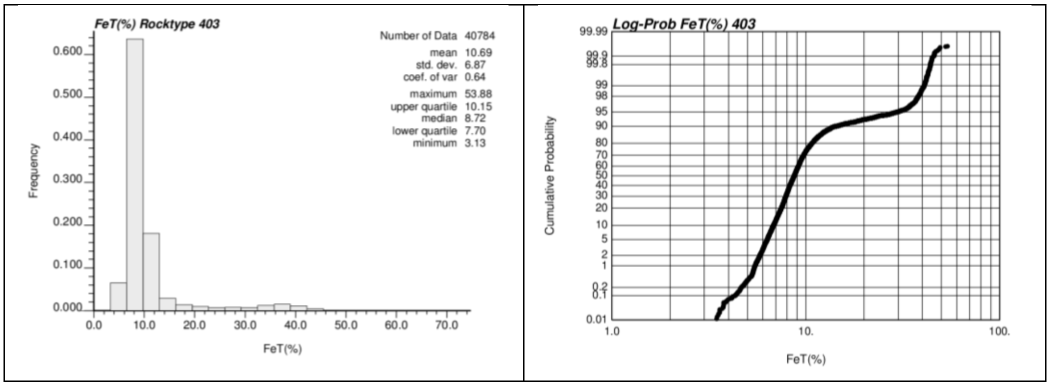

Figure Appendix 11: Histogram for FeT(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte considering blocks with less than 8%FeM

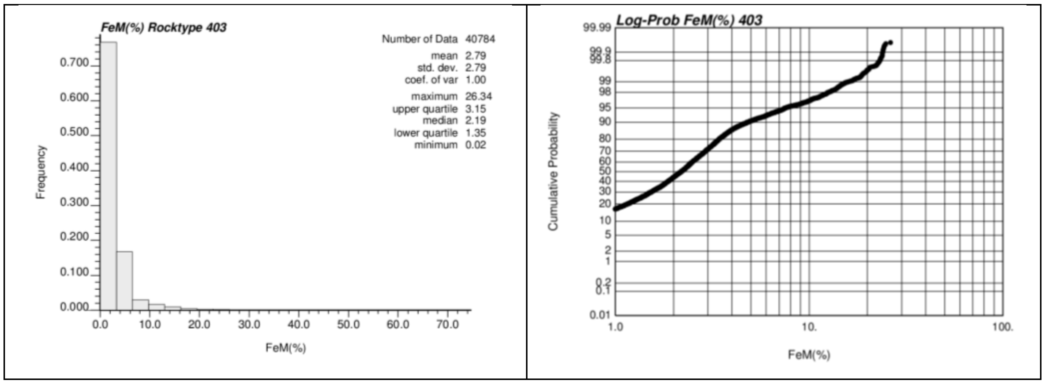

Figure Appendix 12: Histogram for FeM(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte considering blocks with less than 8%FeM

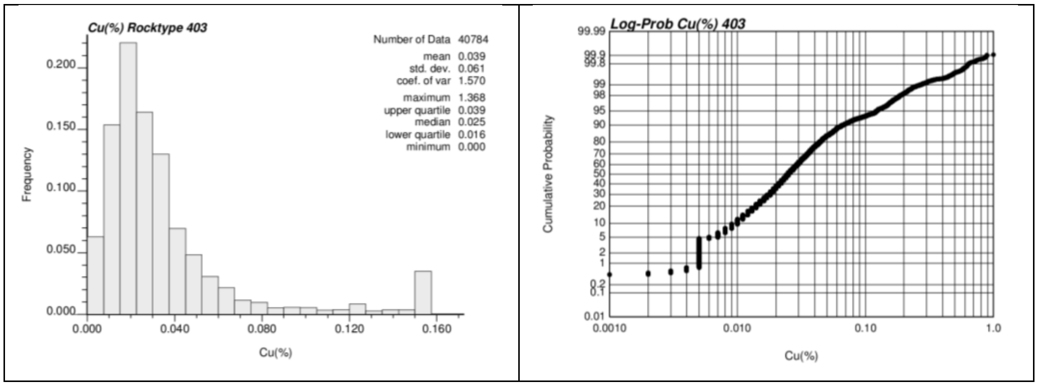

Figure Appendix 13: Histogram for Cu(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte considering blocks with less than 8%FeM

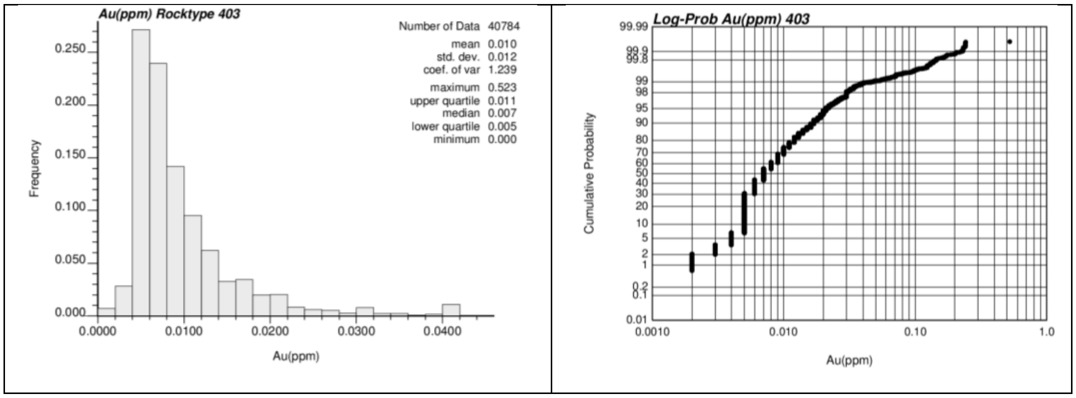

Figure Appendix 14: Histogram for Au(ppm) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Norte considering blocks with less than 8%FeM

The following figures show basic statistics for FeT, FeM, Cu and Au for Dominga Sur for rocktypes 401-402 and 403.

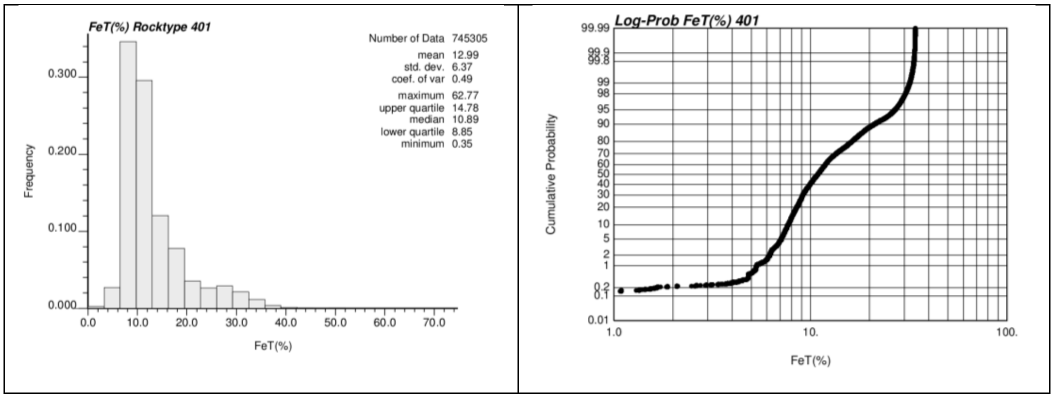

Figure Appendix 15: Left: Histogram for FeT(%) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Sur

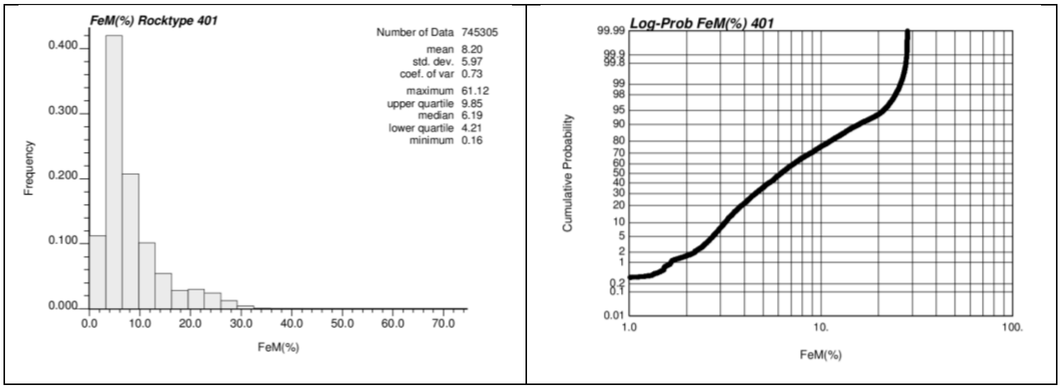

Figure Appendix 16: Left: Histogram for FeM(%) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Sur

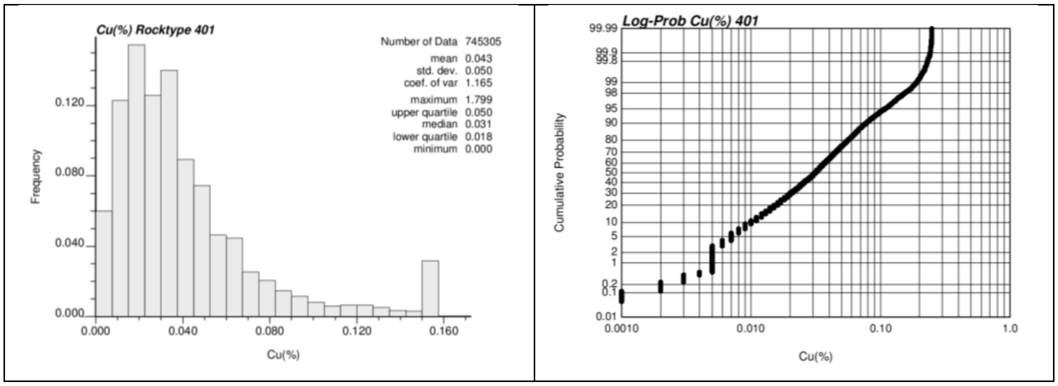

Figure Appendix 17: Left: Histogram for Cu(%) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Sur

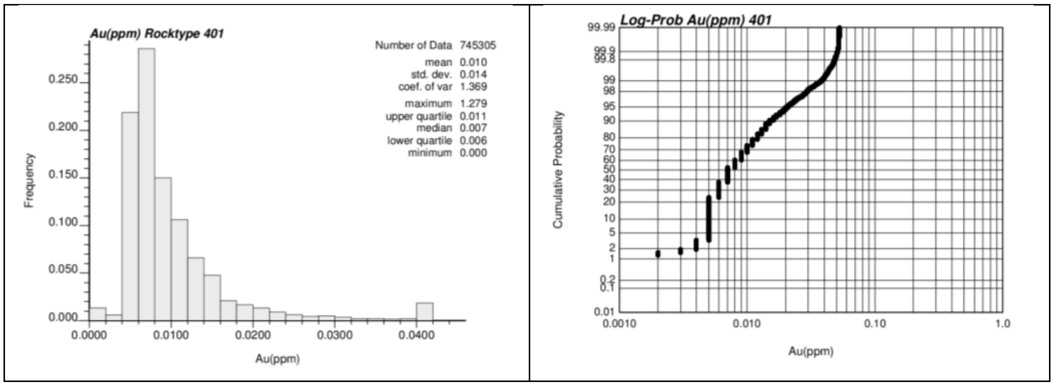

Figure Appendix 18: Left: Histogram for Au(ppm) for rocktype 401 , Right: Log-prob graph rocktype 401, Measured and Indicated resources, Dominga Sur

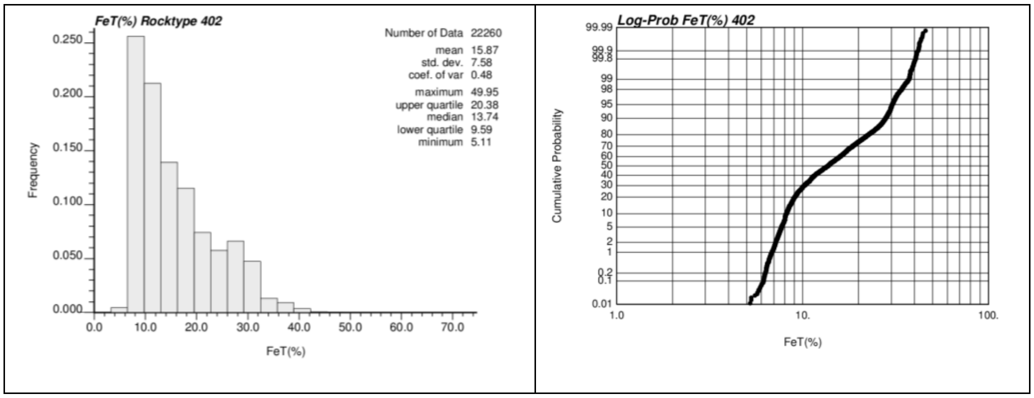

Figure Appendix 19: Left: Histogram for FeT(%) for rocktype 402 , Right: Log-prob graph rocktype 402,

Measured and Indicated resources, Dominga Sur

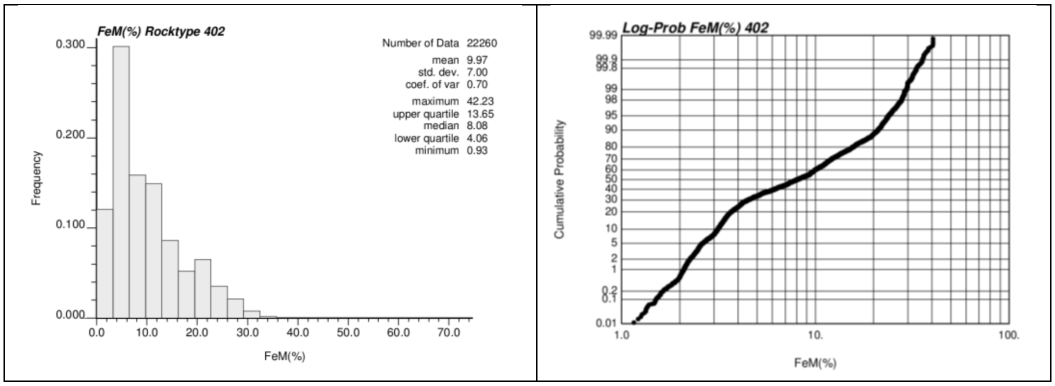

Figure Appendix 20: Histogram for FeM(%) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Sur

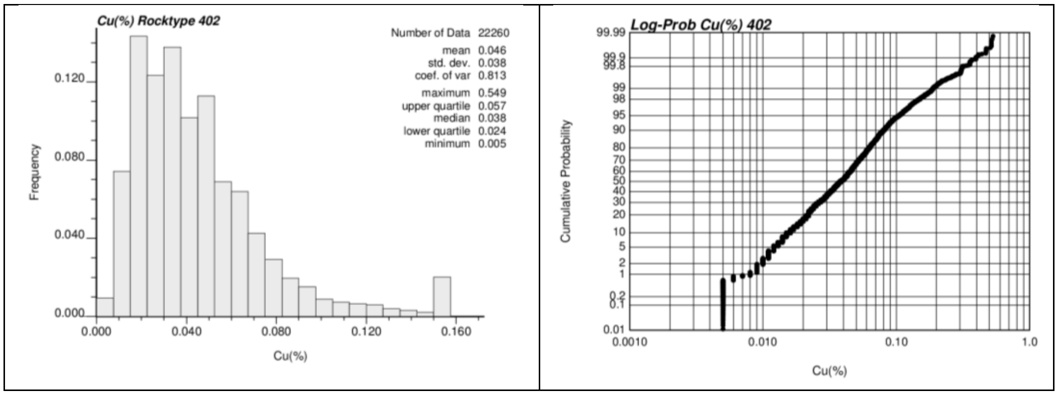

Figure Appendix 21: Histogram for Cu(%) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Sur

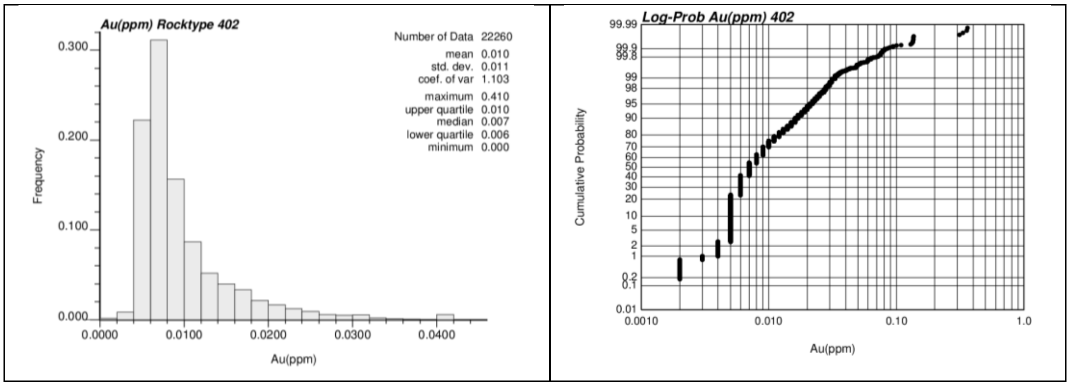

Figure Appendix 22: Histogram for Au(ppm) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Sur

The following figures show basic statistic for FeT and FeM for Dominga Sur and rocktype 403 not considering the grade of FeT that has less than 8%FeM.

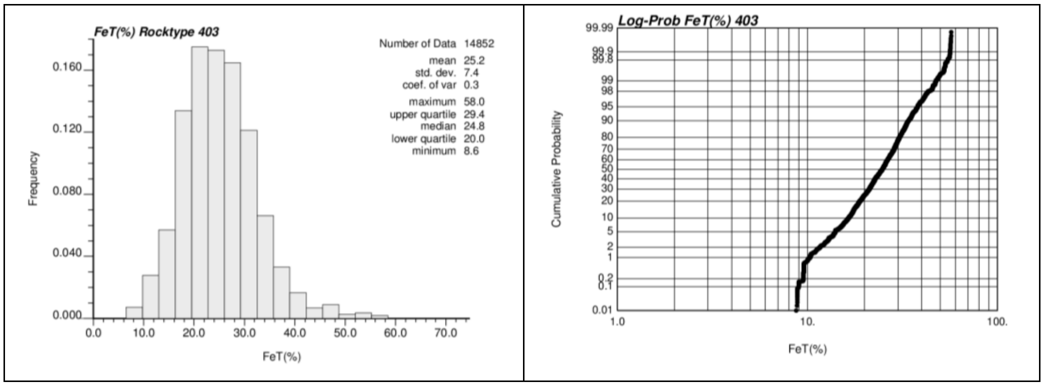

Figure Appendix 23: Histogram for FeT(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Sur not considering blocks with less than 8%FeM

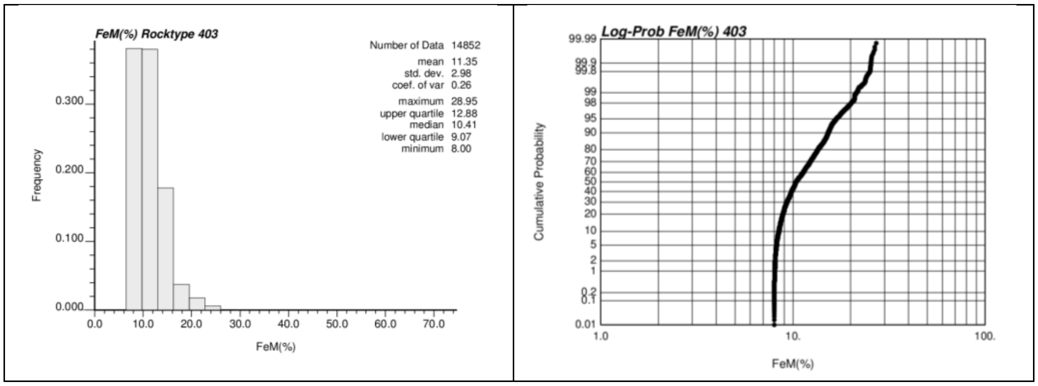

Figure Appendix 24: Histogram for FeT(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Sur not considering blocks with less than 8%FeM

The following figure shows basic statistic for FeT, FeM, Cu and Au for Dominga Sur and rocktype 403 considering the grade of FeT that has less than 8%FeM.

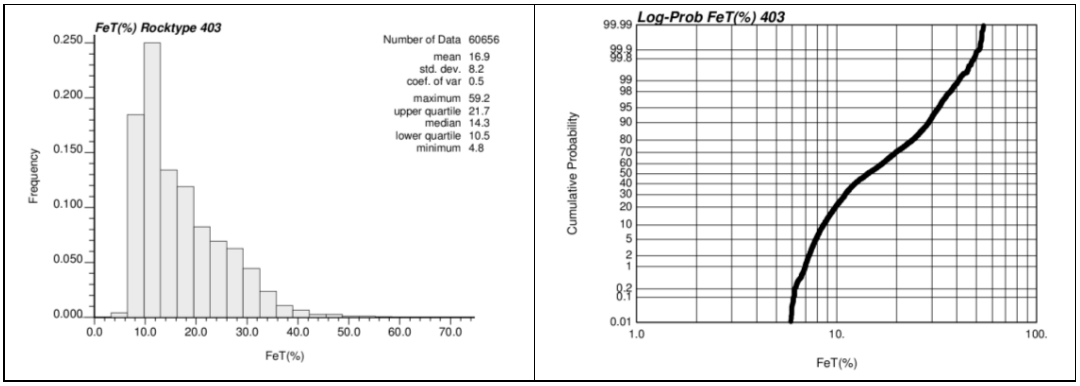

Figure Appendix 25: Histogram for FeT(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Sur considering blocks with less than 8%FeM

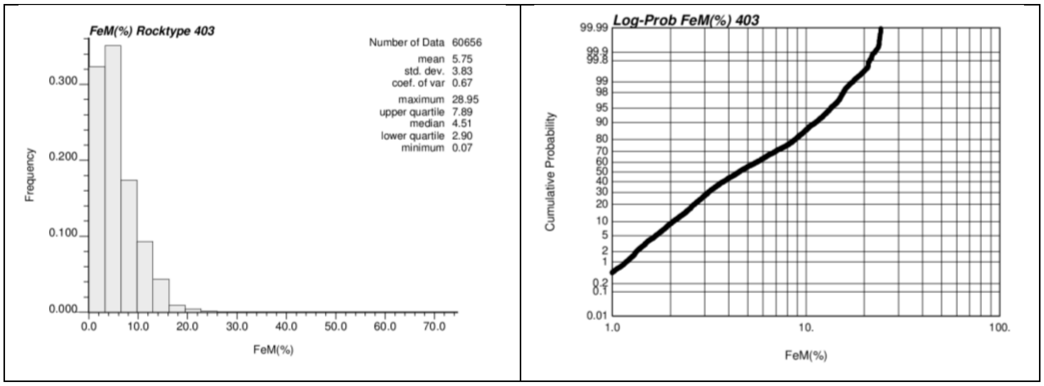

Figure Appendix 26: Histogram for FeM(%) for rocktype 403 , Right: Log-prob graph rocktype 403, Measured and Indicated resources, Dominga Sur considering blocks with less than 8%FeM

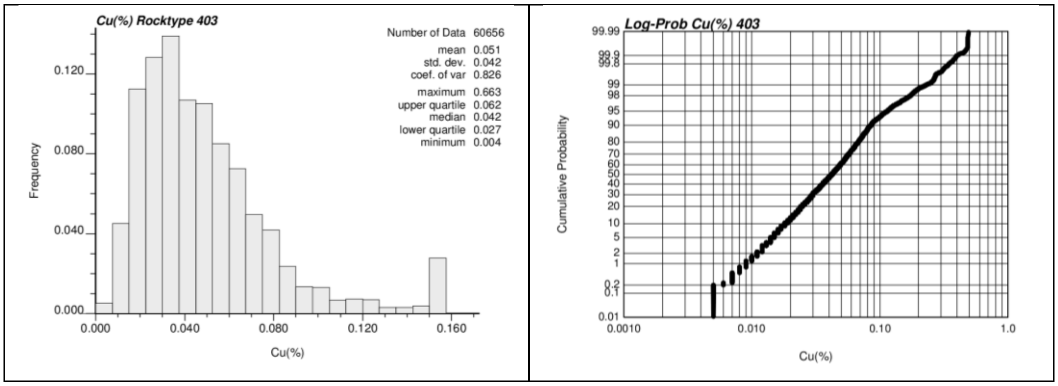

Figure Appendix 27: Histogram for Cu(%) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Sur considering blocks with less than 8%FeM

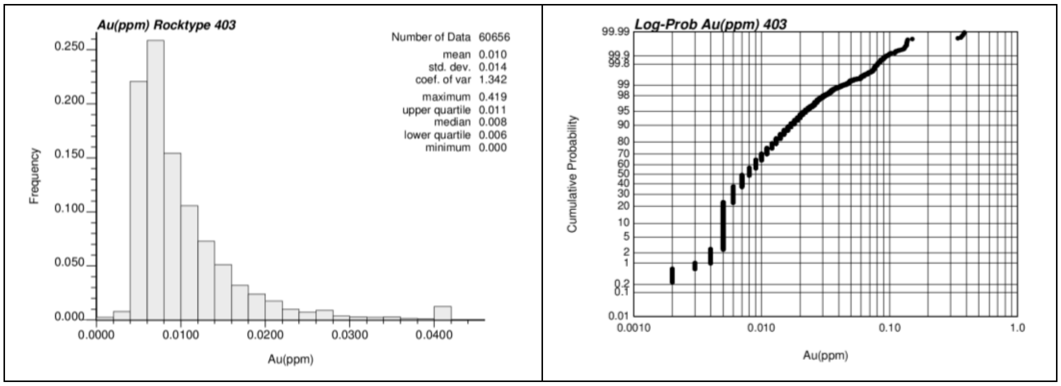

Figure Appendix 28: Histogram for Au(ppm) for rocktype 402 , Right: Log-prob graph rocktype 402, Measured and Indicated resources, Dominga Sur considering blocks with less than 8%FeM

Appendix B

Validation of the Recovery Models

The following table shows the results from the L&G algorithm applied in Dominga Norte based on the model with variable recoveries.

Base Model								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.36	23,829,552	5,335,929	3.5	34.73	24.32	0.527	0.097
2	0.38	26,309,625	6,670,440	2.9	35.04	23.97	0.444	0.082
3	0.40	30,017,874	7,987,202	2.8	35.09	24.08	0.396	0.071
4	0.42	35,469,435	10,016,888	2.5	35.29	23.86	0.340	0.061
5	0.44	38,169,549	10,632,519	2.6	34.96	23.63	0.338	0.062
6	0.46	40,304,081	11,414,390	2.5	34.50	23.19	0.330	0.060
7	0.48	96,889,641	24,301,901	3.0	34.03	24.23	0.224	0.036
8	0.50	123,120,941	29,651,285	3.2	34.05	24.44	0.206	0.032
9	0.52	125,753,376	30,265,334	3.2	33.95	24.42	0.204	0.032
10	0.54	138,641,954	32,669,988	3.2	33.86	24.41	0.199	0.031
11	0.56	156,443,178	35,554,934	3.4	33.87	24.58	0.192	0.029
12	0.58	165,082,272	37,166,958	3.4	33.59	24.40	0.192	0.029
13	0.60	211,128,057	44,053,836	3.8	33.36	24.44	0.182	0.027
14	0.62	339,672,008	63,152,606	4.4	33.15	24.02	0.167	0.024
15	0.64	428,869,772	76,328,084	4.6	32.89	23.97	0.156	0.021
16	0.66	436,699,751	78,876,569	4.5	32.48	23.64	0.154	0.021
17	0.68	452,029,172	81,880,064	4.5	32.19	23.43	0.152	0.021
18	0.70	470,299,829	85,701,618	4.5	31.80	23.14	0.149	0.020
19	0.72	507,112,160	92,279,699	4.5	31.27	22.74	0.146	0.020
20	0.74	511,673,135	94,061,175	4.4	31.01	22.51	0.145	0.020
21	0.76	524,686,631	97,681,737	4.4	30.57	22.14	0.143	0.020
22	0.78	544,096,373	102,973,488	4.3	29.98	21.64	0.140	0.019
23	0.80	559,979,166	107,164,388	4.2	29.55	21.29	0.137	0.019
24	0.82	585,855,857	114,039,731	4.1	28.80	20.68	0.134	0.019
25	0.84	598,559,046	118,353,497	4.1	28.34	20.28	0.132	0.018
26	0.86	620,035,044	125,232,677	4.0	27.69	19.75	0.128	0.018
27	0.88	1,198,318,224	205,064,501	4.8	25.79	18.50	0.114	0.016
28	0.90	1,216,631,318	213,187,551	4.7	25.35	18.12	0.112	0.016
29	0.92	1,222,681,836	220,576,626	4.5	24.90	17.72	0.110	0.016

Base Model								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
30	0.94	1,251,405,054	235,584,191	4.3	24.16	17.09	0.105	0.016
31	0.96	1,289,576,144	247,625,936	4.2	23.71	16.70	0.103	0.016
32	0.98	1,295,124,386	255,790,589	4.1	23.29	16.34	0.101	0.015
33	1.00	1,326,466,709	272,554,227	3.9	22.63	15.76	0.098	0.015

Table Appendix 1: Results from the L&G algorithm applied in Dominga Norte base in the model with variable recoveries.

The following table shows the results from the L&G algorithm applied in Dominga Norte based on Model 1: Recovery based on Recovery Distribution

Model 1: Recovery based on Recovery Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.36	23,038,116	5,067,680	3.6	35.03	23.67	0.539	0.101
2	0.38	24,097,080	5,651,709	3.3	35.17	23.72	0.498	0.092
3	0.40	26,997,458	6,992,288	2.9	35.60	23.88	0.420	0.077
4	0.41	30,116,837	8,121,011	2.7	35.61	23.96	0.381	0.069
5	0.43	32,733,458	9,194,396	2.6	35.60	23.80	0.350	0.063
6	0.44	35,641,176	10,056,987	2.5	35.68	23.92	0.330	0.059
7	0.46	38,379,039	10,578,818	2.6	35.36	23.81	0.331	0.061
8	0.48	38,422,346	10,643,390	2.6	35.27	23.74	0.330	0.061
9	0.49	41,389,787	11,643,689	2.6	34.91	23.34	0.314	0.058
10	0.51	118,261,640	28,365,975	3.2	34.43	24.61	0.204	0.032
11	0.52	123,400,010	29,504,280	3.2	34.32	24.57	0.201	0.031
12	0.54	123,531,537	29,686,800	3.2	34.22	24.48	0.201	0.031
13	0.56	147,560,484	33,580,692	3.4	34.23	24.71	0.192	0.029
14	0.57	152,110,493	34,468,007	3.4	34.18	24.74	0.189	0.029
15	0.59	173,571,872	37,665,870	3.6	34.10	24.78	0.185	0.028
16	0.60	192,071,412	40,674,267	3.7	33.92	24.73	0.179	0.027
17	0.62	272,062,578	52,724,499	4.2	33.86	24.36	0.168	0.024
18	0.64	340,012,289	62,995,407	4.4	33.33	24.06	0.163	0.023
19	0.65	423,870,080	75,035,004	4.7	33.15	24.08	0.154	0.021
20	0.67	433,379,925	77,028,335	4.6	32.94	23.93	0.152	0.021
21	0.68	435,341,552	77,931,519	4.6	32.76	23.77	0.152	0.021
22	0.70	451,354,070	80,639,841	4.6	32.56	23.63	0.150	0.020
23	0.72	464,907,147	83,348,000	4.6	32.28	23.42	0.148	0.020

Model 1: Recovery based on Recovery Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
24	0.73	478,690,359	86,795,462	4.5	31.87	23.08	0.145	0.020
25	0.75	506,937,864	92,145,338	4.5	31.41	22.71	0.143	0.019
26	0.76	510,067,221	93,697,197	4.4	31.15	22.50	0.142	0.019
27	0.78	526,304,661	97,335,363	4.4	30.78	22.19	0.139	0.019
28	0.80	531,652,502	100,070,028	4.3	30.37	21.83	0.138	0.019
29	0.81	536,030,552	102,280,995	4.2	30.05	21.56	0.136	0.019
30	0.83	563,361,462	108,003,003	4.2	29.48	21.11	0.134	0.018
31	0.84	583,748,300	113,315,940	4.2	28.96	20.69	0.131	0.018
32	0.86	590,533,086	116,467,352	4.1	28.57	20.34	0.130	0.018
33	0.88	597,904,776	119,523,440	4.0	28.24	20.06	0.128	0.018
34	0.89	1,180,277,162	195,294,536	5.0	26.42	18.91	0.116	0.016
35	0.91	1,188,512,700	201,933,308	4.9	25.98	18.52	0.114	0.016
36	0.92	1,207,223,837	209,806,485	4.8	25.55	18.13	0.112	0.016
37	0.94	1,211,690,934	216,011,696	4.6	25.15	17.77	0.110	0.016
38	0.96	1,224,838,557	225,558,147	4.4	24.63	17.32	0.107	0.016
39	0.97	1,230,005,852	233,124,662	4.3	24.20	16.93	0.105	0.015
40	0.99	1,275,218,357	252,662,775	4.1	23.39	16.25	0.100	0.015
41	1.00	1,282,983,446	262,895,225	3.9	22.92	15.82	0.098	0.015

Table Appendix 2: Results from the L&G algorithm applied in Dominga Norte base in Model 1: Recovery based on Recovery distribution

The following table shows the results from the L&G algorithm applied in Dominga Norte based on Model 2: Recovery based on FeT Distribution.

Model 2: Recovery based on FeT Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.36	23,538,896	5,238,362	3.5	34.85	23.68	0.537	0.099
2	0.38	26,043,452	6,551,622	3.0	35.10	23.49	0.454	0.083
3	0.40	31,738,052	9,031,623	2.5	35.24	23.37	0.361	0.065
4	0.42	34,254,435	9,998,477	2.4	34.95	23.13	0.339	0.060
5	0.44	37,006,388	10,880,541	2.4	34.87	22.91	0.322	0.057
6	0.46	42,135,377	12,249,420	2.4	34.33	22.63	0.315	0.058
7	0.48	42,437,276	12,456,585	2.4	34.02	22.41	0.314	0.058
8	0.50	98,748,053	25,133,924	2.9	33.80	23.77	0.222	0.036
9	0.52	126,662,609	30,839,871	3.1	33.82	24.05	0.204	0.032

Model 2: Recovery based on FeT Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
10	0.54	129,197,898	31,558,899	3.1	33.66	23.96	0.202	0.031
11	0.56	132,416,846	32,452,187	3.1	33.46	23.81	0.199	0.031
12	0.58	172,648,002	39,688,923	3.4	33.28	23.21	0.192	0.029
13	0.60	193,633,616	42,958,412	3.5	33.22	23.31	0.187	0.028
14	0.62	256,005,740	52,658,745	3.9	32.96	23.36	0.174	0.025
15	0.64	298,301,991	59,993,697	4.0	32.47	23.11	0.166	0.023
16	0.66	426,859,352	80,051,627	4.3	31.98	22.95	0.153	0.021
17	0.68	436,830,567	82,669,439	4.3	31.67	22.69	0.150	0.021
18	0.70	453,319,677	86,557,877	4.2	31.24	22.34	0.148	0.020
19	0.72	455,539,662	88,376,120	4.2	30.89	22.03	0.147	0.020
20	0.74	503,197,016	97,817,738	4.1	30.20	21.51	0.141	0.019
21	0.76	514,432,740	101,682,776	4.1	29.75	21.13	0.138	0.019
22	0.78	518,140,823	103,840,757	4.0	29.45	20.85	0.137	0.019
23	0.80	539,072,225	109,463,450	3.9	28.92	20.44	0.133	0.019
24	0.82	565,069,995	115,163,168	3.9	28.44	20.04	0.131	0.019
25	0.84	569,520,369	117,056,676	3.9	28.23	19.88	0.130	0.019
26	0.86	589,967,292	122,414,573	3.8	27.74	19.49	0.129	0.018
27	0.88	596,973,702	125,182,365	3.8	27.46	19.26	0.128	0.018
28	0.90	609,112,151	129,594,770	3.7	27.06	18.94	0.125	0.018
29	0.92	1,188,381,261	206,675,286	4.8	25.64	18.12	0.114	0.016
30	0.94	1,219,112,094	215,350,691	4.7	25.25	17.79	0.112	0.016
31	0.96	1,221,297,785	221,089,500	4.5	24.87	17.44	0.111	0.016
32	0.98	1,234,636,067	230,858,594	4.4	24.34	16.96	0.109	0.016
33	1.00	1,243,984,356	239,694,191	4.2	23.86	16.52	0.107	0.016
34	1.02	1,285,384,422	257,217,842	4.0	23.14	15.88	0.103	0.016
35	1.04	1,307,765,076	275,182,454	3.8	22.41	15.23	0.099	0.015
36	1.06	1,331,364,975	291,600,734	3.6	21.82	14.72	0.096	0.015
37	1.08	1,335,945,735	305,359,806	3.4	21.30	14.25	0.093	0.015
38	1.10	1,360,905,597	323,309,000	3.2	20.75	13.75	0.091	0.015

Table Appendix 3: Results from the L&G algorithm applied in Dominga Norte base in Model 2: Recovery based on FeT distribution

The following table shows the results from the L&G algorithm applied in Dominga Norte based on Model 3: Recovery based on (FeM/FeT) Distribution.

Model 3: Recovery based on (FeM/FeT) Distribution

Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.36	22,993,412	5,014,616	3.6	34.99	23.76	0.544	0.102
2	0.38	24,097,080	5,644,505	3.3	35.10	23.74	0.499	0.092
3	0.40	27,096,420	7,044,572	2.9	35.65	23.79	0.417	0.077
4	0.41	29,985,596	8,025,857	2.7	35.64	23.96	0.384	0.069
5	0.43	32,905,199	9,222,078	2.6	35.62	23.79	0.350	0.063
6	0.44	35,641,176	10,085,607	2.5	35.64	23.87	0.330	0.059
7	0.46	38,379,039	10,572,275	2.6	35.35	23.82	0.332	0.061
8	0.48	38,997,749	10,970,462	2.6	35.13	23.51	0.323	0.060
9	0.49	40,677,147	11,395,761	2.6	34.92	23.36	0.318	0.059
10	0.51	115,514,742	27,592,311	3.2	34.43	24.51	0.208	0.033
11	0.52	123,411,683	29,450,505	3.2	34.34	24.60	0.201	0.031
12	0.54	123,494,012	29,605,812	3.2	34.26	24.53	0.201	0.031
13	0.56	147,562,788	33,497,631	3.4	34.27	24.76	0.192	0.029
14	0.57	151,990,866	34,378,706	3.4	34.20	24.77	0.189	0.029
15	0.59	159,687,722	35,809,254	3.5	34.03	24.66	0.188	0.028
16	0.60	191,868,224	40,586,238	3.7	33.90	24.74	0.179	0.027
17	0.62	311,119,260	58,012,094	4.4	33.65	24.31	0.166	0.023
18	0.64	337,881,468	62,431,274	4.4	33.39	24.14	0.163	0.023
19	0.65	422,938,745	74,404,853	4.7	33.27	24.20	0.154	0.021
20	0.67	432,057,116	76,335,110	4.7	33.05	24.03	0.153	0.021
21	0.68	439,550,409	77,912,075	4.6	32.87	23.89	0.152	0.020
22	0.70	451,314,075	80,165,967	4.6	32.65	23.73	0.150	0.020
23	0.72	457,641,432	82,453,355	4.6	32.28	23.40	0.149	0.020
24	0.73	477,228,234	85,951,916	4.6	32.00	23.20	0.146	0.020
25	0.75	509,162,643	91,814,319	4.6	31.51	22.82	0.143	0.019
26	0.76	509,956,118	92,871,518	4.5	31.30	22.64	0.142	0.019
27	0.78	525,807,072	96,263,202	4.5	30.96	22.36	0.140	0.019
28	0.80	528,333,549	97,988,544	4.4	30.67	22.11	0.139	0.019
29	0.81	535,466,207	100,947,147	4.3	30.27	21.75	0.137	0.019
30	0.83	553,371,176	105,043,070	4.3	29.85	21.41	0.135	0.019
31	0.84	581,520,260	111,905,486	4.2	29.14	20.85	0.132	0.018
32	0.86	588,355,208	114,975,792	4.1	28.75	20.50	0.131	0.018
33	0.88	595,656,311	117,877,314	4.1	28.42	20.23	0.129	0.018
34	0.89	1,174,748,463	193,522,200	5.1	26.49	18.99	0.116	0.016
35	0.91	1,195,391,567	202,819,526	4.9	25.96	18.51	0.114	0.016
36	0.92	1,208,387,909	210,105,602	4.8	25.53	18.13	0.112	0.016

Model 3: Recovery based on (FeM/FeT) Distribution

Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
37	0.94	1,212,374,045	216,128,838	4.6	25.14	17.78	0.110	0.016
38	0.96	1,229,096,657	226,830,240	4.4	24.57	17.28	0.107	0.015
39	0.97	1,230,169,545	234,274,398	4.3	24.12	16.88	0.105	0.015
40	0.99	1,275,746,343	254,145,989	4.0	23.32	16.20	0.100	0.015
41	1.00	1,284,933,206	264,903,821	3.9	22.82	15.76	0.098	0.015
42	1.02	1,289,298,195	273,701,306	3.7	22.43	15.41	0.096	0.015
43	1.04	1,299,935,517	284,926,995	3.6	21.99	15.02	0.093	0.015
44	1.05	1,335,862,919	304,181,589	3.4	21.37	14.48	0.091	0.015
45	1.07	1,341,203,438	316,808,603	3.2	20.92	14.08	0.088	0.014
46	1.08	1,367,570,363	335,056,850	3.1	20.39	13.63	0.086	0.014
47	1.10	1,404,883,128	352,761,513	3.0	19.97	13.27	0.084	0.014

Table Appendix 4: results from the L&G algorithm applied in Dominga Norte base in Model 3: Recovery based on (FeM/FeT) Distribution

The following graphs show the results from the L&G algorithm applied to Dominga Norte for all the models to be compared with the base model.

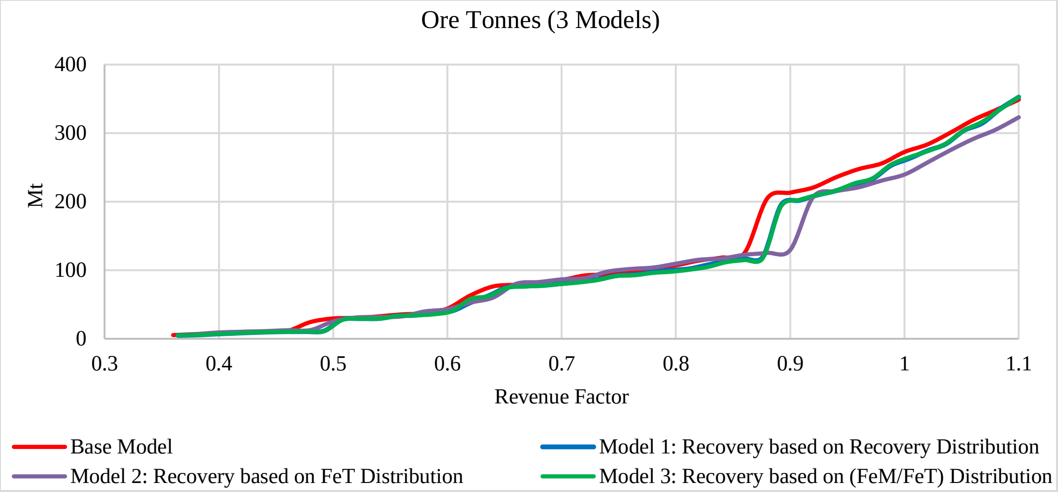

Figure Appendix 29: Ore tonnes from the models to reproduce Base Model for Dominga Norte

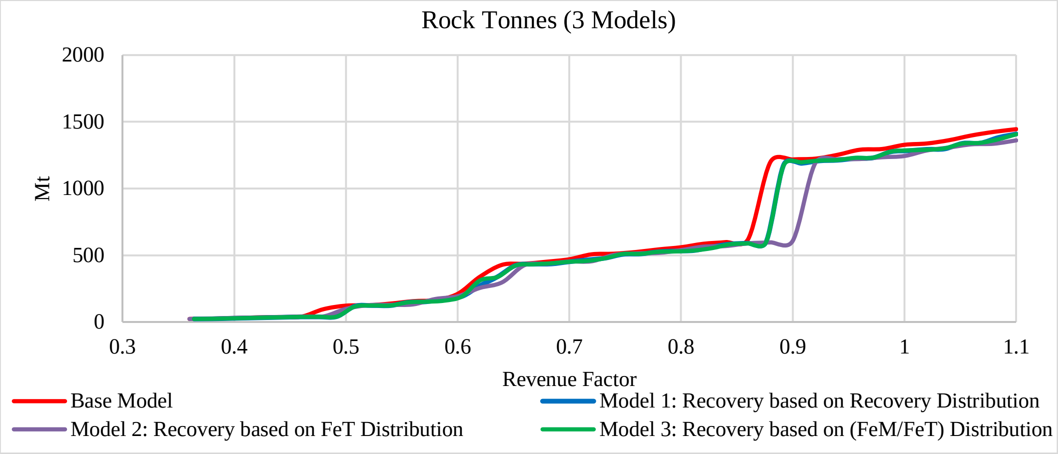

Figure Appendix 30: Rock tonnes from the models to reproduce Base Model for Dominga Norte

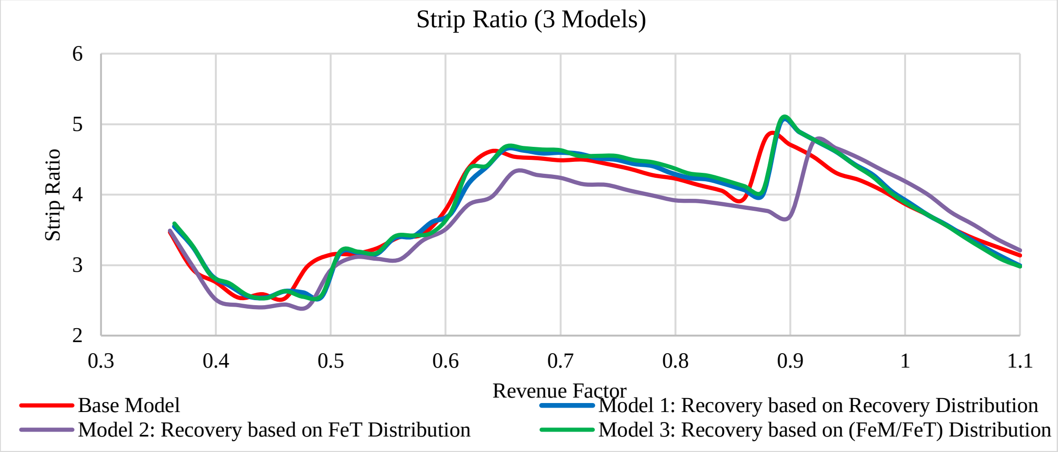

Figure Appendix 31: Strip ratio from the models to reproduce Base Model for Dominga Norte

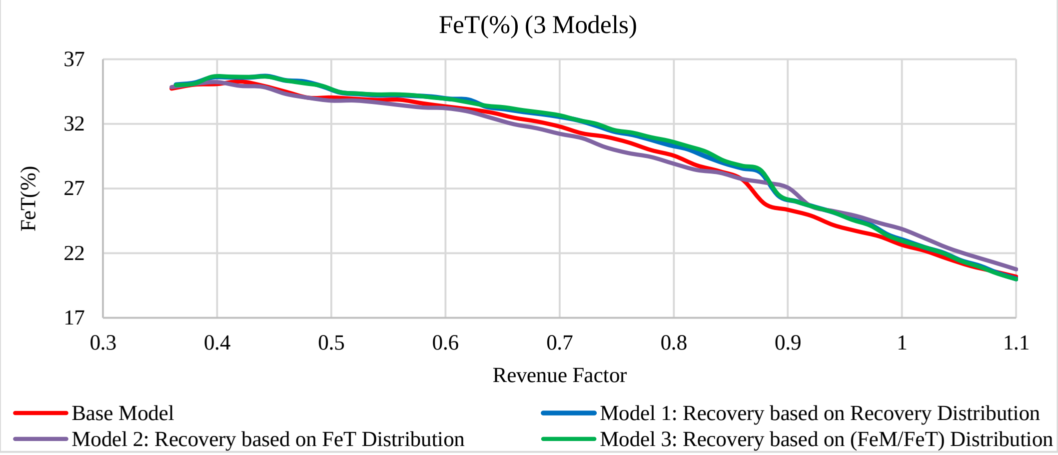

Figure Appendix 32: FeT(%) from the models to reproduce Base Model for Dominga Norte

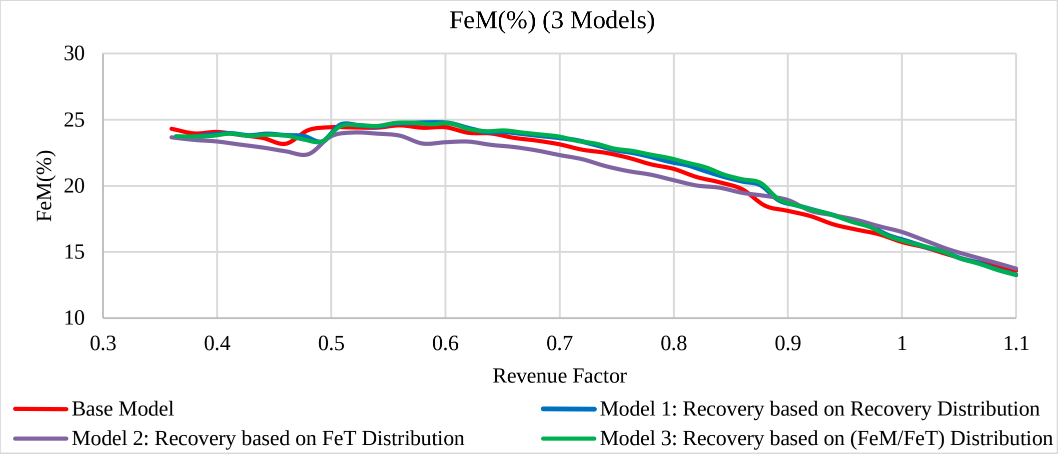

Figure Appendix 33: FeM(%) from the models to reproduce Base Model for Dominga Norte

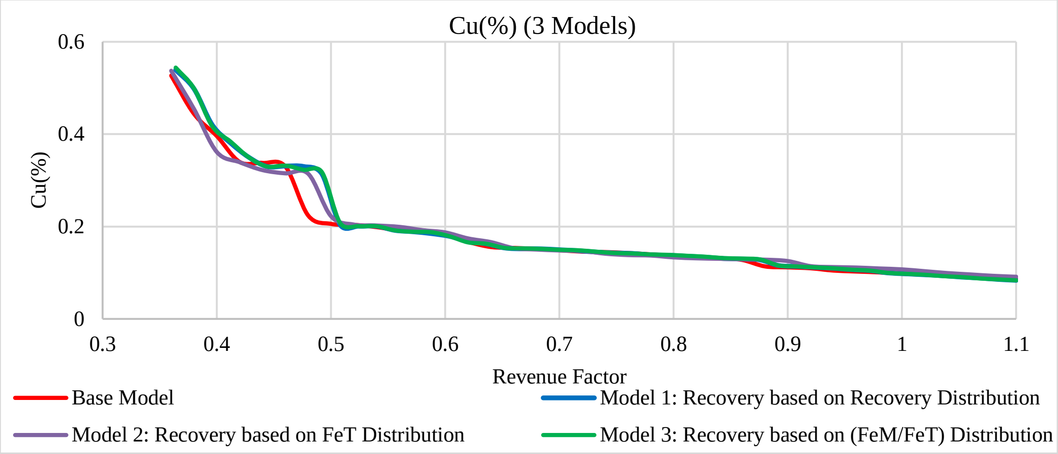

Figure Appendix 34: Cu(%) from the models to reproduce Base Model for Dominga Norte

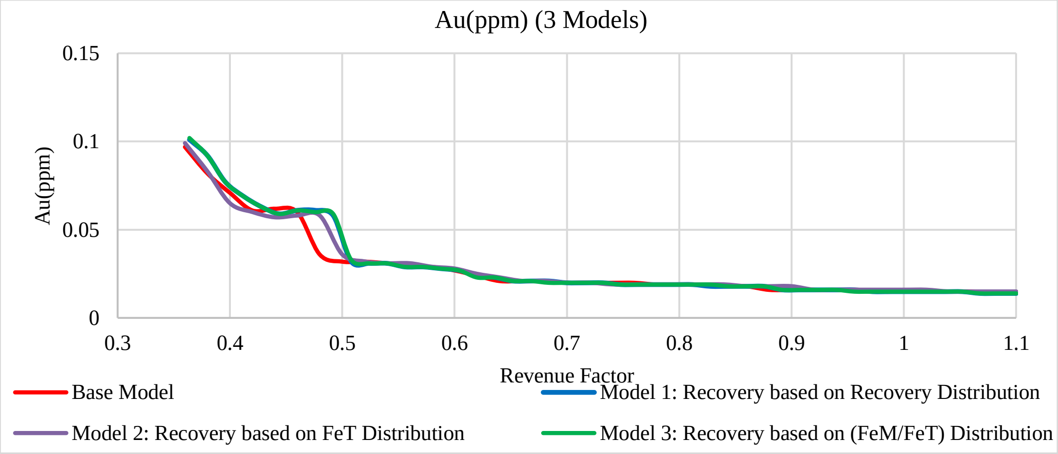

Figure Appendix 35: Au(ppm) from the models to reproduce Base Model for Dominga Norte

The following table shows the results from the L&G algorithm applied to Dominga Sur based on the model with variable recoveries.

Base Model								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.40	606,219	188,151	2.2	52.21	23.93	0.072	0.010
2	0.46	556,377,722	234,487,422	1.4	26.20	19.24	0.073	0.013
3	0.48	621,700,298	274,505,175	1.3	25.57	18.71	0.072	0.013
4	0.50	691,352,244	315,360,506	1.2	25.00	18.26	0.071	0.013
5	0.52	725,553,635	343,676,667	1.1	24.45	17.81	0.071	0.013
6	0.54	806,351,471	386,164,277	1.1	23.95	17.38	0.070	0.013
7	0.56	1,746,844,469	723,557,667	1.4	22.85	16.72	0.068	0.013
8	0.58	1,883,651,388	795,351,824	1.4	22.39	16.36	0.068	0.013
9	0.60	1,954,694,565	845,785,287	1.3	22.03	16.06	0.067	0.013
10	0.62	2,001,816,161	886,486,196	1.3	21.71	15.79	0.066	0.013
11	0.64	2,125,526,862	957,023,612	1.2	21.26	15.43	0.066	0.013
12	0.66	2,253,593,180	1,030,171,245	1.2	20.85	15.09	0.065	0.013
13	0.68	2,315,125,620	1,081,855,617	1.1	20.53	14.80	0.064	0.013
14	0.70	2,394,339,548	1,145,357,049	1.1	20.14	14.48	0.063	0.012
15	0.72	2,464,216,919	1,202,671,682	1.1	19.81	14.20	0.062	0.012
16	0.74	2,581,661,853	1,270,487,013	1.0	19.50	13.93	0.061	0.012
17	0.76	2,670,070,886	1,331,107,151	1.0	19.20	13.68	0.061	0.012
18	0.78	2,760,093,996	1,388,919,414	1.0	18.95	13.44	0.060	0.012
19	0.80	2,781,333,602	1,421,717,700	1.0	18.77	13.28	0.060	0.012
20	0.82	2,830,888,323	1,464,274,080	0.9	18.56	13.10	0.059	0.012
21	0.84	2,878,939,476	1,507,146,536	0.9	18.36	12.92	0.059	0.012
22	0.86	3,035,801,622	1,589,929,997	0.9	18.04	12.64	0.059	0.012
23	0.88	3,187,293,296	1,664,007,684	0.9	17.81	12.42	0.058	0.012
24	0.90	3,312,208,985	1,728,155,756	0.9	17.61	12.24	0.058	0.012
25	0.92	3,428,675,465	1,798,662,221	0.9	17.37	12.02	0.057	0.012
26	0.94	3,481,453,262	1,845,335,133	0.9	17.20	11.87	0.056	0.012
27	0.96	3,547,045,422	1,895,778,059	0.9	17.03	11.72	0.056	0.011
28	0.98	3,671,902,287	1,966,716,834	0.9	16.82	11.52	0.055	0.011
29	1.00	3,698,996,802	2,000,141,448	0.9	16.71	11.41	0.055	0.011
30	1.02	3,782,578,950	2,052,643,814	0.8	16.56	11.27	0.055	0.011
31	1.04	3,900,351,740	2,113,824,612	0.9	16.39	11.12	0.054	0.011
32	1.06	3,977,407,065	2,160,153,384	0.8	16.27	11.00	0.054	0.011
33	1.08	4,027,504,812	2,195,966,166	0.8	16.16	10.91	0.054	0.011

Base Model								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
34	1.10	4,065,912,275	2,228,301,917	0.8	16.07	10.82	0.053	0.011

Table Appendix 5: Results from the L&G algorithm applied in Dominga Sur base in the model with variable recoveries.

The following table shows the results from the L&G algorithm applied in Dominga Sur based on Model 1: Recovery based on Recovery Distribution.

Model 1: Recovery based on Recovery Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.38	606,219	188,151	2.2	52.21	23.93	0.072	0.010
2	0.48	193,152,383	70,637,957	1.7	29.02	20.39	0.073	0.013
3	0.50	442,624,551	176,851,343	1.5	27.06	19.56	0.072	0.013
4	0.52	589,370,310	258,294,726	1.3	25.82	18.73	0.072	0.013
5	0.54	656,185,470	296,567,462	1.2	25.28	18.34	0.072	0.013
6	0.56	703,997,924	333,082,020	1.1	24.58	17.77	0.072	0.013
7	0.58	752,756,645	366,126,048	1.1	24.05	17.35	0.071	0.013
8	0.60	828,656,526	410,769,426	1.0	23.49	16.87	0.070	0.013
9	0.62	1,742,709,428	755,509,595	1.3	22.42	16.20	0.068	0.013
10	0.64	1,863,136,821	827,942,915	1.3	21.95	15.81	0.068	0.013
11	0.66	1,967,380,803	894,757,611	1.2	21.56	15.49	0.066	0.013
12	0.68	2,047,477,994	957,546,294	1.1	21.12	15.10	0.065	0.013
13	0.70	2,139,398,315	1,027,018,668	1.1	20.68	14.74	0.065	0.013
14	0.72	2,258,291,528	1,107,059,373	1.0	20.24	14.37	0.064	0.013
15	0.74	2,322,960,684	1,160,634,702	1.0	19.94	14.11	0.063	0.012
16	0.76	2,411,418,384	1,241,895,185	0.9	19.49	13.73	0.061	0.012
17	0.78	2,508,404,724	1,313,627,223	0.9	19.14	13.43	0.061	0.012
18	0.80	2,626,119,305	1,391,184,101	0.9	18.80	13.15	0.060	0.012
19	0.82	2,727,279,318	1,461,595,059	0.9	18.49	12.89	0.059	0.012
20	0.84	2,798,834,933	1,521,106,941	0.8	18.23	12.66	0.059	0.012
21	0.86	2,836,045,766	1,565,767,128	0.8	18.02	12.48	0.058	0.012
22	0.88	2,947,031,985	1,649,536,704	0.8	17.68	12.17	0.057	0.012
23	0.90	3,068,464,352	1,734,906,008	0.8	17.37	11.91	0.057	0.012
24	0.92	3,187,365,185	1,818,331,422	0.8	17.08	11.65	0.056	0.012
25	0.94	3,283,748,133	1,892,840,675	0.7	16.83	11.43	0.055	0.011
26	0.96	3,391,667,037	1,962,845,553	0.7	16.64	11.27	0.054	0.011

Model 1: Recovery based on Recovery Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
27	0.98	3,585,757,265	2,062,896,963	0.7	16.40	11.05	0.054	0.011
28	1.00	3,680,132,018	2,128,998,578	0.7	16.21	10.89	0.053	0.011
29	1.02	3,762,484,454	2,191,728,498	0.7	16.04	10.73	0.053	0.011
30	1.04	3,935,674,503	2,285,303,564	0.7	15.81	10.52	0.052	0.011
31	1.06	4,042,958,351	2,345,097,189	0.7	15.67	10.39	0.052	0.011
32	1.08	4,087,149,168	2,372,741,694	0.7	15.61	10.34	0.052	0.011
33	1.10	4,181,763,452	2,426,682,800	0.7	15.49	10.23	0.051	0.011

Table Appendix 6: Results from the L&G algorithm applied in Dominga Sur base in Model 1: Recovery based on Recovery Distribution

The following table shows the results from the L&G algorithm applied in Dominga Sur based on Model 2: Recovery based on FeT(%) Distribution

Model 2: Recovery based on FeT Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
1	0.38	606,219	188,151	2.2	52.21	23.93	0.072	0.010
2	0.42	975,870	357,924	1.7	44.81	17.44	0.085	0.016
3	0.46	259,708,371	96,384,948	1.7	28.50	20.30	0.072	0.014
4	0.48	612,706,458	268,361,486	1.3	25.79	18.61	0.073	0.013
5	0.50	662,123,757	304,389,609	1.2	25.10	18.10	0.072	0.013
6	0.52	692,413,850	331,748,550	1.1	24.53	17.67	0.071	0.013
7	0.54	764,054,556	371,820,774	1.1	24.06	17.28	0.070	0.013
8	0.56	842,938,112	412,781,780	1.0	23.67	16.91	0.069	0.013
9	0.58	1,695,950,493	718,045,979	1.4	22.81	16.35	0.069	0.013
10	0.60	1,904,316,182	808,931,091	1.4	22.41	16.11	0.068	0.013
11	0.62	1,966,026,792	843,089,061	1.3	22.21	15.95	0.067	0.013
12	0.64	2,036,099,979	887,382,630	1.3	21.89	15.68	0.067	0.013
13	0.66	2,159,470,862	946,461,119	1.3	21.58	15.41	0.067	0.013
14	0.68	2,216,611,205	991,624,743	1.2	21.26	15.14	0.066	0.013
15	0.70	2,304,114,221	1,051,858,992	1.2	20.88	14.83	0.065	0.013
16	0.72	2,369,374,689	1,112,521,514	1.1	20.47	14.47	0.064	0.013
17	0.74	2,474,394,479	1,186,059,866	1.1	20.05	14.11	0.064	0.013
18	0.76	2,557,480,929	1,244,383,683	1.1	19.74	13.86	0.063	0.012
19	0.78	2,666,589,287	1,318,134,494	1.0	19.38	13.56	0.062	0.012
20	0.80	2,697,009,066	1,364,914,109	1.0	19.10	13.33	0.061	0.012

Model 2: Recovery based on FeT Distribution								
Pit	Revenue Factor	Rock Tonnes	Ore Tonnes	Strip Ratio	FeT (%)	FeM (%)	Cu (%)	Au (ppm)
21	0.82	2,741,933,919	1,418,537,072	0.9	18.81	13.09	0.060	0.012
22	0.84	2,785,864,994	1,467,375,638	0.9	18.56	12.87	0.060	0.012
23	0.86	2,843,299,938	1,524,649,115	0.9	18.28	12.64	0.059	0.012
24	0.88	3,027,984,353	1,626,638,000	0.9	17.91	12.33	0.058	0.012
25	0.90	3,184,190,757	1,722,055,514	0.9	17.56	12.02	0.058	0.012
26	0.92	3,324,408,089	1,806,501,440	0.8	17.28	11.79	0.057	0.012
27	0.94	3,388,711,409	1,861,985,120	0.8	17.08	11.62	0.056	0.012
28	0.96	3,527,590,832	1,950,024,380	0.8	16.82	11.39	0.056	0.011
29	0.98	3,546,400,167	1,986,506,693	0.8	16.69	11.27	0.055	0.011
30	1.00	3,761,479,232	2,095,548,710	0.8	16.40	11.01	0.054	0.011
31	1.02	3,822,372,240	2,150,194,400	0.8	16.24	10.86	0.054	0.011
32	1.04	3,894,926,900	2,204,128,215	0.8	16.09	10.73	0.053	0.011
33	1.06	3,955,680,360	2,259,419,420	0.8	15.93	10.59	0.053	0.011
34	1.08	4,079,010,348	2,344,063,353	0.7	15.71	10.40	0.052	0.011
35	1.10	4,126,692,306	2,381,854,941	0.7	15.62	10.31	0.052	0.011

Table Appendix 7: results from the L&G algorithm applied in Dominga Sur base in Model 2: Recovery based on FeT(%) Distribution

The following graphs show the results from the L&G algorithm applied to Dominga Norte for all the models to be compared with the base model.

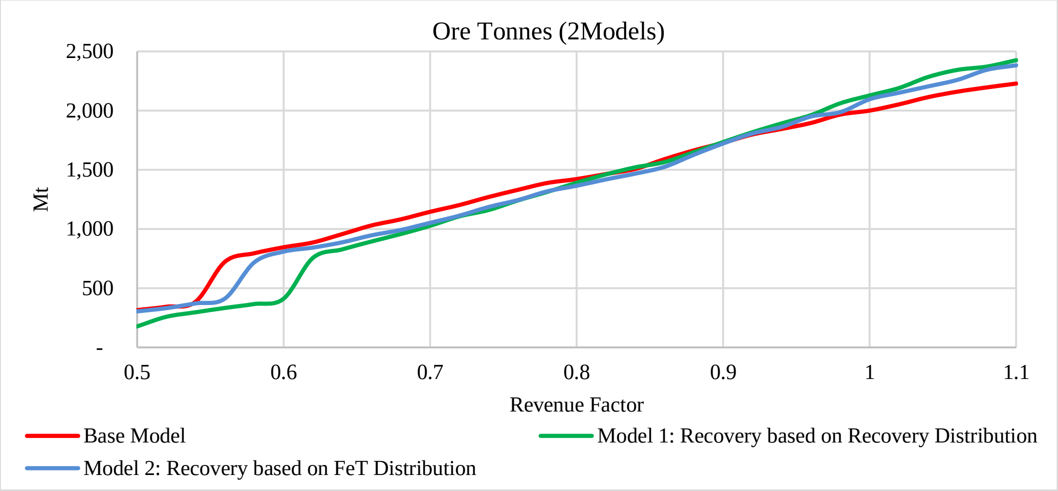

Figure Appendix 36: Ore Tonnes from the models to reproduce Base Model for Dominga Sur

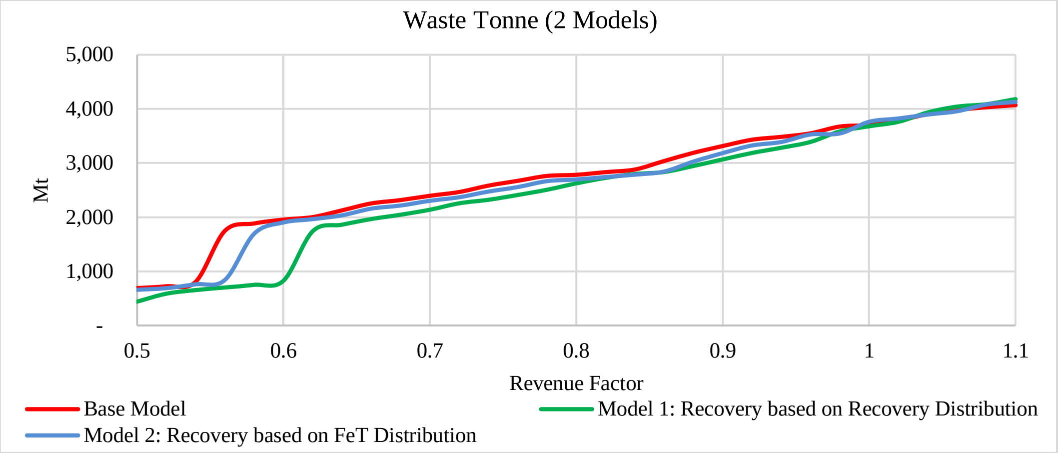

Figure Appendix 37: Rock Tonnes from the models to reproduce Base Model for Dominga Sur

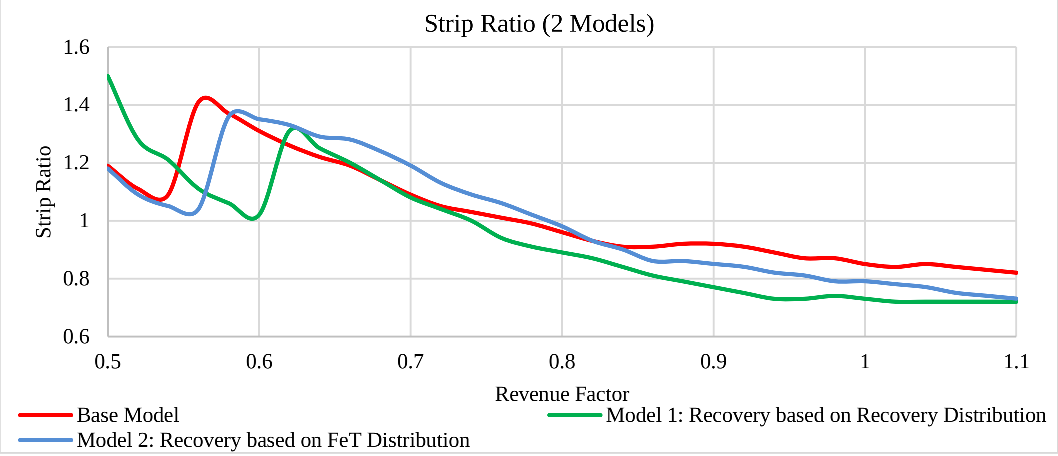

Figure Appendix 38: Strip Ratio from the models to reproduce Base Model for Dominga Sur

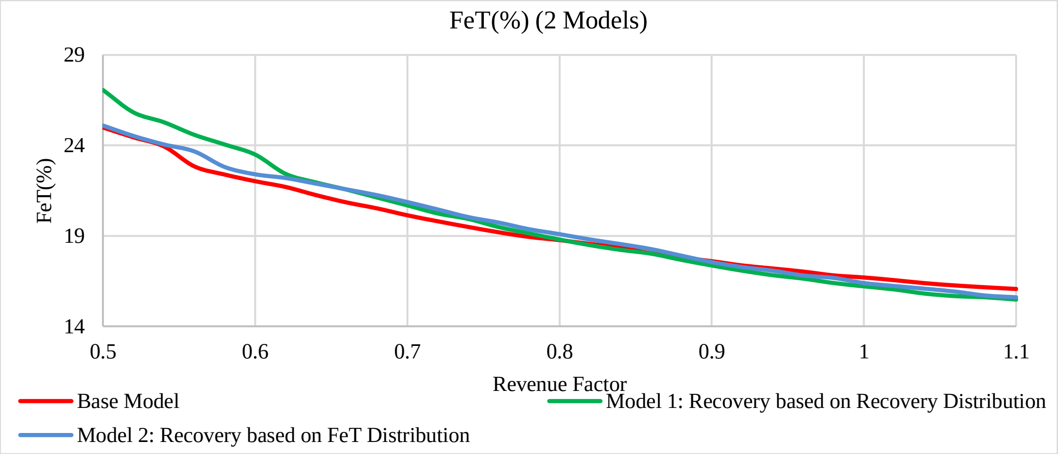

Figure Appendix 39: FeT(%) from the models to reproduce Base Model for Dominga Sur

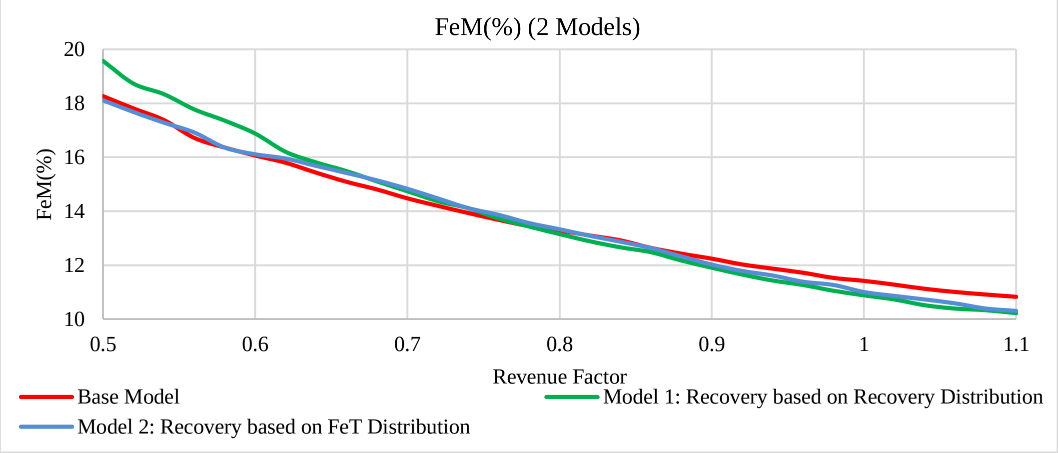

Figure Appendix 40: FeM(%) from the models to reproduce Base Model for Dominga Sur

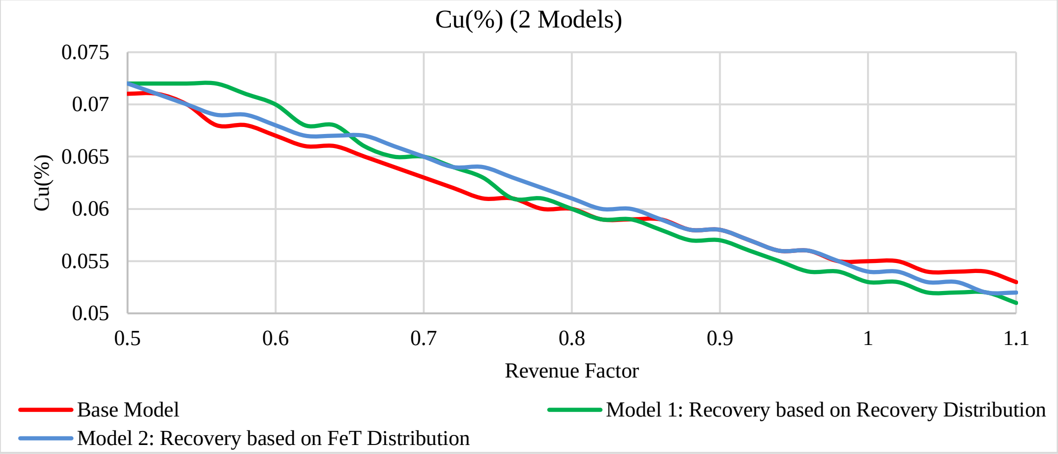

Figure Appendix 41: Cu(%) from the models to reproduce Base Model for Dominga Sur

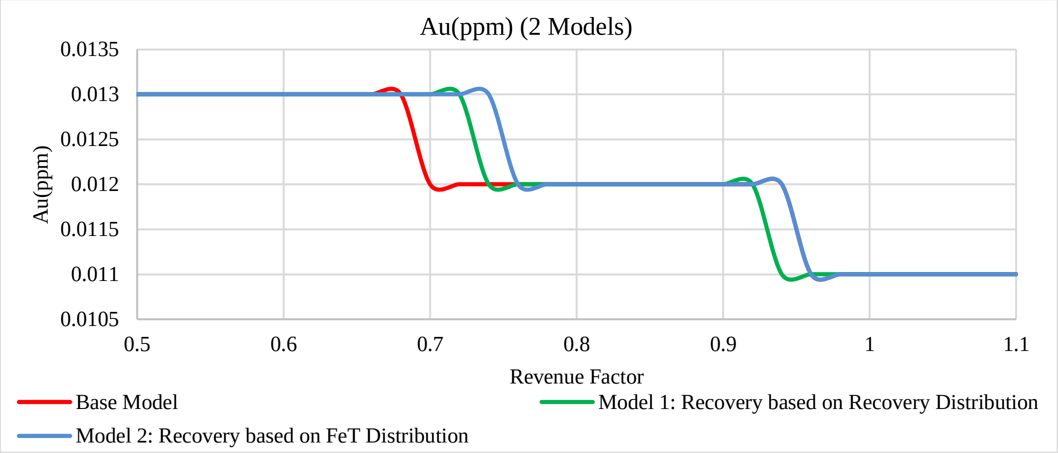

Figure Appendix 42: Au(ppm) from the models to reproduce Base Model for Dominga Sur

Appendix C

Different ways to look for a defined FeT(%) COG

As was said in the literature review (Chapter 2), Whittle software offers the option to choose the "Ore Selection Method" to be applied. This option allows choosing between different methodologies to define what is ore from what is waste. In this thesis just two of the methodologies are analyzed.

The first one is the "Cut-off" ore selection method. This method evaluates the material based on a pre-calculated COG. The pre-calculated COG could be the marginal COG or a defined COG depending on the strategy. The idea is to compare the grades of the material with the COG mentioned before and if it does not satisfy the COG, the material is treated as waste. In the case that just one element is taken into account and there is just one process, Whittle Software uses the following formula for the marginal COG (see Equation 2-23) (Dassault Systems, 2015).

$$Marginal\ COG_{(one\ element)} = \frac{MINDIL * PRORAT * PROADJ - REHRAT}{RECOVERY * (PRICE - SELL) - ELRAT}$$

Where:

Code	Description
GRADE	Grade of the element
RECOVERY	Element recovered
MINDIL	Overall mining dilution
PRORAT	Processing cost unit rate
PROADJ	Processing cost adjustment factor
REHRAT	Rehabilitation unit cost rate
PRICE	Unit price of the element
SELL	Unit element selling cost
ELRAT	Element processing unit cost rate

Table Appendix 8: Code and description for marginal COG terms in Whittle Software

For Dominga project, if just FeT(%) is taken into consideration and using the same economic parameters described in the Table 4-1, a search of a defined combination of COG for FeT(%) is made. The following table shows the results of this exercise, with changing grades for both Dominga Norte (DN) and Dominga Sur (DS). For example, the first combination 9DN-9DS means that there is a cut-off 9%FeT for Dominga Norte and 9%FeT for Dominga Sur. As was said before, in this case FeT(%) is going to be used to search for the defined COG. Cu(%) and Au(ppm) are not going to be considered because the main product is iron concentrate.

FeT(%) Cut-off Combination	**Cut-off Best Case Multimine (US$)**	**FeT(%) Cut-off Combination**	**Cut-off Best Case Multimine (US$)**
No Cutoff	3,955,290,380	11DN-12DS	4,154,644,627
9DN-9DS	3,955,290,380	12DN-13DS	4,173,738,710
10DN-10DS	4,094,332,930	16DN-16DS	3,932,434,540
9DN-12DS	4,154,644,627	17DN-17DS	3,779,629,824
9DN-13DS	4,173,738,710	18DN-18DS	3,605,468,221
12DN-12DS	4,154,644,627	19DN-19DS	3,429,363,865
12DN-16DS	3,953,476,144	20DN-20DS	3,259,774,394
13DN-13DS	4,165,481,201	17DN-18DS	3,606,973,204
14DN-15DS	4,046,515,009	16DN-17DS	3,781,499,687
15DN-15DS	4,043,601,726	15DN-17DS	3,784,802,837
10DN-12DS	4,154,644,627	14DN-17DS	3,788,094,284

Table Appendix 9: Defined FeT(%) COG using Cut-off Ore Selection Method considering just FeT(%) as an element in the COG calculation.

The COG considers a defined FeT(%) COG for Dominga Norte and Dominga Sur, which is 9%FeT and 13%FeT respectively

As it was also described in the literature review, if two or more elements are included with COG, Whittle uses an approach that has the same effects as using an equivalent grade.

In the case of Dominga project, if FeT(%) and Cu(%) are taken into consideration and using the same economic parameters described in the Table 4-1, a search of a defined combination of COG for FeT(%) is made. The following table shows the result of this exercise, with changing grades for both Dominga Norte (DN) and Dominga Sur (DS). As it was said before, in this case FeT(%) and Cu(%) are going to be used to search for the defined COG.

FeT(%) Cut-off Combination	**Cut-off Best Case Multimine (US$)**	**FeT(%) Cut-off Combination**	**Cut-off Best Case Multimine (US$)**
No Cutoff	3,792,510,139	11DN-12DS	3,866,041,703
9DN-9DS	3,792,510,139	12DN-13DS	3,887,268,061
10DN-10DS	3,816,602,516	16DN-16DS	3,972,156,351
9DN-12DS	3,866,041,703	17DN-17DS	3,964,225,468
9DN-13DS	3,887,268,061	18DN-18DS	3,961,846,771
12DN-12DS	3,866,041,703	19DN-19DS	4,078,926,075
12DN-16DS	3,972,815,468	20DN-20DS	4,073,253,659
13DN-13DS	3,887,283,659	17DN-18DS	3,962,747,586
14DN-15DS	3,951,345,947	16DN-17DS	3,965,013,816
15DN-15DS	3,952,455,653	15DN-17DS	3,965,509,698
10DN-12DS	3,866,041,703	14DN-17DS	3,965,262,096

Table Appendix 10: Defined FeT(%) COG using Cut-off ore selection method considering just FeT(%) as an element in the COG calculation.

The COG considers a defined FeT(%) COG for Dominga Norte and Dominga Sur, which is 19%FeT and 19%FeT respectively.

If FeT(%), Cu(%) and Au(ppm) are taken into consideration and using the same economic parameters described in the Table 4-1, a search of a defined combination of COG for FeT(%) is made. The following table shows the result of this exercise, with changing grades for both Dominga Norte (DN) and Dominga Sur (DS). As was said before, in this case FeT(%) and Cu(%) are going to be used to search for the defined COG.

FeT(%) Cut-off Combination	Cut-off Best Case Multi-mine (US$)	FeT(%) Cut-off Combination	Cut-off Best Case Multi-mine (US$)
No Cutoff	3,772,372,477	11DN-12DS	3,859,518,915
9DN-9DS	3,772,372,477	12DN-13DS	3,879,767,165
10DN-10DS	3,784,980,014	16DN-16DS	2,958,024,860
9DN-12DS	3,859,518,915	17DN-17DS	3,969,305,255
9DN-13DS	3,879,767,165	18DN-18DS	3,958,864,463
12DN-12DS	3,859,518,915	19DN-19DS	3,969,560,307
12DN-16DS	3,957,726,409	20DN-20DS	4,069,377,466
13DN-13DS	3,879,733,886	17DN-18DS	3,959,482,155
14DN-15DS	3,915,848,952	16DN-17DS	3,970,030,093
15DN-15DS	3,916,541,654	15DN-17DS	3,970,345,458
10DN-12DS	3,859,518,915	14DN-17DS	3,969,969,312

Table Appendix 11: Defined FeT(%) COG using Cut-off Ore Selection Method considering FeT(%) and Cu(%) and Au(ppm) as an elements to calculate cut-offs.

The COG considers a defined FeT(%) COG for Dominga Norte and Dominga Sur, which is 15%FeT and 17%FeT respectively. The value 20DN-20DS is not considered because is a high cut-off for this deposit decreasing the reserves.

The second Ore Oelection Method analyzed in this report is “Cash Flow”. This method evaluates the material comparing the cash flow generated by processing it and the cash flow generated by treating it as waste. If the cash flow from processing it is higher then the material is treated as ore.

The following table shows the result of this exercise, with changing FeT(%) grades for both Dominga Norte (DN) and Dominga Sur (DS) using Cash Flow ore selection method.

FeT(%) Cut-off Combination	Cut-off Best Case Multimine (US$)	FeT(%) Cut-off Combination	Cut-off Best Case Multimine (US$)
No Cutoff	3,914,127,798	11DN-12DS	4,226,313,568
9DN-9DS	4,107,263,611	12DN-13DS	4,251,893,967
10DN-10DS	4,148,115,237	16DN-16DS	4,013,533,777
9DN-12DS	4,228,270,213	17DN-17DS	3,875,163,126
9DN-13DS	4,256,793,090	18DN-18DS	3,832,220,790
12DN-12DS	4,223,845,768	19DN-19DS	3,635,347,504
12DN-16DS	4,029,951,868	20DN-20DS	3,444,090,175
13DN-13DS	4,247,352,213	17DN-18DS	3,832,767,952
14DN-15DS	4,136,217,777	16DN-17DS	3,876,683,100
15DN-15DS	4,133,212,980	15DN-17DS	3,879,579,033
10DN-12DS	4,227,632,479	14DN-17DS	3,882,683,907

Table Appendix 12: Defined FeT(%) COG using CashFlow Ore Selection Method considering

The following table shows a summary of the COG obtained form this exercise:

Ore Selection Method	FeT(%) cut-off combination
Cut-off considering FeT	9DN-13DS
Cut-off considering FeT-Cu	19DN-19DS
Cut-off considering FeT-Cu-Au	15DN-17DS
Cash flow	9DN-13DS

Table Appendix 13: Summary FeT(%) COG combination

The result using the “Cut-off” ore selection method considering FeT and the “Cash Flow” ore selection method are the same, however using the other 2 methodologies the results present some important differences.

In order to compare these 4 different methodologies to define a FeT(%) COG for Dominga projects, a series of graphs has been obtained from the results of these methods. Defining “Cut-off FeT” as the exercise using Cut-off ore selection method considering just FeT(%),“Cut-off FeT-Cu” as the exercise using Cut-off ore selection method considering FeT(%) and Cu(%),“Cut-off FeT-Cu-Au" as the exercise using Cut-off ore selection method considering FeT(%), Cu(%) and Au(ppm), "CashFlow" as the exercise using Cash Flow ore selection method.

To compare these different methodologies, a Pit-by-Pit graph analysis is carried out in Whittle Software using and not using defined FeT(%) COG (Table Appendix 13). Finally, revenue factor equal to 0.6 has been chosen to do the analysis. The ore tonnes generated for that scenario and the different grades are going to be observed.

The following tables show the output of the Pit by pit graph for revenue factor 0.6 considering a defined FeT(%) COG for Dominga Norte and Sur.

Ore Selection Method	Tonnes input to process (Mt)	Waste tonnes	Mine life	FeT(%) grade input to process	FeM(%) grade input to process	Cu(%) grade input to process	Au(ppm) grade input to process
Cut-off FeT	827	1,262	28.6	23.3	16.8	0.070	0.013
Cut-off FeT-Cu	826	1,260	28.7	23.0	16.6	0.074	0.013
Cut-off FeT-Cu-Au	901	1,185	31.0	22.2	15.8	0.071	0.013
CashFlow	834	1,252	28.9	23.1	16.6	0.068	0.012

Table Appendix 14

The following tables show the output of the Pit by pit graph for revenue factor 0.6 not considering a defined FeT(%) COG for Dominga Norte and Sur.

Ore Selection Method	Tonnes input to process (Mt)	Waste tonnes	Mine life	FeT(%) grade input to process	FeM(%) grade input to process	Cu(%) grade input to process	Au(ppm) grade input to process
Cut-off FeT	1,004	1,085	33.7	21.2	15.0	0.066	0.012
Cut-off FeT-Cu	1,109	976	36.8	19.9	14.0	0.063	0.012
Cut-off FeT-Cu-Au	1,119	967	37.0	19.8	13.9	0.063	0.012
CashFlow	1,119	967	37.0	19.9	13.9	0.063	0.012

Table Appendix 15

The following figures show the comparison considering FeT(%) defined COG

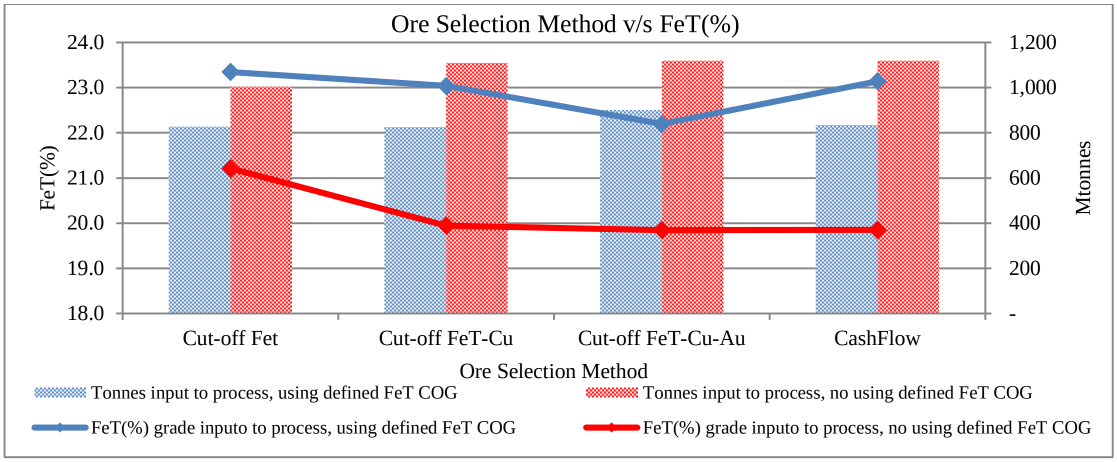

Figure Appendix 43

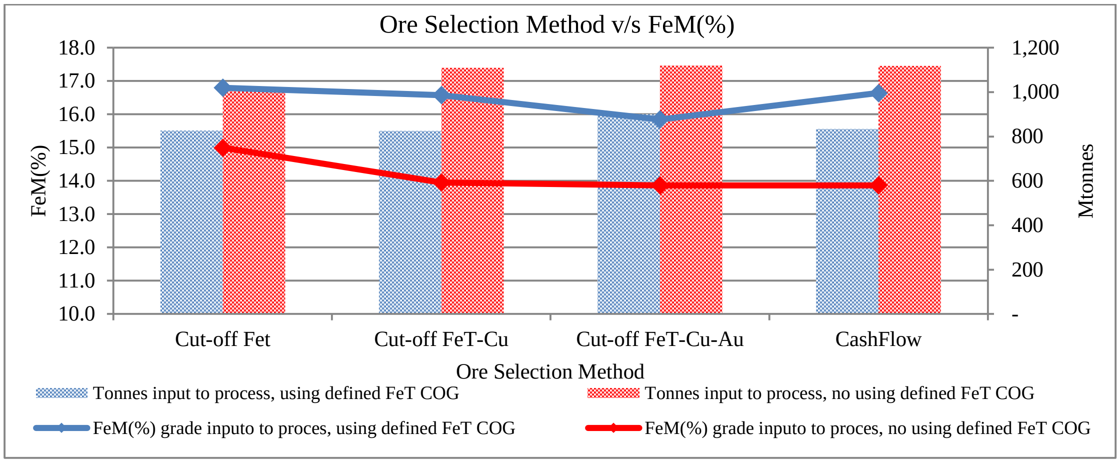

Figure Appendix 44

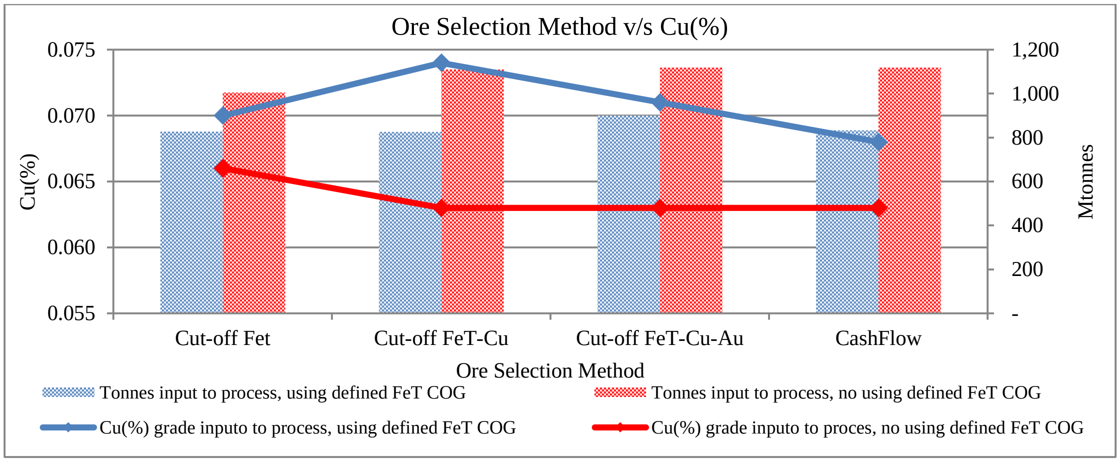

Figure Appendix 45

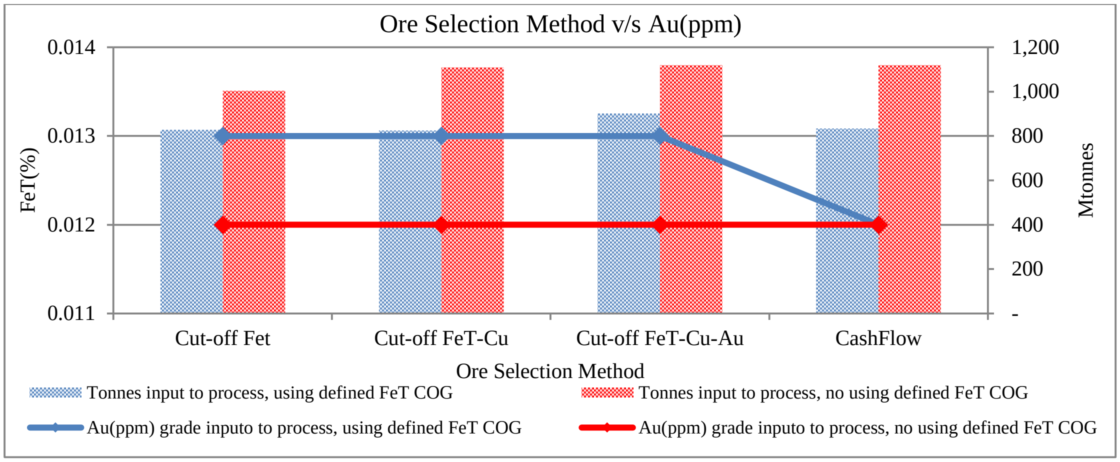

Figure Appendix 46

The following tables show the output of the pit by pit graph for revenue factor 0.6 considering a defined FeT(%) COG for Dominga Norte. The tables also show the COG used in each scenario.

Ore Selection Method	Tonnes Norte input to process (Mt)	Waste (Mt)	FeT(%) grade input to process	FeM(%) grade input to process	Cu(%) grade input to process	Au(ppm) grade Input to process
Cut-off Fet	47	153	32.6	23.0	0.157	0.023
Cut-off FeT-Cu	42	139	31.8	22.6	0.134	0.016
Cut-off FeT-Cu-Au	46	136	30.2	21.2	0.127	0.016
CashFlow	46	136	30.4	21.3	0.120	0.015

Table Appendix 16

Ore Selection Method	FeT(%) COG Rocktype 501	Cu(%) COG Rocktype 501	Au(ppm) COG Rocktype 501	FeT(%) COG Rocktype 5012	Cu(%) COG Rocktype 5012	Au(ppm) COG Rocktype 5012	FeT(%) COG Rocktype 5013	Cu(%) COG Rocktype 5013	Au(ppm) COG Rocktype 5013
Cut-off Fet	14.1	0	0	10.2	0	0	9.0	0	0
Cut-off FeT-Cu	19.0	0.163	0	19.0	0.163	0	19.0	0.163	0
Cut-off FeT-Cu-Au	15.0	0.163	0.340	15.0	0.163	0.34	15.0	0.163	0.340
CashFlow	14.1	0.163	0.340	10.2	0.163	0.34	9.0	0.163	0.340

Table Appendix 17

Ore Selection Method	FeT(%) COG Rocktype 5013	Cu(%) COG Rocktype 5013	Au(ppm) COG Rocktype 5013	FeT(%) COG Rocktype 5022	Cu(%) COG Rocktype 5022	Au(ppm) COG Rocktype 5022	FeT(%) COG Rocktype 5023	Cu(%) COG Rocktype 5023	Au(ppm) COG Rocktype 5023
Cut-off Fet	17.1	0	0	10.2	0	0	9.0	0	0
Cut-off FeT-Cu	19.0	0.163	0	19.0	0.163	0	19.0	0.163	0
Cut-off FeT-Cu-Au	17.1	0.163	0.340	15.0	0.163	0.34	15.0	0.163	0.340
CashFlow	17.1	0.163	0.340	10.2	0.163	0.34	9.0	0.163	0.340

Table Appendix 18

Ore Selection Method	FeT(%) COG Rocktype 503	Cu(%) COG Rocktype 503	Au(ppm) COG Rocktype 503	FeT(%) COG Rocktype 5032	Cu(%) COG Rocktype 5032	Au(ppm) COG Rocktype 5032	FeT(%) COG Rocktype 5033	Cu(%) COG Rocktype 5033	Au(ppm) COG Rocktype 5033
Cut-off Fet	11.1	0	0	11.1	0	0	12.6	0	0
Cut-off FeT-Cu	19.0	0.246	0	19.0	0.246	0	19.0	0.246	0
Cut-off FeT-Cu-Au	15.0	0.246	0	15.0	0.246	0	15.0	0.246	0
CashFlow	11.1	0.246	0	11.1	0.246	0	12.6	0.246	0

Table Appendix 19

The following tables show the output of the Pit by pit graph for revenue factor 0.6 considering a defined FeT(%) COG for Dominga Sur. The tables also show the COG used in each scenario.

Ore Selection Method	Tonnes Sur input to process (Mt)	Waste (Mt)	FeT(%) grade input to process	FeM(%) grade input to process	Cu(%) grade input to process	Au(ppm) grade input to process
Cut-off Fet	780	1,108	22.8	16.4	0.065	0.012
Cut-off FeT-Cu	783	1,120	22.6	16.3	0.071	0.013
Cut-off FeT-Cu-Au	855	1,049	21.8	15.6	0.068	0.013
CashFlow	788	1,116	22.7	16.4	0.065	0.012

Table Appendix 20

Ore Selection Method	FeT(%) COG Rocktype 401	Cu(%) COG Rocktype 401	Au(ppm) COG Rocktype 401	FeT(%) COG Rocktype 4012	Cu(%) COG Rocktype 4012	Au(ppm) COG Rocktype 4012	FeT(%) COG Rocktype 4013	Au(ppm) COG Rocktype 4013	FeT(%) COG Rocktype 402
Cut-off Fet	13	0	0	13	0	0	13	0	13
Cut-off FeT-Cu	19	0.14	0	19	0.14	0	19	0	19
Cut-off FeT-Cu-Au	17	0.14	0.293	17	0.14	0.293	17	0.293	17
CashFlow	13	0.14	0.293	13	0.14	0.293	13	0.293	13

Table Appendix 21

Ore Selection Method	Cu(%) COG Rocktype 402	Au(ppm) COG Rocktype 402	FeT(%) COG Rocktype 4022	Cu(%) COG Rocktype 4022	Au(ppm) COG Rocktype 4022	FeT(%) COG Rocktype 4023	Cu(%) COG Rocktype 4023	Au(ppm) COG Rocktype 4023	FeT(%) COG Rocktype 403
Cut-off Fet	0	0	13	0	0	13	0	0	13
Cut-off FeT-Cu	0.140	0	19	0.140	0	19	0.140	0	19
Cut-off FeT-Cu-Au	0.140	0.293	17	0.140	0.293	17	0.140	0.293	17
CashFlow	0.140	0.293	13	0.140	0.293	13	0.140	0.293	13

Table Appendix 22

Ore Selection Method	Cu(%) COG Rocktype 403	Au(ppm) COG Rocktype 403
Cut-off Fet	0	0
Cut-off FeT-Cu	0.212	0
Cut-off FeT-Cu-Au	0.212	0
CashFlow	0.212	0

Table Appendix 23

The following tables show the output of the Pit by pit graph for revenue factor 0.6 not considering a defined FeT(%) COG for Dominga Norte. The tables also show the COG used in each scenario.

Ore Selection Method	Tonnes Norte input to process (Mt)	Waste (Mt)	FeT(%) grade input to process	FeM(%) grade input to process	Cu(%) grade input to process	Au(ppm) grade input to process
Cut-off Fet	47.1	152.9	32.6	23.0	0.157	0.023
Cut-off FeT-Cu	46.5	134.9	29.9	20.9	0.125	0.016
Cut-off FeT-Cu-Au	47.1	134.3	29.7	20.7	0.124	0.016
CashFlow	47.1	134.3	29.7	20.7	0.124	0.016

Table Appendix 24

Ore Selection Method	FeT(%) COG Rocktype 501	Cu(%) COG Rocktype 501	Au(ppm) COG Rocktype 501	FeT(%) COG Rocktype 5012	Cu(%) COG Rocktype 5012	Au(ppm) COG Rocktype 5012	FeT(%) COG Rocktype 5013	Cu(%) COG Rocktype 5013	Au(ppm) COG Rocktype 5013
Cut-off Fet	14.1	0	0	10.2	0	0	7.9	0	0
Cut-off FeT-Cu	14.1	0.163	0	10.2	0.163	0	7.9	0.163	0
Cut-off FeT-Cu-Au	14.1	0.163	0.340	10.2	0.163	0.340	7.9	0.163	0.34
CashFlow	14.1	0.163	0.340	10.2	0.163	0.340	7.9	0.163	0.34

Table Appendix 25

Ore Selection Method	FeT(%) COG Rocktype 5013	Cu(%) COG Rocktype 5013	Au(ppm) COG Rocktype 5013	FeT(%) COG Rocktype 5022	Cu(%) COG Rocktype 5022	Au(ppm) COG Rocktype 5022	FeT(%) COG Rocktype 5023	Cu(%) COG Rocktype 5023	Au(ppm) COG Rocktype 5023
Cut-off Fet	17.1	0	0	10.2	0	0	8.1	0	0
Cut-off FeT-Cu	17.1	0.163	0	10.2	0.163	0	8.1	0.163	0
Cut-off FeT-Cu-Au	17.1	0.163	0.340	10.2	0.163	0.340	8.1	0.163	0.340
CashFlow	17.1	0.163	0.340	10.2	0.163	0.340	8.1	0.163	0.340

Table Appendix 26

Ore Selection Method	FeT(%) COG Rocktype 503	Cu(%) COG Rocktype 503	Au(ppm) COG Rocktype 503	FeT(%) COG Rocktype 5032	Cu(%) COG Rocktype 5032	Au(ppm) COG Rocktype 5032	FeT(%) COG Rocktype 5033	Cu(%) COG Rocktype 5033	Au(ppm) COG Rocktype 5033
Cut-off Fet	11.1	0	0	11.1	0	0	12.7	0	0
Cut-off FeT-Cu	11.1	0.246	0	11.1	0.246	0	12.7	0.246	0
Cut-off FeT-Cu-Au	11.1	0.246	0	11.1	0.246	0	12.7	0.246	0
CashFlow	11.1	0.246	0	11.1	0.246	0	12.7	0.246	0

Table Appendix 27

The following tables show the output of the Pit by pit graph for revenue factor 0.6 not considering a defined FeT(%) COG for Dominga Sur. The tables also show the COG used in each scenario.

Ore Selection Method	Tonnes Sur input to process (Mt)	Waste (Mt)	FeT(%) grade input to process	FeM(%) grade input to process	Cu(%) grade input to process	Au(ppm) grade input to process
Cut-off Fet	957.3	931.8	20.7	14.6	0.061	0.012
Cut-off FeT-Cu	1,063.0	841.3	19.5	13.6	0.061	0.012
Cut-off FeT-Cu-Au	1,071.8	832.5	19.4	13.6	0.06	0.012
CashFlow	1,071.7	832.6	19.4	13.6	0.06	0.012

Table Appendix 28

Ore Selection Method	FeT(%) COG Rocktype 401	Cu(%) COG Rocktype 401	Au(ppm) COG Rocktype 401	FeT(%) COG Rocktype 4012	Cu(%) COG Rocktype 4012	Au(ppm) COG Rocktype 4012	FeT(%) COG Rocktype 4013	Cu(%) COG Rocktype 4013	Au(ppm) COG Rocktype 4013
Cut-off Fet	9.7	0	0	7.8	0	0	6.723	0	0
Cut-off FeT-Cu	9.7	0.140	0	7.8	0.140	0	6.723	0.140	0
Cut-off FeT-Cu-Au	9.7	0.140	0.293	7.8	0.140	0.293	6.723	0.140	0.293
CashFlow	9.7	0.140	0.293	7.8	0.140	0.293	6.723	0.140	0.293

Table Appendix 29

Ore Selection Method	FeT(%) COG Rocktype 402	Cu(%) COG Rocktype 402	Au(ppm) COG Rocktype 402	FeT(%) COG Rocktype 4022	Cu(%) COG Rocktype 4022	Au(ppm) COG Rocktype 4022	FeT(%) COG Rocktype 4023	Cu(%) COG Rocktype 4023	Au(ppm) COG Rocktype 4023
Cut-off Fet	11.8	0	0	8.8	0	0	7.1	0	0
Cut-off FeT-Cu	11.8	0.140	0	8.8	0.140	0	7.1	0.140	0
Cut-off FeT-Cu-Au	11.8	0.140	0.293	8.8	0.140	0.293	7.1	0.140	0.293
CashFlow	11.8	0.140	0.293	8.8	0.140	0.293	7.1	0.140	0.293

Table Appendix 30

Ore Selection Method	FeT(%) COG Rocktype 403	Cu(%) COG Rocktype 403	Au(ppm) COG Rocktype 403
Cut-off Fet	9.4	0	0
Cut-off FeT-Cu	9.4	0.212	0
Cut-off FeT-Cu-Au	9.4	0.212	0
CashFlow	9.4	0.212	0

Table Appendix 31

The following graphs (from 47 to 52) are the representation of the grades input to process for Dominga Norte and Dominga Sur considering a defined FeT COG. The figures also show the tonnes input to process.

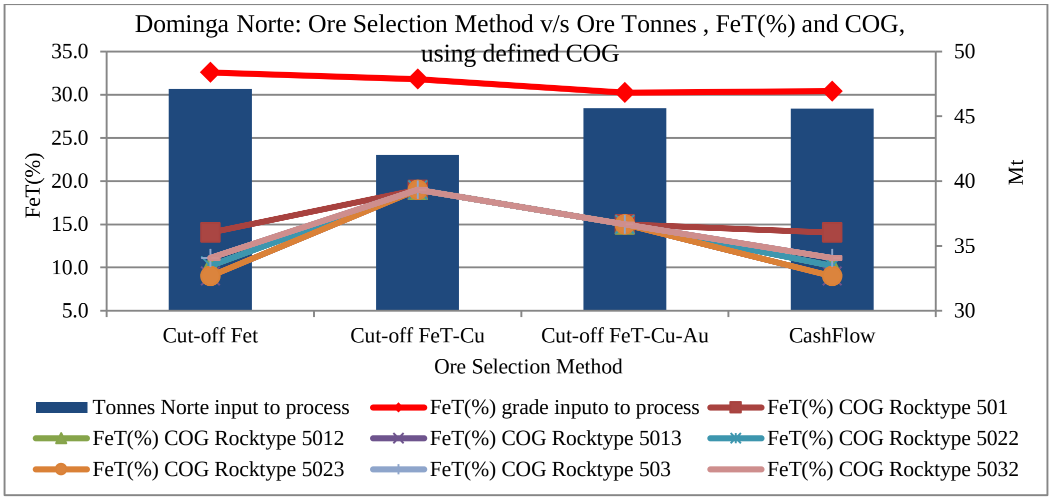

Figure Appendix 47

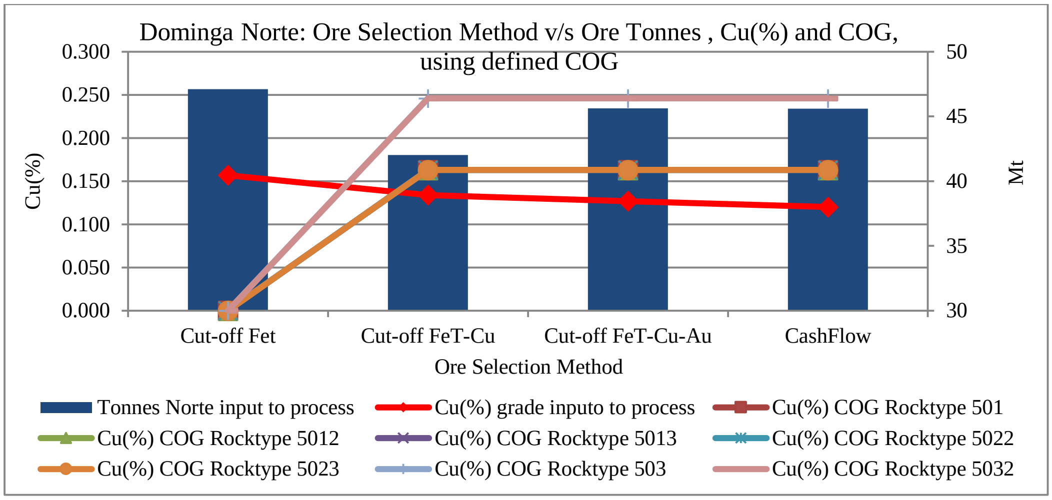

Figure Appendix 48

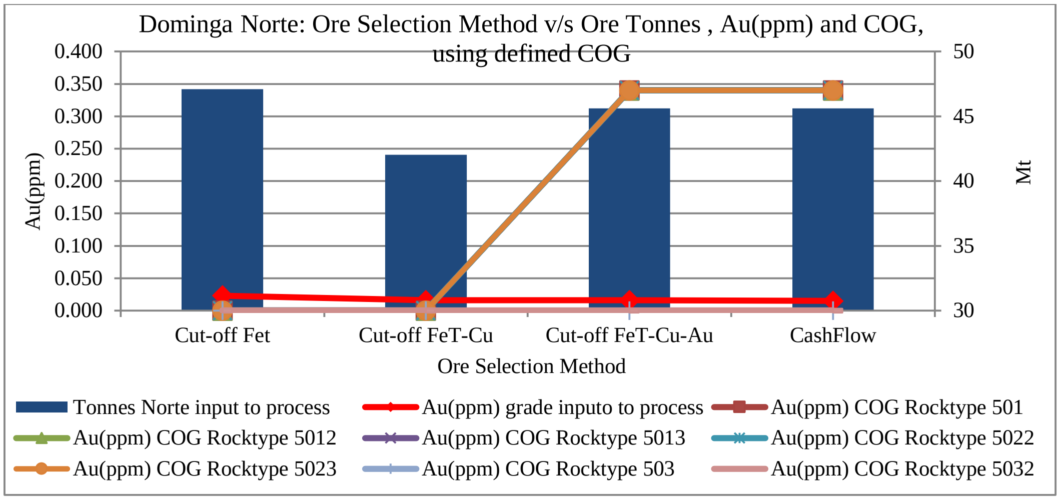

Figure Appendix 49

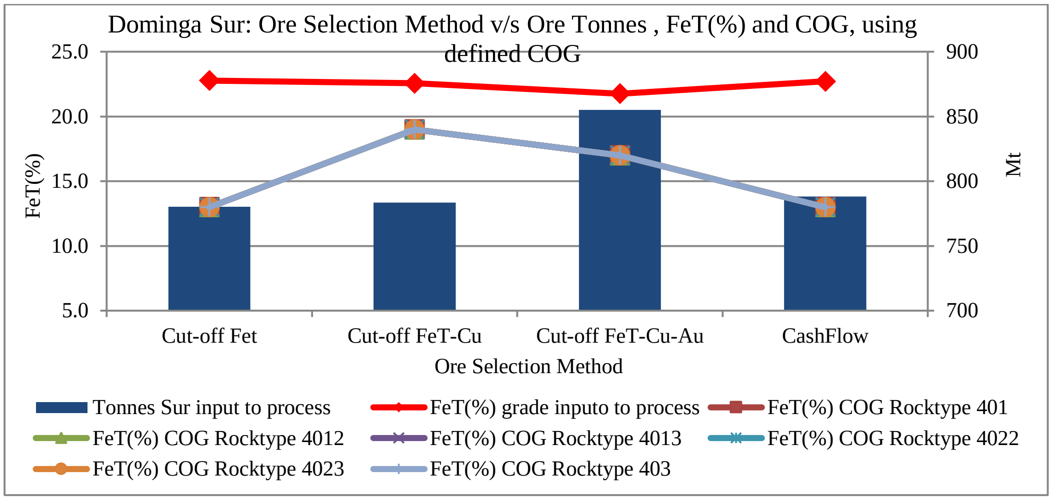

Figure Appendix 50

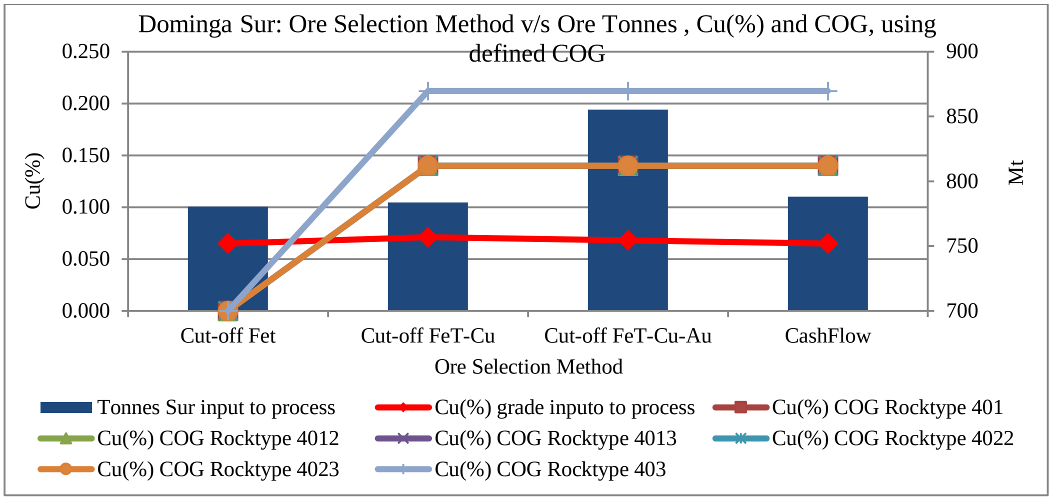

Figure Appendix 51

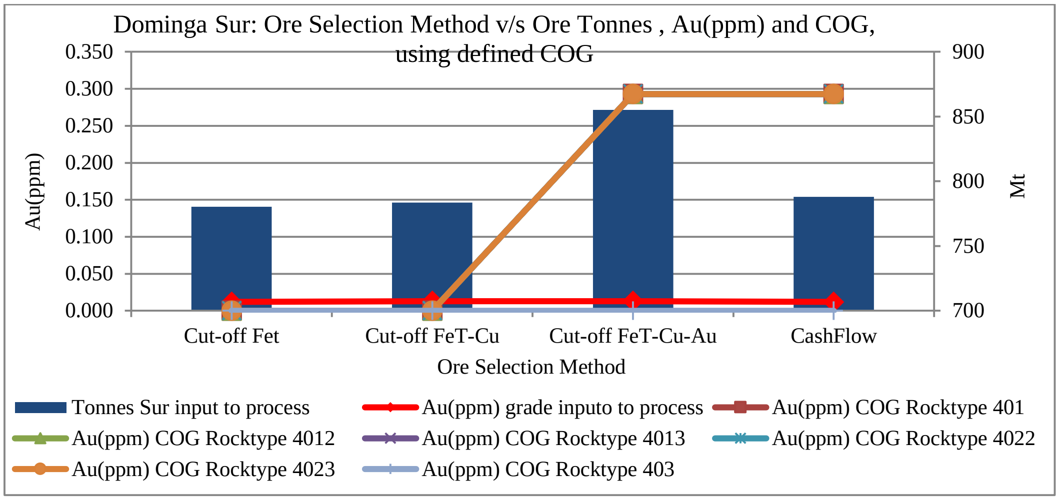

Figure Appendix 52

The following graphs (from 53 to 58) are the representation of the grades input to process for Dominga Norte and Dominga Sur not considering a defined FeT COG (not using FeT COG). The figures also show the tonnes input to process.

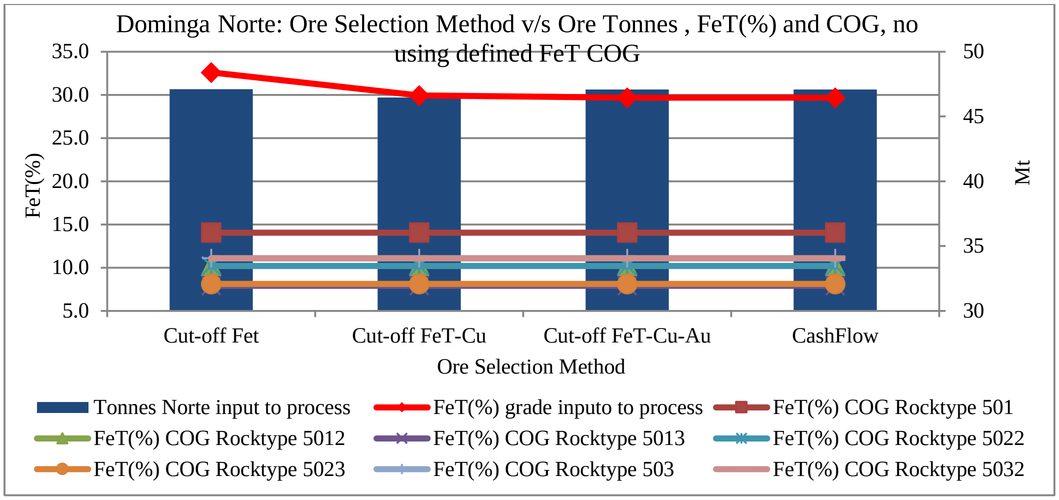

Figure Appendix 53

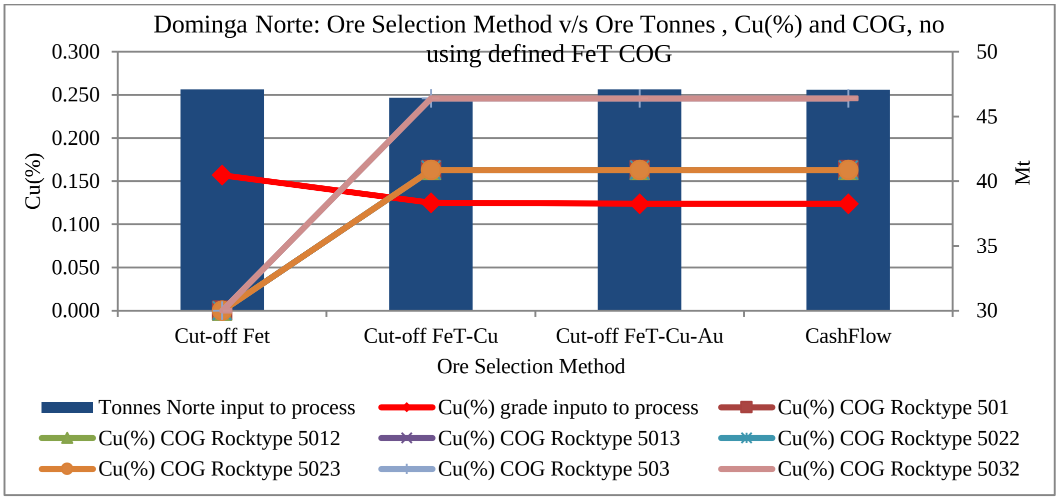

Figure Appendix 54

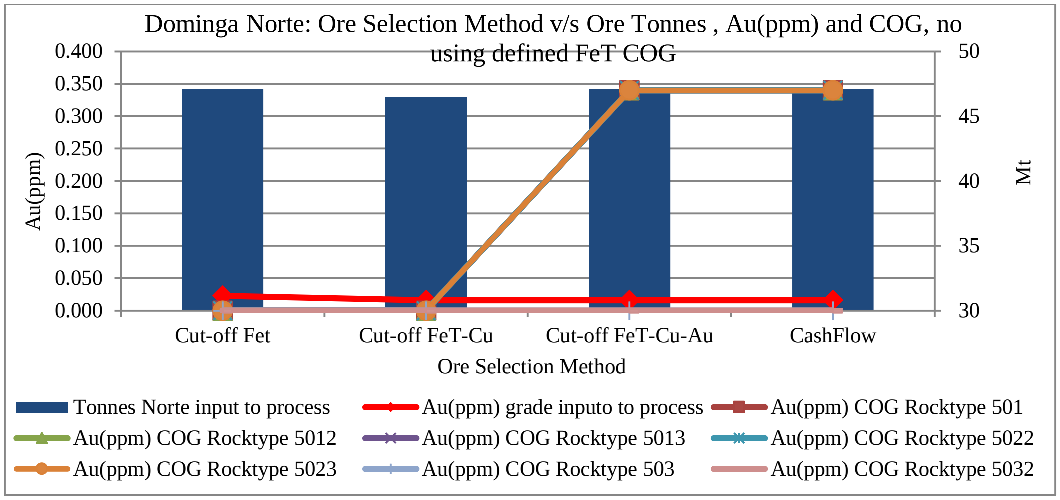

Figure Appendix 55

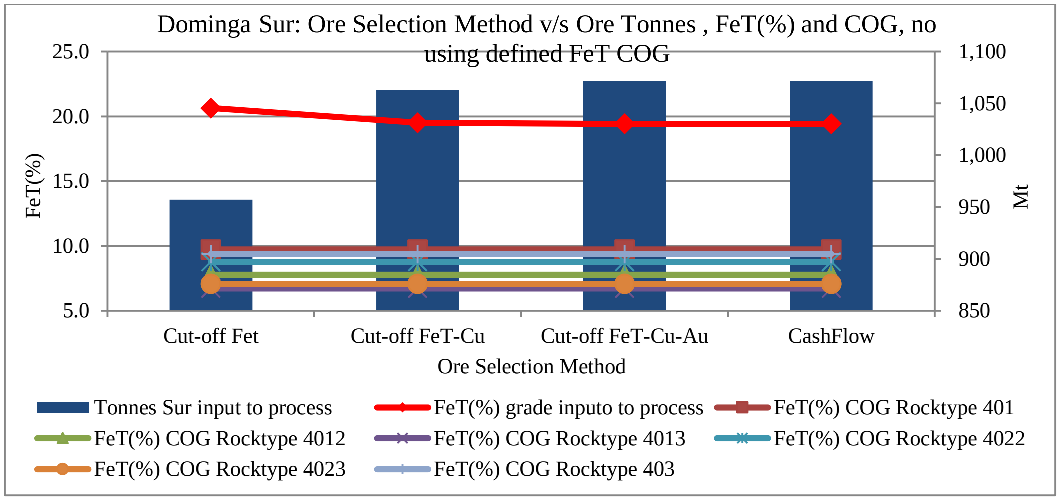

Figure Appendix 56

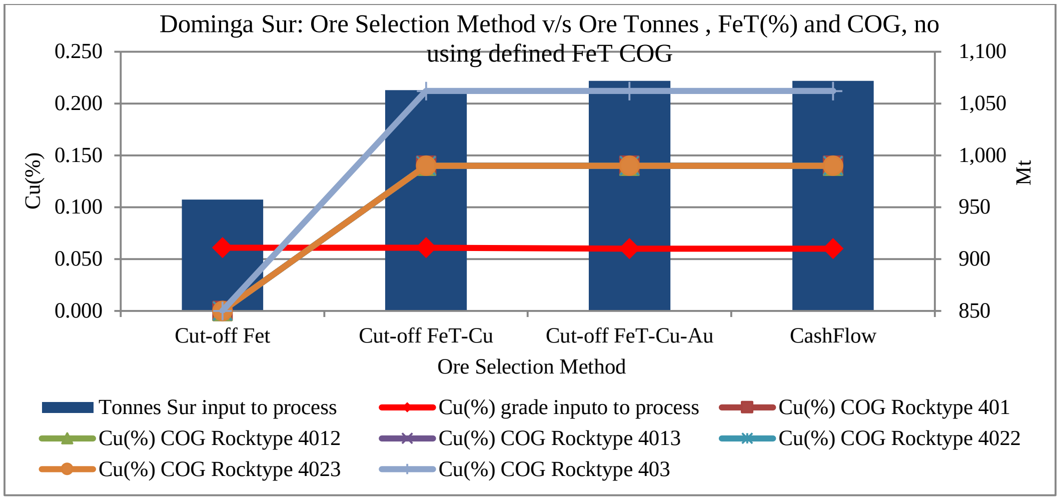

Figure Appendix 57

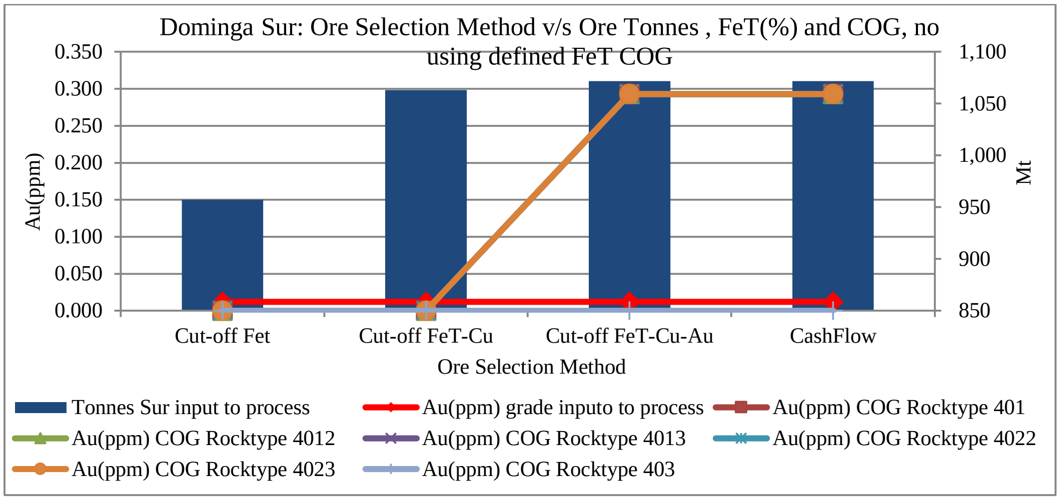

Figure Appendix 58

Appendix D

Introduction to the Iron Ore Industry

D.1 Iron Definition

Iron is a chemical element with the symbol Fe and the atomic number 26. It is the fourth most common element in the earth's crust after oxygen, silicon and alumina. (Fleischer, 1952)

Element	Percentage Weight (%)
1.Oxygen	46.6
2.Silicon	27.7
3.Alumina	8.1
4.Iron	5.0
5.Calcium	3.6
6.Sodium	2.8
7.Potassium	2.6

Table Appendix 32: Element Percentage Weight in the earth's crust (Fleischer, 1952)

There are many minerals that contain iron. The principal sources of this element are: Hematite (Fe_2O_3), Magnetite (Fe_3O_4), Goethite ($Fe_2O_3H_2O$) and Siderite ($FeCo_3$).

From the list above, hematite is the most common iron ore mineral on earth and generally is easier to extract and trade than the other iron ore minerals because it has high grades and also because most hematite deposits do not require treatment and can be mined as a direct shipping ore (DSO). However, in general, contaminants are present in high levels in iron ore from hematite mineralization (Banco BTG Pactual S.A., 2015). The following figure shows common varieties of hematite:

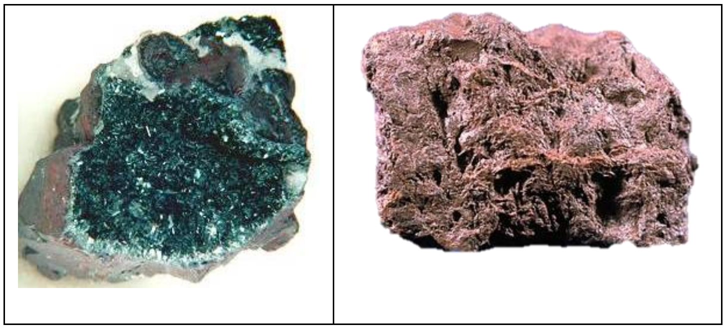

Figure Appendix 59: Left: Specularite, variety of Hematite, (Friedman, 1997-2015): Right: Hematite (Mineral Education Coalition)

Magnetite is also a common iron ore mineral. Iron grades for a magnetite deposit are typically around 25-40% iron content. One of the big differences with hematite is that magnetite requires important upgrading or processing before it can be marketed as a salable iron ore product. The magnetic properties of magnetite allow magnetic separation techniques to be used to produce iron concentrate (Banco BTG Pactual S.A., 2015). For the Dominga Project, the main mineral is magnetite and the process identified to obtain the final product is magnetic recovery. The following figure shows a typical magnetite rock.

Figure Appendix 60:Typical magnetite specimen exhibiting a gray metallic luster. (Geology.com, 2005-2015)

Other iron-bearing minerals, defined as secondary minerals since they result from an alteration process, are Goethite and Limonite (iron oxides). According to the Banco BTG Pactual report, most of the Chinese iron ores have low grades of this type of minerals. Finally, there are other minerals that contain iron ore such as Siderites, Taconites and Itabirite (iron formation composed of hematite-magnetite ore, quartz and other minor minerals)

Figure Appendix 61: Left: Goethite. Right: Limonite. Source: (Mineral Education Coalition)

D.2 Iron Ore Products

Iron ore is the primary source for steel production and almost 98% of the total production is for that propose. Iron (Fe) is not a commodity by definition (Willmot, 2007), because all iron products may contain different quantities of contaminants and different amounts of iron. For this reason, the price of the sellable product depends on the quality of the product, which can be measured by the grade of Fe content, the sizing of the product, and the levels of the different contaminants that may be included. However according to Platts, an international provider of metals market assessments and price benchmarks, iron ore is a commodity with widely varying quality specifications. (Platts, 2015)

Because of the information presented in the previous paragraph, it is important to define the different products from iron ore. Generally, iron ore containing more than 54% Fe, is considered as high-grade material and requires no further beneficiation other than sizing before being sold or marketed. Ore with iron content less than 54% is considered low grade and requires upgrading to increase the Fe content and reduce impurities to become in a sellable product (Natural Resources Canada, 2014)

Iron ore is usually traded as three different main products. These products can be divided based on size as follow (Barclays Capital Inc., 2012):

1. Fines: There are 2 different products called Fines and their classification depends on the size of the particle:
    - *a) Sinter Feed:* Iron ore fines with particles ranging from 0.15 mm to 6.35 mm in diameter
    - *b) Pellet Feed:* Ultra fine iron ore, diameter less than 0.15 mm.

2. Lump Ore: Iron ore with particle sizes from 6.35mm to 50mm in diameter. It is most commonly used as a direct charge in a blast furnace.
3. Pellets: Pellets range sizes are from 8mm to 18mm. This product is made from the transformation of pellet feed into a pelletized form.

D.2.1 Agglomeration Process

The process of agglomeration is a necessary process to prepare the iron ore products from the mine site to be charged in the blast furnace or in a direct reduction plant (DRI) (These processes are defined in Section 3.4 and 3.5 respectively). For this, sinter feed and pellet feed are used as a main product to prepare the material. The following figure shows a diagram of the different iron ore products and the process to obtain them.

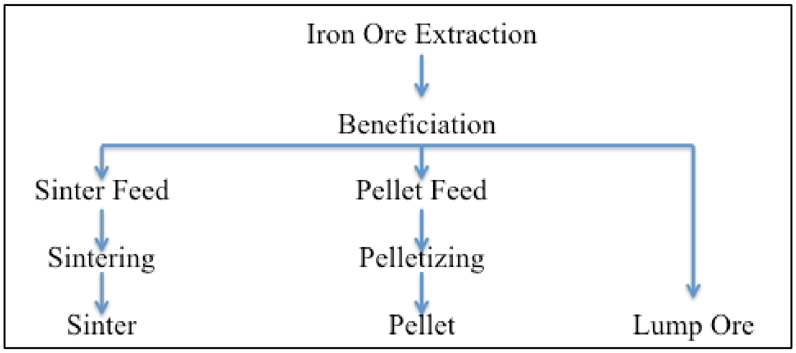

Figure Appendix 62: Diagram that shows the different process to obtain material as a sellable product, (Source: (Banco BTG Pactual S.A., 2015))

As shown in the figure above, the beneficiation process is the process which produces the fines and lump ore from the material extracted from the mine (the ore). Magnetic recovery for magnetite ore deposits is one example of a beneficiation process. After beneficiation, there are two different processes to agglomerate raw material as is shown in the figure above, the first one is the sintering process and the second one is the pelletizing process.

D.2.1.1 Sintering Process

The sintering process is a form of agglomeration that prepares or transforms sinter feed into sinter material to be charged in a blast furnace. In general, the non-ferrous input materials included are coke, limestone and minor amounts of other materials as required. As is indicated in the Iron Ore Handbook (Banco BTG Pactual S.A., 2015), the process of sintering consists of mixing the sinter feed with water for cohesion, then placing the material on a conveyor belt sinter strand. The material on the belt is ignited with gas burners at the start of the strand (1300-1480°C), and finally the mass is cooled in open air, crushed and screened. This methodology of agglomeration generates high levels of carbon emissions, and for that reason has a negative environmental impact. (Barclays Capital Inc., 2012)

D.2.1.2 Pelletizing Process

Pelletizing is the industrial process of agglomerating pellet feed to build iron ore pellets. According to the Iron Ore Handbook (Banco BTG Pactual S.A., 2015), the process can be summarized as follows: water is added to the fines (pellet feed) to a obtain moisture content of approximately to 8-9%. Then the pellet feed is mixed with additives, such as bentonite (clay), and fluxes such as limestone, olivine and dolomite, and processed into 8–18mm balls called "green pellets". The green pellets have low mechanical strength, and they are sent to a process to be hardened by heating the material to 1250°C to obtain high strength pellets. After this process pellets are cooled. Undersized or broken pellets are generally recycled. The main reason to prefer pellet feed versus sinter feed in the blast furnace is because it reduces the time that the material is in the furnace.

Compared to sintered iron, the iron content in pellets is higher (normally above 65% Fe) and contains lower contaminants making it perfect for use in DRI plants. (Banco BTG Pactual S.A., 2015)

The following table shows the production of pellets by the 4 biggest pellet producer companies in the world:

Company	Production 2014 (Mt)	World Capacity (%)
Vale	43	14.3
Cliffs	33	11.0
ArcelorMittal	25	8.3
US Steel	25	8.3

Figure Appendix 63: Biggest pellet producer companies globally (Banco BTG Pactual S.A., 2015)

D.3 Blast Furnaces

A blast furnace is a large, steel stack used in steel production. The furnace is lined with refractory brick, and iron ore, coke and limestone are dumped into the top, with preheated air is blown into the bottom. The blast furnace is the first step in producing steel from iron oxides. The main purpose of a blast furnace is to chemically reduce and physically convert iron oxides into molten iron called "hot metal" or Pig Iron, which has a very high carbon content, typically 3.5-4.5%. The raw materials require 6 to 8 hours to descend to the bottom of the furnace where they form the final products of liquid slag and pig iron. These liquid products are drained from the furnace at regular intervals. The hot air that was blown into the bottom of the furnace ascends to the top in 6 to 8 seconds after going through numerous chemical reactions (Steel Works, 2015)

D.4 Direct-Reduced Iron (DRI)

DRI is produced from the direct reduction of iron ore (in form of lumps, pellets or fines) by a reducing gas produced from natural gas or coal. Direct-reduced iron is richer in iron than pig iron (produced as a result of the blast furnace), typically 90-94% total iron. (International Iron Metallics Association, 2015)

D.5 Iron Ore Contaminants

The most common impurities or contaminant found in iron ore products are: Silica, Alumina, Phosphorus and Sulphur. (The Independent Geologist, 2015)

D.5.1 Silica

Silica is the most common impurity in iron ore products. It is easy to separate through the beneficiation or upgrading process. Silica levels in an ore product should ideally be <3.5%, however for high-grade ores (>54%Fe) they may be less than 2%. High silica ores can still be used but will probably be blended with high-grade ores to reduce the overall impurity level

D.5.2 Alumina

Alumina is more difficult to remove than silica and is not so easily blended into the smelted product. Alumina also increases the viscosity of a slag formed during the smelting process and as a result the viscous liquid waste is harder to remove and slows down the smelting process.

D.5.3 Phosphorous

Phosphorous is one of the most complicated impurities in iron ore. The main problem of high levels of phosphorous content in iron ore is that it increases the brittleness of steel, which is an undesirable characteristic in the steel industry. According to the source, only low levels of phosphorous are tolerated. If the iron ore product has more than 0.01% of Phosphorous, then the price of the product will be reduced, because the ore will require blending with a low phosphorous ore to reach a tolerable grade of this element. It is not easy to remove phosphorous so it is preferable that ores are low in phosphorous from the beginning.

D.5.4 Sulphur

Sulphur is another impurity of the iron ore product which is not easy to deal with it. Iron ore with high levels of sulphur (>0.01-0.03%) are not preferably used in the industry because produces iron ore products hard and breakables. Sulphur may emit gas from smelting which is a source of sulphur dioxide that can interact with moisture in the atmosphere to produce sulphuric acid.

Another type of contamination that products can have is the quantity of water content in the ore that evaporates when the ore is charged in the blast furnace. This can be measured with a factor called Loss on Ignition (LOI).

D.6 Ore Production and Uses

As described before, almost 98% of the iron ore production is used as input for steel production and the remaining 2% is used in the manufacture of cement, pigments, ballast, agricultural products, or specialty chemicals. Iron ore is mined in about 50 countries however Australia and Brazil together dominate the world's iron ore exports (U.S Geological Survey). Currently iron ore is mined in many countries, however the bulk production comes from Australia, Brazil, China and India. The following table shows the world's iron production. The production on the table considers agglomerates, concentrates, DRI, direct-shipping ore, iron nuggets, pellets, and byproduct ore for consumption:

	Production Iron (Mt)	
Country	Year 2013	Year 2014
China	1,450	1,500
Australia	609	660
Brazil	317	320
India	150	150
Russia	105	105
Ukraine	82	82
South Africa	72	78
United States	53	58
Iran	50	45
Canada	43	41
Kazakhstan	26	26
Sweden	26	26
Other countries	127	131
World total (rounded)	3,110	3,222

Table Appendix 33: World iron product production. Source: USGS, Mineral Commodity Summaries, January 2015

The following table shows the most important iron ore producer companies in the world. Vale, Rio Tinto, and BHP are the dominant companies in terms of production.

Company	Country	Production	
		2014 (Mt)	%World Capacity
Vale	Brazil	317	16.7
Rio Tinto	UK	305	16.1
BHP	UK/Australia	230	12.1
Fortescue	Australia	155	8.2
Anglo American	UK	61	3.2
LKAB	Sweden	32	1.7
CSN	Brazil	34	1.8
Cliffs	USA	11	0.6
Other	-	755	39.7

Table Appendix 34: Largest iron ore producer companies in 2014. (Source: (Banco BTG Pactual S.A., 2015))

D.7 Iron Ore Markets

The biggest iron ore producer countries in order are China, Australia, and Brazil. Worldwide, 50 countries produce iron ore, but 96% of this ore is produced by only 15 of those countries. The production capacity is concentrated in only a few companies, known in the industry as the "big three" producers. These companies are Vale, Rio Tinto and BHP (U.S Geological Survey). It is useful to know and understand the terms used in the iron ore industry. For that reason the following section presents a glossary about some important concepts that can help to understand this industry. This glossary can be very helpful to people that have worked in other commodity industries and started to work in the iron industry.

D.7.1 Glossary Iron Ore Market

D.7.1.1 Seaborne iron ore market

The "seaborne iron ore market" refers to iron ore traded and transported by ocean shipment. The seaborne iron ore market represents more than 50% of total global iron ore production, and is mainly dominated by the "big three" (Banco BTG Pactual S.A., 2015). The following figure shows the percentage of demand of the most important consumer of iron ore products:

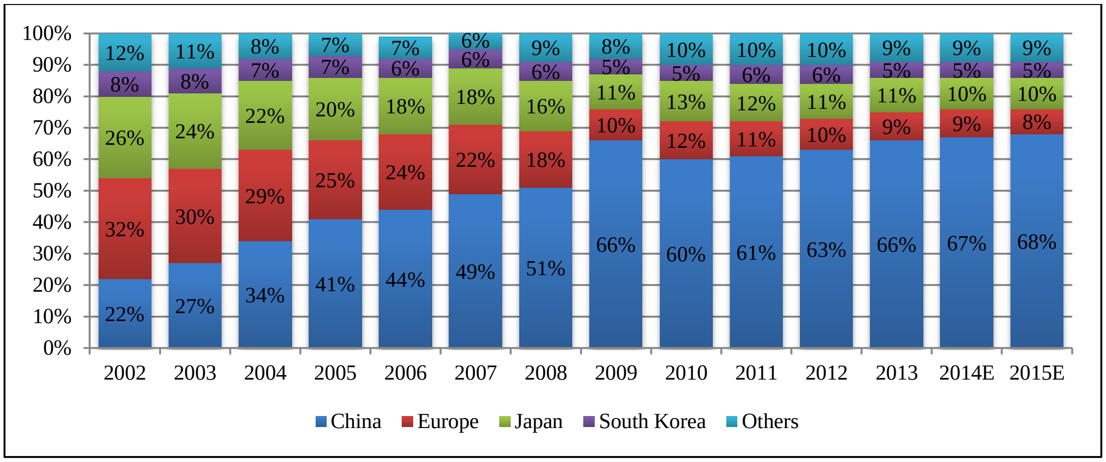

Figure Appendix 64: Seaborne iron ore demand (Source: (Banco BTG Pactual S.A., 2015))

From the figure above, China is the most important seaborne consumer, followed by Japan. The following figure shows the most important suppliers of iron ore:

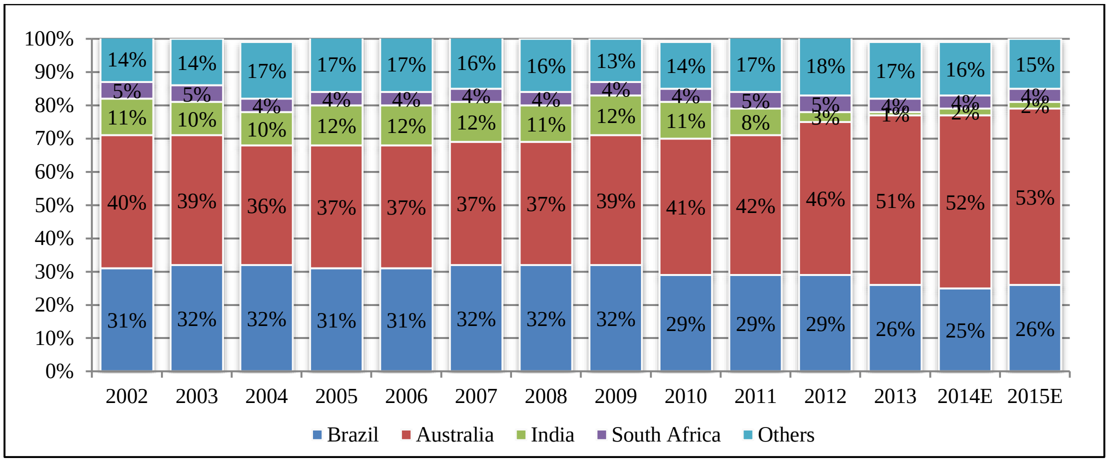

Figure Appendix 65: Seaborne iron ore supply. (Source: (Banco BTG Pactual S.A., 2015))

D.7.1.2 Direct Shipping Ore:

The "Direct Shipping Ore" (DSO) is the material that can be exported directly with minimal processing and beneficiation (Mining-Crushing-Stockpiling and Selling).

According with Banco BTG Pactual, hematite deposits usually have DSO material due high iron content.

D.7.1.3 Free on Board

The "Free on Board" (FOB) concept (Investopedia) refers "to a trade term requiring the seller to deliver goods on board a vessel designated by the buyer". It is also mentioned that "contracts involving international transportation often contain abbreviated trade terms that describe matters such as the time and place of delivery and payment, when the risk of loss shifts from the seller to the buyer, as well as who pays the costs of freight and insurance." (Investopedia)

D.7.1.4 Cost and Freight

The "Cost and Freight" (CFR) term, as Investopedia mentioned in their website, refers "to a trade term requiring the seller to arrange for the carriage of goods by sea to a port of destination, and provide the buyer with the documents necessary to obtain the goods from the carrier". In this case, "the seller does not have to procure marine insurance against the risk of loss or damage to the goods during transit". (Investopedia)

D.7.1.5 Cost, Insurance and Freight

The "Cost, Insurance and Freight " (CIF) concept (Investopedia) refers "to a trade term requiring the seller to arrange for the carriage of goods by sea to a port of destination, and provide the buyer with the documents necessary to obtain the goods from the carrier". It is important to mention that for this case the "contracts involving international transportation often contain abbreviated trade terms that describe matters such as the time and place of delivery, payment, when the risk of loss shifts from the seller to the buyer and who pays the costs of freight and insurance." (Investopedia)

D.7.1.6 Spot Price

Spot price is defined as “the current price at which a particular security can be bought or sold at a specified time and place” (EquinoxFunds, 2015). According to Banco BGT Pactual, in the past “iron ore was priced between the largest steelmakers and iron ore suppliers through annual negotiation” and the iron ore cost curves were designed using FOB as a reference. However the growth of the Chinese crude steel capacity during 2000-2014 caused an increase in demand in the seaborne iron ore market, passing from an oversupplied market to a tight market. This system had some problems when the buyers (Chinese steel makers) broke contracts. It became necessary to adopt a system based on periodic contract renegotiation, on a regional and client basis. This system adopted considers the use of a cost curve CIF basis. (Banco BTG Pactual S.A., 2015)

D.7.1.7 Iron ore Index

Iron ore standardization is required for spot price calculations considering that between products the differences of iron content and contaminants can be significant. There are three recognized indices to price iron ore, these are IODEX, The Steel Index (TSI) and The Metal Bulletin Iron Ore Index (MBIO). These indices are not origin specific and they can consider cargos from any iron ore producer in any region in the world. The indices normalize the iron content to 62% Fe as a reference, however they accept different ranges of iron content.

D.7.1.7.1 IODEX

IODEX is the Platts Iron Ore Index. Platts is a “global provider of energy, petrochemicals, metals and agriculture information, and a premier source of benchmark price assessments for those commodity markets” (Platts, McGraw Hill Financial, 2015). It is a benchmark assessment of the spot price of iron ore. This index is used to price iron ore in the form of lump ore, pellet and concentrate using the application of premiums and discounts depending on the quality of the product based in the base specifications. These base specifications are shown in the Table

Appendix 35. The index is published on a CFR to Qingdao Port, in North China. The IODEX compiles transactions with iron content from 60.0% to 63.5%. (Banco BTG Pactual S.A., 2015)

D.7.1.7.2 TSI

The Steel Index (TSI) is an iron ore reference price. TSI compiles transactions with iron content from 60.01% to 68.0% (Banco BTG Pactual S.A., 2015). The index is published on a CFR to Tiajin Port, in North China.

D.7.1.7.3 MBIO

According to Metal Bulletin, MBIO is an accurate representation of the seaborne market for sinter fines delivered to China (CFR China spot basis). (Metal Bulletin Iron Ore Index, 2015). The index is published on a CFR to Qingdao Port.

The following table is a summary of some specifications related with the three indices explained above.

	Index		
Factor	**IODEX**	**TSI**	**MBIO**
Iron Content	62%	62%	62%
Moisture	8%	8%	8%
Alumina	2%	3.50%	2%
Silica	4.50%	4%	3.50%
Phosphorus	0.075%	0.07%	0.05%
Sulphur	0.02%	0.05%	0.02%
Lot Size	Minimum 35kt	Minimum 20kt	Minimum 30kt
Lead Time	Delivery within 2-8 weeks	Delivery within 2-12 weeks	Delivery within 8 weeks
Payment	100% at sight	100% at sight	100% at sight
Currency and Units	US$/dmt	US$/dmt	US$/dmt
Frequency	Daily	Daily	Daily

Table Appendix 35: Iron ore indices specifications (Source: (Banco BTG Pactual S.A., 2015))

D.7.1.8 Dry Metric Tonne Unit

The “Dry Metric Tonne Unit” (dmtu) refers to the measurement unit applied to iron ore concentrate prices in terms of negotiations. The dmtu is the metric tonne unit without moisture. As an example a particular contract says that the deal is supply X tonnes of ore concentrate at 58% Fe with 10% moisture. The price defined for this is given using 80 $/dmtu. The concentrate contains moisture, however, the price defined is without moisture. The total revenue that can be obtained from the X tonnes is:

$$Revenues = (x\ tonnes) * (1 - 0.1) * (58\%\ Fe) * \left(80 \frac{\$}{dmtu}\right)$$