RODRIGO AUGUSTO NUNES

Technological innovation to support the decision-making process for open pit mining: The application of technological models and semi-mobile in-pit crushing and conveying scenario's evaluation

São Paulo
2018

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Dissertation presented to the Escola Politécnica de São Paulo to obtain the degree of Master of Science.

Concentration Area:
Mineral Engineering

Advisor:
Prof. Dr. Giorgio de Tomi

São Paulo
2018

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Technological innovation to support the decision-making process for open pit mining: The application of technological models and semi-mobile in pit crushing and conveying scenario's evaluation / R. A. Nunes -- São Paulo, 2018.

39 p.

Dissertação (Mestrado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia de Minas e Petróleo.

1.Strategic mine planning 2.Pit-to-plant 3.Technological model
4.Geometallurgy 5.Semi-mobile IPCC I.Universidade de São Paulo. Escola Politécnica. Departamento de Engenharia de Minas e Petróleo II.t.

ACKNOWLEDGMENTS

Firstly, I would like to thank God, the creator of everything.

A special thanks to my family and specifically to my parents Margareth A. Nunes and Rui R. Nunes for the solid creation I got and the help to overcome all challenges that I have had on my life.

I would like to thank my lovely wife, Gabriela D. Nunes for the great incentive and help to accomplish this objective.

To my colleagues at Yamana Gold, the source of many technical discussion fundamental to the construction of this dissertation.

To Metso, for allowing me to use the supporting data referent to the excellent work they done for Chapada mine in 2014.

Finally, yet importantly, I would like to thank my advisor Prof. Dr. Giorgio de Tomi for all the support provided during this long but productive journey.

RESUMO

Este trabalho apresenta duas maneiras inovadoras de avaliar projetos de mineração. A primeira é a elaboração e aplicação do modelo tecnológico para uma mina de cobre e ouro já a segunda refere-se à confecção de um modelo de tomada de decisão a ser usado para a análise dos benefícios de aplicação de britagem semimóvel em cava. Para melhorar os processos e maximizar a produção e/ou o valor de um projeto de mineração, existe a necessidade de integração dos dados de geologia, planejamento de mina, beneficiamento e geometalurgia. Com esse foco, uma nova metodologia foi proposta para a criação do modelo tecnológico. Este modelo pode ser interpretado como a consolidação dos diferentes modelos necessários para uma melhor compreensão das informações geológicas e técnicas do depósito. Este conceito foi desenvolvido e aplicado em uma mina de cobre de ouro localizada no Brasil. Com base na avaliação de diferentes cenários de perfuração e desmonte de rochas e de produtividade do moinho, usando uma abordagem de mina-usina, foi possível obter ganhos operacionais de curto prazo, tais como um aumento de 10,7% na taxa de produção de usina e um aumento de 2,2% na taxa de alimentação da britagem com pouco ou nenhum investimento de capital. Uma outra questão relevante para empresas de mineração é o transporte de material. Um custo significativo na maioria das minas surge da compra e manutenção de caminhões de transporte. A britagem em cava e correias (IPCC em inglês) vem sendo avaliada em diversos casos devido ao seu potencial para reduzir os custos de transporte. Neste estudo, um modelo de tomada de decisão foi criado para identificar em etapas iniciais de um projeto os benefícios de aplicação de IPCC semimóvel (SMIPCC em inglês) em comparação com método convencional, exclusivamente por caminhões. O método baseia-se na análise de custos e na avaliação de impactos ambientais testado em uma mina a céu aberto, onde os resultados indicaram que o SMIPCC foi a opção mais econômica para a operação. Embora o investimento inicial do IPCC foi 60% maior do que a abordagem convencional, o custo operacional do IPCC foi 43% menor, resultando em uma redução de 28% do custo total a valor presente.

Palavras-Chave: Planejamento estratégico de mina. Mina-Usina. Modelo tecnológico. Geometalurgia. Britagem semimóvel. Redução de custo. Redução de CO.

ABSTRACT

This work presents two innovative ways to evaluate mining projects. The first is the application of a Technological Model in a copper-gold mine and the second is a decision making model to evaluate the benefit of semi-mobile in pit crusher and conveyor alternatives during the early stages of mining projects. In order to improve the process and to maximize the production and/or value of a mining project, there needs to be an integration of the geology, the mine plan, the processing and the geometallurgy data. In order to accomplish this, a new methodology is proposed for the creation of a technological model. This model can be interpreted as the consolidation of the different models required for a better understanding of the geological and technical information of the deposit. This concept was developed and applied at a copper and gold mine site located in Brazil. Based on the evaluation of different blasting and mill productivity scenarios through a pit-to-plant approach, it was possible to obtain operational short-term gains such as a 10.7% increase in the plant production rate and a 2.2% increase in the crusher's feed rate with little or no capital investment. Another important issue faced by mining companies is related to material handling. A significant cost in the operating budget of most mining operations arises from purchasing and maintaining haulage trucks. Recently, in-pit crushing and conveying (IPCC) has been subject to research because of its potential to reduce haulage costs. A decision-making model was created to identify early on in a project whether or not the semi-mobile IPCC (SMIPCC) is an appropriate alternative to the conventional truck haulage based on the loading and hauling approaches. The method is based on cost analysis and the evaluation of environmental impacts, being successfully tested at an existing open-pit mine, where the results indicated that the IPCC was the most cost-effective option for the operation. Although the IPCC's initial CAPEX was 60% higher than the conventional approach, the IPCC's OPEX was 43% lower, resulting in a 28% reduction of the life-of-mine net present cost (NPC).

Key words: Strategic mine planning. Pit-to-plant. Technological model. Geometallurgy. Semi-mobile IPCC. Cost saving. CO reduction.

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1. GENERAL INTRODUCTION

The strategic mine plan is a crucial step for the success of mining companies and for its development it is necessary to use a number of inter-related variables that are usually estimated independently. These variables include operational data that is traditionally isolated in information islands between the different departments in the mine or they are consolidated into individual models. This reduces the holistic view of the deposit thereby causing a negative impact on the results of the strategic planning itself. In order to improve the process and to maximize the production and/or value of a mining project, there needs to be an integration of the geology, the mine plan, the processing and the geometallurgy data.

Another important issue faced by mining companies is related to material handling. A significant cost in the operating budget of most mining operations arises from purchasing and maintaining haulage trucks. Recently, in-pit crushing and conveying (IPCC) has been subject to research because of its potential to reduce haulage costs, however it is normally considered as an alternative during later stages of the project development, in feasibility studies. A tool to analyse it during early stages of a mining project can be very helpful as it has the potential to reduce an enormous amount of engineering hours that in many cases is applied to the project that does not have the propensity for semi-mobile IPCC application (SMIPCC).

This study presents two innovative ways to evaluate mining projects. The first is the development of a Technological Model applied to a copper-gold mining project. This methodology integrates the geometallurgy and the mine-to-mill concept aimed to optimize mill productivity. The second is the creation and use of a decision-making model in the early stage of Front End Loading (FEL) studies of a Mining Project.

The first innovative way to evaluate mining projects, the technological model can be interpreted as the consolidation of the different models required for a better understanding of the geological and technical information of the deposit. This concept was developed and applied at a copper and gold mine site located in Brazil together with the consultant support of Metso. Based on the evaluation of different blasting and mill productivity scenarios through a pit-to-plant approach, it was possible to obtain operational short-term gains as the plant and crusher's feed rate increased.

The second innovative way to evaluate mining projects, the decision-making model to evaluate the SMIPCC benefit is based on cost analysis and the evaluation of environmental impacts. It was successfully tested at an existing open-pit mine, where the results indicated that the IPCC was the most cost-effective option for the operation.

1.1.OBJECTIVES

- To develop a methodology for the creation and application of the technological model for a copper-gold deposit;
- To technically evaluate the use of the decision-making model to assess the benefits of a semi-mobile in-pit crushing and conveying alternative during the early stages of a mining project.

1.2. STRUCTURE OF THIS DISSERTATION

According to the outlined objectives, the dissertation was organised following the sequence below:

- Chapter 1: Problem presentation and objectives discussion;
- Chapter 2: Literature review, methodology, results an research analyses involving mine-to-mill, geometallurgy and the technological model;
- Chapter 3: Literature review, methodology, results and research analyses involving the decision making model to evaluate SMIPCC benefits during the early stages of a mining project;
- Chapter 4: Conclusions of the two studies developed and the relationship with the research objectives.

2. AN INTEGRATED PIT-TO-PLANT APPROACH USING TECHNOLOGICAL MODELS FOR STRATEGIC MINE PLANNING OF COPPER AND GOLD DEPOSITS

2.1. INTRODUCTION

This research topic is part of an article to be published by the author in 2019¹. The strategic planning of a mine is a crucial step for the success of mining companies, since it provides the necessary information for the decision-making process concerning the development of the deposit (SILVA, 2008). Therefore, in terms of strategic mine planning, it is important that the uncertainty related to the orebody is properly quantified, assessed, and managed (GODOY, 2018). For the preparation of the strategic mine plan, it is necessary to use models and data that are often estimated independently.

The technological model presented in this manuscript aims to solve the disconnected and in many times, inaccurate view of the deposit. This new approach consolidates the different data used to gain a better understanding of the geological, mine planning and processing data of the project. Lund and Lamberg (2014) state that the construction of technological models can reduce operational risks and could help to optimize the production, taking into account sustainability and socio-economic factors.

The data that is being referred to in this study includes the resource and structural models, the geometallurgical model, the cost model and the operating Selective Mining Unit (SMU) model, which is the smallest volume of material that the classification of ore and waste can be determined (SINCLAIR; BLACKWELL, 2002).

¹ NUNES, R.; DE TOMI, G.; ALLAN, B.; BEZERRA E.; SILVA, R. (2019). **An integrated pit-to-plant approach using technological models for strategic mine planning of copper and gold deposits.** REM – International Engineering Journal. Published in 2019-(2) April-June

The Geometallurgical model, a component of the technological model, allows for a better understanding of the ore characteristics. The importance of this increased knowledge base is that by knowing the strength, structure, and grade, there are adjustments that can be made to the crushing, grinding, and flotation processes (LA ROSA et al., 2014).

Gomes et al. (2016) used a geometallurgical model to support an economic study considering reserve volumes, product quality and operational cost. From the model remarkable gains were obtained in the iron ore reserve and in the reduction of the operation cost. Its use is also essential to strategic mining planning for mines that seek to optimize the use of mining resources over the life of mine (PHILANDER; ROZENDAAL, 2014). Navarra et al. (2018) incorporated the geometallurgical modelling in long-term planning and confirmed its great impact on the life of mine.

As noted by Augustin et al. (2017) the models should continually be updated whenever possible, by way of additional exploratory drill holes, to ensure that a greater detail of accuracy is achieved. Nadolski et al. (2015) complement that these models require constant adjustment, with the insertion of the geotechnical, geological, metallurgical and other operational data from the plant, which will also serve to calibrate predictive models.

The development process for the preparation of the technological model in question, used the work undertaken at a large-scale copper and gold open-pit mine of sulphide ore located in Brazil, as a reference. This work was carried out between the mine and the consultant expertise of Metso (2014). The process includes crushing, grinding, and flotation. The saleable product is a copper-gold concentrate.

In the studied mine, the ore comes from different mining faces feeding the plant at the same time. The technological model created tracked the ore characteristics back to its original mining face. One of the main objectives of the technological model was to determine the plant performance by the ore domain on an industrial scale and, to adjust the blasting parameters aiming to increase the plant throughput but keeping the metallurgical recoveries at similar or higher levels. This concept of pit-to-plant optimization has been used at other mine sites around the world where different processes of integration and optimization were applied (JANKOVIC; VALERY, 2011).

2.2.METHODOLOGY

As a starting point for the model, the different unit operations of the mine and plant were characterized. Blasting designs, mine and plant sampling, and operational testing were carried out. The data obtained was used to develop the specific models for the prediction processes of blasting, crushing, and grinding. These models were the basis of the construction of the technological model. Figure 1 summarizes the components of the technological model.

Source: Prepared by the author

The methodology used for the preparation of the technological model is based on the following steps:

- Characterization and delineation of areas based on their geological structure, strength, and correlation with their lithological and structural domains.
- Establishing operating restrictions such as the stability of benches, the presence of water, SMU size, ore dilution allowance, the blast pile characteristics, the size of the equipment, and the size/power of the crushers/mills, in addition to any other bottlenecks in the process.
- Defining the main requirements of the subsequent steps to plan for each geological domain in order to meet their specific requirements.
- Use of software, mathematical models, and process simulation.

- Implementation and monitoring of the defined operational strategy (suitable plans for each domain followed by the ideal adjustment for the crushing and grinding cycle).
- Analysis and management of data and results.
- Project implementation and maintaining the benefits obtained.

The above methodology is simplified in the Figure 2.

Figure 2 - Project Flow Chart

Source: Modified from PIO (Mine to Mill) – Metso, 2014

The first step required an audit to be carried out during the drilling and blasting operations. This was necessary in order to obtain data, pictures, and other observations that are required to provide enough information for the creation of the fragmentation models. Once the information is obtained, the blasting techniques can be tailored to the rock characteristics, which will allow for substantial improvements in the downstream operations (KANCHIBOLTA et al., 2015).

Simulations of the blasting plan were executed with both the soft and hard ore. Various parameters were changed depending on the simulation. Compared to the base case these variations included, a slight increase in bench height, an increase in hole diameter, a change in spacing, sub drilling, hole depth, stemming, and an increase in the column charge.

In the second phase of the preparation of the technological model, laboratory tests, image analyses, data processing, and mathematical models were consolidated. In order to optimize the ROM fragmentation from the mine blasting, a fragmentation model was developed. This model is sensitive to the main parameters that affect the blasting performance. The fragmentation model was then calibrated with the data

obtained from the observed blasting during the audit process and used to predict changes in the particle size distribution of the ROM.

2.2.1. Fragmentation Measurement Using Image Analysis

Particle size distribution of the ROM is one of the parameters used in calibrating the fragmentation model. Prior studies of operations around the world have indicated that image analysis is a good and practical method for this purpose. Photographs of the piles formed after the verified blasting and primary crushing were processed using the Split-Desktop software (SPLIT ENGINEERING, 2017). Each image contains an object for scale. For this project, two Styrofoam balls were used and are pictured in Figure 3.

Figure 3 - Example of a rendered image from the Split-Desktop software.

Source: PIO (Mine to Mill) – Metso, 2014

2.2.2. Blast Tracking

Electronic tags were used to track the blasted material, enabling the verification of when the material enters the crushing/grinding cycle. Therefore, the complete sampling of the plant could be performed using the audited blasted material. Samples collected from the conveyor belts and the main streams for laboratory tests determined the breaking characteristics of the material. Specific models were developed for the blasting, crushing, grinding, and classification processes by using the audited blast data, sampling, and testing. Figure 4 shows the electronic tag with a diameter of 60mm and a height of 30mm used in the study as well as the typical installation of the electronic tag system with an antenna positioned above the conveyor belt.

Figure 4 - The Reinforced Electronic Tag and the antenna above the conveyor belt

Source: PIO (Mine to Mill) – Metso, 2014

In total 274 electronic tags were used in the survey data. They were put in the stem, in the piles formed after detonation, and in the feed of each primary crusher. In order to obtain the data for calibrating the mathematical models for the different equipment in the circuit, sampling was performed in the crushing and grinding circuit. Operational data was also collected during the sampling to determine the production rates and power consumption of each piece of equipment listed in Table 1. The sampling points are shown in the flowchart in Figure 5. Once the sampling was complete, the data was balanced and modelling was performed in the JKSImMet software (JKTECH, 2014).

Table 1 - List of the comminution equipment's circuit

Equipment	Description
Primary Crushers	<ul style="list-style-type: none"> •MMD Sizer S100-20, 400kW •Metso C160, 220kW
SAG Mill	1 mill with an internal diameter of 10.01m and 4.95m of EGL, 11000 kW, 10.34rpm
Pebble Crusher	2 Metso HP800, 600kW
Ball Mill	1 mill with an internal diameter of 7.09m and 11.94m of EGL, 12500 kW, 12.19rpm
Cyclones	<ul style="list-style-type: none"> •Cluster SAG: 6 Multotec HC900-L20 cyclones, with a 360mm equivalent entry diameter, a 340mm vortex, and a 170mm apex •Cluster Ball: 8 Krebs GMAX 33 cyclones, with a 390mm equivalent entry diameter, a 305mm vortex, and a 180 mm apex

Source: Yamana Gold Inc

Figure 5 - Sampling points in the grinding cycle

Source: Yamana Gold Inc

After the completion of the mass balancing, the mathematical models of all the processing units were calibrated according to the Anderson and Awachie model for the primary crushers in the JKSimMet software version 6.0 (JKTECH, 2014) and Whiten (Whiten and White, 1979). The objective was to model the grinding cycle at the time of sampling. The perfect blend model and the variable rate model were adjusted to the ball and SAG mills, respectively. The cyclones were adjusted using Nageswararao's model (NAGESWARARAO, 1995).

Using the balanced flow data, that includes the mass flow rate, the percentage of dry solids, and the particle size distribution, the models could be adjusted with respect to the parameters of each specific operation. Other information taken into account were the characteristics of the ore, the dimensions of the equipment, and the information related to the operation during sampling, which includes the load and speed levels of the mills, the energy consumption, and the operating pressure of the cyclones. Historical data was also considered to ensure that the results are consistent and that they represent the operation of the cycle as accurately as possible.

2.3. RESULTS AND DISCUSSION

In total there were 24 blasting simulations carried out. Eleven of those simulations were performed on soft ore, and the remaining thirteen, which are shown below, were carried out on hard ore. Once the simulations were complete, one of the thirteen (base case) was selected to be applied to the blasting plan in the field. The hard ore simulations are presented in the Table 2 below.

Table 2 - Blasting Scenarios for Hard Ore

Long Term - Hard Ore		Base Case	Sim LP D												
			1	2	3	4	5	6	7	8	9	10	11	12	13
Dimensions															
Bench Height	m	9.9	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Hole Diameter	mm	6.75	10	10	10	10	10	10	10	9	9	9	9	9	9
Burden	m	3.9	4.8	4.6	4.3	4.1	3.8	3.6	3.6	4.3	4.1	3.9	3.7	3.4	3.2
Spacing	m	4.7	5.6	5.3	5.0	4.7	4.5	4.2	4.1	5.0	4.7	4.5	4.2	4.0	3.7
Subdrilling	m	1.20	1.30	1.30	1.30	1.20	1.20	1.10	1.10	1.30	1.20	1.20	1.10	1.00	1.00
Hole Depth	m	11.1	11.3	11.3	11.3	11.2	11.2	11.1	11.1	11.3	11.2	11.2	11.1	11.0	11.0
Stem	m	2.80	3.40	3.40	3.40	3.40	3.40	3.40	3.40	3.10	3.10	3.10	3.10	3.10	3.10
Explosives															
Column Charge	-	Pumped Emulsion	E.B. 70	E.B. 71	E.B. 72	E.B. 73	E.B. 74	E.B. 75	E.B. 76	E.B. 77	E.B. 78	E.B. 79	E.B. 80	E.B. 81	E.B. 82
Column Load Density	t/m ³	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
	kg	202	422	422	422	417	417	412	412	355	351	351	347	342	342
Column Charge	m	8.3	7.9	7.9	7.9	7.8	7.8	7.7	7.7	8.2	8.1	8.1	8	7.9	7.9
	kg/m	24.4	53.5	53.5	53.5	53.5	53.5	53.5	53.5	43.3	43.3	43.3	43.3	43.3	43.3
Blasting Parameters															
Blasted Volume	m ³	182	269	244	215	193	171	151	148	215	193	176	155	136	118
Rock Density	t/m ³	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Blasted Mass	t	491	726	658	581	520	462	408	399	581	520	474	420	367	320
Specific Drilling	m ³ /m	18.4	26.9	24.4	21.5	19.3	17.1	15.1	14.8	21.5	19.3	17.6	15.5	13.6	11.8
	t/m	49.6	72.6	65.8	58.1	52.0	46.2	40.8	39.9	58.1	52.0	47.4	42.0	36.7	32.0
Powder Factor	g/t	412	582	642	728	802	903	1009	1033	612	674	741	826	932	1071
	kg/m ³	1.11	1.57	1.73	1.96	2.16	2.44	2.72	2.79	1.65	1.82	2.00	2.23	2.52	2.89
ROM Specifications															
P100	mm	1092	933	861	764	724	637	598	595	816	770	706	661	593	533
P80	mm	379	310	287	258	241	217	201	199	282	264	244	226	204	184
Passing 10mm	%	11.9	15.6	16.9	18.7	20.2	22.2	24.2	24.6	13.3	17.7	19.0	20.7	22.8	25.5

Source: PIO (Mine to Mill) – Metso, 2014

The use of electronic tags in the blasted material proved to be effective in tracking the ore from the mine to the plant and assured that the audited blasted material was fed to the plant during sampling. During the 34-hour monitoring period, 131 electronic tags out of the 274 were detected. The spatial coordinates of each detected electronic tag are shown in Figure 6 below.

Figure 6 - The positioning of each electronic tag detected.

Source: Yamana Gold Inc

After the completion of the plant sampling and gathering of the experimental data, the model could be created. The mass balancing results compared well to the experimental data, indicating that the sampling data is valid for further analysis. In general, the models developed in JKSimMet (JKTECH, 2014) were well adjusted with respect to the data, and are considered appropriate for long-term simulation studies that are to be used in strategic mine planning. The experimental and modelled data can be compared in Table 3 below.

Table 3 - Experimental and Modelled Data from the Main Streams

Mine Modelling		Solids, t/h		P80, mm		% Solids	
		Exp	Mod	Exp	Mod	Exp	Mod
SAG	feed	2026	2026	157.6	157.6	94.6	94.6
	Prod.		2484		8.73		70
Sieve SAG	O/S	458	458	54.2	51.7	98.5	98.9
	U/s		2026	1.351	1.21	65.2	65.7
Pebble Crusher	Prod.		458	19.1	19.4	99	98.9
Cyclone SAG	feed		2026	0.836	1.21	46.1	47.6
	O/f		768	0.196	0.196	35.3	32.8
	U/f		1258	2.593	2.62	64.7	65.7
Ball Mill	feed		5411		1.68		70
	Prod.		5411	0.803	0.811	72.3	70
Ball Cyclone	feed		5411	2.625	0.811	71.9	61.5
	O/f		1258	0.177	0.177	34.4	37
	U/f		4153	2.187	1.333	76.5	76.9

Source: Modified from PIO (Mine to Mill) – Metso, 2014

The results of the simulated scenarios with different mill loads are presented in Table 4.

Table 4 - Simulated Scenarios with the Optimization of the SAG

Simulated Scenarios		Sampling	100% Hard Ore		CP F 07	3.5" Grates	Ball load	
SAG Optimization	Units	Base Case	Base Case	PF 2.78	CP D 07	12% Open Area	10%	13%
Production Rate	t/h	2026	1269	1405	2530	2585	2630	2690
Δ in Production Rate	%			10.7		2.2	3.9	6.3
F80 of Feed	mm	157.6	142.4	102.1	102.7	102.7	102.7	102.7
Feed Passing 12.5 mm	%	31.7	16.9	29.8	42.6	42.6	42.6	42.6
Power SAG	kW	9053	9053	9053	9053	9053	9560	10400
Pebble Production	t/h	458	412	404	534	610	577	491
Pebble Crusher Power	kW	690	658	640	770	854	804	684
Sieve Undersize P80	mm	1.21	1.55	1.48	1.29	1.44	1.56	1.64
Partition of the SAG cyclone	%	39.7	40.1	33.0	38.6	39.0	38.4	37.6
Cyclone SAG Overflow P80	mm	0.196	0.179	0.200	0.197	0.191	0.194	0.199
Cyclone SAG P80 Underflow	mm	2.615	3.610	2.894	2.808	3.104	3.174	3.113
Ball Mill Power Consumption	kW	11201	11201	11201	11201	11201	11201	11201
Rolling Charge	%	330	287	369	327	329	340	353
Ball Cyclone Overflow of P80	mm	0.177	0.176	0.188	0.208	0.214	0.219	0.224
Grinding Circuit P80	mm	0.184	0.177	0.192	0.204	0.205	0.209	0.214
Total Power Consumed	kW	20994	20912	20894	21024	21108	21565	22285
Specific Energy Consumption	kWh/t	10.3	16.5	14.9	8.3	8.2	8.1	8.1
Operational WI	kWh/t	14.5	22.7	21.5	12.4	12.2	12.3	12.5

Source: Modified from PIO (Mine to Mill) – Metso, 2014

The results of the rock blasting simulations demonstrated the importance of improving the results of fragmentation, especially when analysing the productivity of an integrated comminution process for harder lithology. There was a 37% reduction in the production rate of the SAG (2026 to 1269 t/h) when the circuit supply consisted only of hard material. Under this same condition, increasing the powder factor to 2.78 kg/m³ resulted in an increase in the mill's productivity by 10.7%. This result directly

relates to the finer particle size distribution obtained from the increased energy in the rocks from the blasting.

The SAG cycle improves with an increase in the load (the percent of mill volume occupied by media plus voids) from 8% mill balls (measured after grinding) to 10-13% mill balls. These changes allowed the grinding circuit to increase to within 2-4% of the productivity achieved with the largest open area. In order to better utilize the installed power of the pebble crushers, SAG mill grates with larger openings were installed. When comparing the scenario to the finer ROM, the simulation resulted in a 14% increase in pebble generation, while the feed rate increased by 2.2%. It is important to note that by increasing the opening of the grate, the grate life is shortened. Therefore, it was suggested to find alternatives in order to minimize the wear on the grate.

An outcome of this methodology, the technological model, has shown to be adherent to the plant results and operational data collected after many reconciliation processes. This methodology is still in use at the mine, which constantly updates the model with the new input data.

3. A DECISION MAKING-METHOD TO ASSESS THE BENEFITS OF A SEMI-MOBILE IN-PIT CRUSHING AND CONVEYING ALTERNATIVE DURING THE EARLY STAGES OF A MINING PROJECT

3.1. INTRODUCTION

This research topic is part of an article to be published by the author in 2019². One of the challenges while evaluating the early stages of open pit mining projects is to determine which of the alternatives for material transportation and which location for the primary crusher should be considered for further detailed studies and scenario selection. A parallel study between the alternative of the conventional truck haulage with the primary crusher located outside of the pit and the in-pit crushing and conveying alternative can be a long, expensive process. Mining companies with portfolios that contain many open pit projects usually face issues in evaluating the benefits of an IPCC implementation due to the massive workload and time necessary for completion. Properly evaluating these alternatives is important since the haulage costs in open pit mines can be 60% or more of the mine's operating cost (RIBEIRO, 2013). IPCC systems are now receiving more attention due to the rising cost of the truck haulage cycles, which can be attributed to the cost of diesel and spare parts, leading to the IPCC being the favourable option. In contrast, the IPCC is considered a low-cost alternative in terms of operating costs due to its continuous operation regime, reduced labour, and lower energy consumption, but it requires a high capital cost, and has reduced flexibility (LONDOÑO et al. 2014).

There have been studies carried out in the past proposing the use of SMIPCC systems as an alternative to conventional trucking and regular IPCC systems, where the crusher is fully mobile and only a conveyor is used for haulage.

² NUNES, R.; DELBONI JR, H.; DE TOMI, G.; INFANTE, C. B.; ALLAN, B. (2019). **A decision-making method to assess the benefits of a semi-mobile in-pit crushing and conveying alternative during the early stages of a mining project**. REM – International Engineering Journal. Published in 2019-(2) April-June.

A SMIPCC can exploit the advantages of both systems, conventional trucking and fully mobile IPCC, but it is important to ensure that the in-pit crusher is at an appropriate distance from the work front and that its location will be suitable for at least one year of operation before it needs to be moved (RAHMANPOUR et al. 2014). SMIPCC systems are considered flexible and adaptable because of the continuous use of trucks and being able to install a crusher in a suitable location (NEHRING et al. 2018). The majority of studies that compare IPCC with truck based haulage systems using conveyors, result in large operational savings due to a more efficient energy and capital allocation.

Although the IPCC concept is not new, as it was introduced in the 1950's in Germany (RITTER et al. 2014), companies are still concerned with the implementation of such an alternative due to the high risk involved. Another issue is that it is not as simple as choosing a particular haulage system; one also needs to know how to adapt it to the mine plan to ensure a reduction in the overall mining costs. Therefore, the uniqueness of a project poses a contractual constraint, as no pre-made off-the-shelf options are available (DEAN et al. 2015).

Furthermore, from environmental licensing process standpoint, the method used for decision-making can be a relevant tool to be used before going through the preliminary environmental licensing process, so that the SMIPCC alternative can be considered to demonstrate a reduction in environmental impact.

To get a better understanding of the IPCC alternative, a new method is proposed that aims to estimate the technical, economic, and environmental benefits of the semi-mobile IPCC alternative from an early project stage. The proposed approach has been tested using data from the initial design studies (PMI, 2013) of an open-pit copper-gold mine located in Brazil.

3.2. METHODOLOGY

The method was designed as a model that uses the data available from the early stages of the evaluation of mining projects, usually from the scoping studies, as its input parameters. The model analyses both the conventional trucking and the SMIPCC scenarios. In order to properly estimate the truck requirements, production capacities,

and costs, the following should be calculated: truck payload, engine powering and propulsion, cycle time estimations, and production rates (HUSTRULID et al. 2013).

The input can be classified into the following groups:

- Material: the material itself, in situ density, and swell factor;
- Truck Size: to be chosen from a payload of either 100, 150, 200, or 250 short tonnes;
- Operating: average haulage distance (flat, uphill, and downhill), rolling resistance, grade, speed limit, typical fixed times for spotting, dumping, and waiting, primary crushing P80 and design safety factor, working hours, hourly efficiency, conveyor's average speed, length, and elevation;
- Production: throughput, and life-of-mine;
- Economic: operating costs, discount rate, and exchange rate (if applicable).

The input models considered for the evaluation of the conventional trucking and the SMIPCC scenarios remain unchanged, with the exception of:

- Operating: Haulage distance (flat, uphill, and downhill) considering the location of the semi-mobile in-pit crusher, the conveyor average speed, length, and elevation;
- Economic: capital and operating costs, considering the capital and operating costs resulting from the implementation of the conveyor, reduction of the haulage fleet, and relocation of the semi-mobile in-pit crusher.

It is important to highlight the three assumptions used in this model:

- (1) The mine's throughput and, consequently, the life of mine for the conventional and SMIPCC scenarios remain the same, given that only the haulage fleet and the conveyor's input must be changed from one scenario to the other;
- (2) The truck payload (referred to below as the truck size) is an input parameter instead of a calculated one and is then used to select the loading equipment. This method is the reverse of the conventional fleet selection method. The payload relates to known off-road truck models that cover most mine operation cases;
- (3) Since both alternatives use the same number of excavators, the excavator CAPEX and OPEX were not included in the economic analysis and calculations because their costs will be equal.

The model continues the analysis as follows:

- (1) Truck and auxiliary equipment fleet dimensioning;
- (2) Conveyor dimensioning;
- (3) Economic Analysis;
- (4) Environmental Impact Analysis.

The method proposed in the article aims to be a tool to help in deciding on the best type of transport alternative to be used. It includes important topics such as the transportation scenario for the open pit mine, a comparison between the conventional model and the SMIPCC, and the economic feasibility and sustainability of each scenario.

The truck fleet size is determined by evaluating the model that is based on the mine's production capacity and operating parameters, specifically, the average haulage distance (AHD). These two factors are very important as they hold great weight in the decision to use the IPCC system (NEHRING et al. 2018). By selecting the truck size (model) from one of the four options, the number of trucks is calculated, as well as the number of bulldozers and motor graders required (Figure 7). It is worth mentioning that, because the transportation model considered in this study is a SMIPCC, it is still necessary to use trucks to move the material from the mining face to the in-pit crusher, where it will then be crushed and loaded onto the conveyors (MCCARTHY, 2011; MOHAMMADI et al. 2011).

Therefore, only the AHD from the mining face to the in-pit crusher is considered in the SMIPCC sizing, whereas the entire route is considered for the conventional model. In Figure 7, the AHD node indicated by [1] is subject to change based on the material transport alternative selected. The output nodes, indicated by [2], can be determined by using a rule of thumb based on the required truck units of one bulldozer for every 20 trucks and one motor grader for every 15 trucks, with a minimum of one unit in both cases.

Figure 7 - Fleet Sizing Flowchart

Source: Prepared by the author

Figure 8 - Conveyor Sizing Flowchart

Source: Prepared by the author

The conveyor's characteristics, such as the width, the power of the required motor, and the data to calculate the SMIPCC installation costs, are selected based on the material characteristics and operating parameters, such as the P80 for the primary crusher, and the mine production data (OSMETTI et al., 2012; BERTINSHAW et al., 2012) (Figure 8). Also in Figure 8, refer to Osmetti et al. (2012), and Bertinshaw et al.

(2012), for three of the input parameter nodes, [3], in order to determine the conveyor dimensioning.

The economic analysis of the mine for the two alternatives is performed considering these inputs. All the costs are included in this analysis and are separated into capital expenditure (CAPEX) and operating expenditure (OPEX) throughout the life of the mine (LOM). The costs are brought to the present value based on the discount rate(s) selected, resulting in the present value of the cost (NPC) (Figure 9).

Figure 9 - Economic Analysis Flowchart

Source: Prepared by the author

Using the discount rate when evaluating mining projects serves the same purpose as it does when evaluating projects in other fields: it considers the time value of money and the project risk (ATAEE-POUR et al., 2009). Since each project involves a different set of risks, the discount rates analysed in each one will be different. Product standards for nodes [4] are used for the input parameters. These standards were based on the truck cost, freight cost, and the import tax associated to it. In addition to the discount rate and the LOM, the total OPEX for the conveyor [5] also considers relocating the in-pit crusher and the cost of the conveyor's electricity consumption.

The model also proposes comparison of each scenario's environmental analysis on gas emissions. Based on the previously sized fleet, the amount of equipment and the type of engine is assessed and the tonnage of gases emitted during the LOM is calculated based on the EPA's Tier 4 Standard (US EPA 2004). The gases being analysed are the following: carbon monoxide (CO), non-methane hydrocarbons, (NMHC), nitrogen oxides (NOx), and particulate matter (PM) (Figure 10).

Figure 10 - Environmental Analysis Flowchart

Source: Prepared by the author

3.3. RESULTS AND DISCUSSION

Data from a Brazilian copper-gold mine was used for for this analysis. This study was implemented for a conceptual study based on the Project Management Body of Knowledge (PMI 2013). This decision-making process can be applied to any open pit mining project, as long as the specifications for each project are incorporated.

The life of mine was set as 20 years with an annual production of 16 million tons using 150-short ton trucks (Table 5). The AHD for the two alternatives was 1.6km. In the case of the SMIPCC scenario, the trucks travel 0.5km from the mining face to the in-pit crusher (IPC), and then for the next 1.1km, the material is transported by the

conveyor to the transfer chute. In the conventional scenario, the trucks travel the entire 1.6km along the ramp that closely follows the conveyor's profile, to a crusher that would be located near the indicated transfer chute in Figure 11.

Table 5 - Production Parameters			
Truck size	[short tons]	150	
LOM	[years]	20	
Estimated Throughput	[Mt]	16	
Material		Copper ores, crushed	

Source: Rodrigo Augusto Nunes

Figure 11 - Location of the SMIPCC alternative

Source: Google Earth

The inputs considered the decision-making model were created using Excel and VBA Macro and are summarized in the table below (Table 6). The calculated fleet sizes for both alternatives are listed in Table 7.

Table 6 - Model Input Parameters for the Study Case

INPUTS					
TRUCKS			EXCAVATORS		
Selected Truck	short tons	150	Bucket Size	m ³	14
	model	785D	Payload	t	38
Max. Speed	km/h	40	Fill Factor	%	85
RESISTANCES			OPERATING PARAMETERS		
Rolling Resistance	%	3	Working days / year	days	365
Grade Resistance	%	8	Shifts	shifts/day	3
Total Resistance (Flat)	%	3	Hours per shift	hrs/shift	8
Total Resistance (Uphill)	%	11	Availability	%	84
Total Resistance (Downhill)	%	11	Utilization	%	80
ORE PARAMETERS			Efficiency	%	83
Density	t/m ³	2.7	Hours per year	hrs/hrs	5887
Swell Factor	%	40	ECONOMIC PARAMETERS		
Moisture content	%	5	Annual Discount Rate	%	5
PRIMARY CRUSHING PARAMETERS			Exchange Rate	R\$/US\$	3.25
Required Nominal Capacity	t/h	2718	CF-CIF+Import Tax+ Custom Clearance	%	30
Design Safety Factor	fixed	1.4	OPEX		
Required Project Capacity	t/h	3805	Electricity Cost	US\$/MWh	73.6
Estimated P80 - approx. 80% fines	mm	250	Diesel Cost	US\$/l	0.7
CONVEYOR			Lubrication Cost	US\$/l	0.1
Average velocity	m/s	3.5	Tire Cost	US\$/h	68
Motor Efficiency	%	95	Labour Cost	US\$/h	63.5

Source: Prepared by the author

Table 7 - Required Fleet Sizes for Each Alternative

Required Fleet Sizing		
Equipment	Conventional	SMIPCC
Trucks	8	3
Excavators	2	2
Graders	1	1
Bulldozers	1	1
Conveyor	0	1

Source: Prepared by the author

The cost values for the mine were obtained by compiling the above data from the previous two tables with the initial data from the mine (Table 8). A noticeable difference in the initial CAPEX (before year 3) is that the SMIPCC installation is approximately 60% higher than the conventional scenario. This is due to the high installation cost of the crusher and conveyor belt.

However, the sustaining CAPEX (after year 3) for the conventional alternative is more than two times greater than that of the SMIPCC, due to the need for fleet replacement. Furthermore, when considering the OPEX, for the conventional case without including the discount rate, it is about 43% greater than that of the SMIPCC because of high maintenance costs, tires, fuel, and labour.

Table 8 - Economic Results

Thousands		Conventional	SMIPCC
Initial CAPEX - Before Year 3	[US\$]	\$28,893	\$46,966
Sustaining CAPEX - After Year 3	[US\$]	\$43,244	\$18,534
OPEX	[US\$]	\$190,313	\$107,959
NPC @ 5% discounted rate	[US\$]	\$174,619	\$126,230

Source: Prepared by the author

The net present cost (NPC) is an important factor for a project. In this study, five different discount rates were taken into account, which expanded the possible number of scenarios. The considered discount rates were 0.0%, 2.5%, 5.0%, 7.5%, and 10.0%. The values obtained from using a discount rate of 5% are presented above (Table 8). It shows that the NPC for the conventional alternative is about 50 million dollars more expensive than using the semi-mobile IPCC. When considering the total cost per ton (CAPEX & OPEX), the SMIPCC has a value almost 34% lower than that of the conventional alternative (Table 9).

Table 9 - Cost per ton Summary

		Conventional	SMIPCC
CAPEX&OPEX	[US\$/t]	\$0.82	\$0.54
CAPEX	[US\$/t]	\$0.23	\$0.20
OPEX	[US\$/t]	\$0.59	\$0.34

Source: Prepared by the author

The results of the environmental analysis were also very insightful. During the LOM, when opting for only using trucks, the carbon monoxide emissions are more than double that of the SMIPCC alternative (Table 10). The additional emissions are due to the high number of trucks required for the conventional trucking compared to the SMIPCC. For the examined mine, eight trucks are needed for the strictly trucking alternative, whereas when using the SMIPCC, only three trucks are needed. Therefore, the results also corroborate that the IPCC alternatives are also a means of reducing carbon emissions (MCCARTHY, 2011; COOPER; TURNBULL, 2009).

Table 10 - Environmental Analysis

		Conventional	SMIPCC
CO - Carbon Monoxide	[t]	3,586	1,516
NMHC – Non-methane Hydrocarbons	[t]	195	82
NOx - Nitrogen Oxides	[t]	3,344	1,274
PM - Particulate Matter	[t]	39	16

Source: Prepared by the author

3.3.1. Discussion

The expected result of the decision-making method presented was to conclude on which alternative should be selected while considering the proposed parameters, the OPEX, the CAPEX, the NPC, and the environmental analysis. Achieving this result was successful. The evaluation method allowed for a broader view of the importance of such variables in the decision-making process. In the discussed case, the SMIPCC alternative resulted in a lower sustaining CAPEX and OPEX, as well as a lower cost per tonne compared to the conventional alternative. There were also environmental benefits from using the SMIPCC system: the amount of carbon monoxide, non-methane hydrocarbons, nitrogen oxides, and other particulate matter was reduced.

The economic, operational, and production data of the initial study were compared for both transportation systems (conventional and SMIPCC), which exposed the pros and cons of each one and allowed the company to improve data interpretation so they could make an informed decision on whether or not to continue to the next project phase. In the case of the studied mine, the SMIPCC was the more viable

method considering the net present value and the lower costs and gas emissions. Even though the production is not extremely high, nor is the AHD very long, there was still a noticeable difference in costs.

4. CONCLUSIONS

With the increased challenge and complexity of mines, it is imperative to evolve the way that projects are being done. The two methodologies presented have shown the value.

In relation to the objective 1, the technological model has proved to be a viable option for the case evaluated and it has the potential to be applied to different projects with similar grinding processes. For the studied mine, the technological model was incorporated into the short and medium term mine-planning schedules. It was formulated as a block model and was used together with the mine planning software.

The different technological variables presented in the model enabled the engineers to simulate different blasting and plant productivity scenarios, supporting the decision making process for the development of the deposit. As a result, it was possible to improve of the plant with little or no capital investment by optimizing the breaking and fragmenting mechanisms through blasting, crushing, and grinding. This resulted in:

- A reduction of the top size of the ROM, which allowed the primary crusher to operate with a higher feed rate by 2.2%, a reduced opening, and to feed the SAG with a smaller top size.
- Operating the SAG with more fines (<10mm) by increasing the powder factor to 2.78kg/m³, increased the plant production rate by 10.7% while using the same power.

In relation to the objective 2, the decision-making method presented to evaluate the SMIPCC alternative is meant to be used for a conceptual study level. By using the proposed decision-making method, it is possible to identify the projects that have the potential for SMIPCC implementation without necessarily spending a large amount of time, which can be expensive and wasteful. Therefore, it enables mining companies to

shift their focus to the alternatives that continue to show potential for further in depth studies. In general, IPCC installation is an attractive option due to its lower sustaining CAPEX and OPEX. After evaluating the decision-making model for the specific case treated, the sustaining CAPEX is approximately halved, and the OPEX is 34% lower.

However, due to the high initial cost of installing the SMIPCC, which in this case is seen to be 60% higher, installation is only feasible when there is a long mine life. In addition, if the mine has a small AHD and/or low production, the IPCC is not very appealing because the initial CAPEX may not be paid back during the LOM. In this particular case, the haulage distance and mine life are sufficient to notice a 0.28\$/t decrease in total expenditure. Savings are not solely restricted to the costs; there are also noticeable environment benefits.

For the discussed case, carbon monoxide emissions drop 58% when using the SMIPCC scenario. Later, the mine moved to a feasibility study and detailed design phases and the SMIPCC is now installed and in operation at the site.

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