EDMO DA CUNHA RODOVALHO

An innovative approach for controlling operational parameters in open pit
mining to reduce costs and environmental impacts

São Paulo
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To my wife, Helena, and my parents

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RESUMO

Na atualidade, a indústria de mineração possui como principal desafio alavancar sua produtividade, controlar custos e reduzir impactos ambientais. Muitas operações de mineração exigem transporte em pequenas distâncias. A comparação de diferentes opções de transporte em distâncias curtas considerando a eficiência energética é uma necessidade de operações de lavra a céu aberto, mas existem poucos estudos recentes que priorizam esta variável em projetos de mineração. As operações de carga e transporte são amplamente dependentes de combustíveis fósseis. Essas operações também necessitam de pneus como um importante insumo. Existem alguns trabalhos que relacionam o consumo de combustíveis e o desgaste dos pneus a variáveis operacionais, mas uma metodologia que identifique as variáveis de maior impacto frente a condições específicas ainda não está disponível. O presente trabalho fornece novos métodos de simulação para equipamentos alternativos, consumo de combustíveis e gestão do desgaste de pneus. Análises de regressão linear múltipla, simulações e ferramentas de desenho de mina permitem identificar e controlar variáveis ligadas ao consumo de combustíveis, desgaste de pneus e seleção de equipamentos. Os estudos envolvendo equipamentos alternativos alcançaram uma redução de 14% no consumo de diesel e um aumento de 16% na produtividade. Com relação às técnicas de gestão do consumo de combustível aplicada aos caminhões observou-se uma redução de 10%. Considerando o sistema de gestão de desgaste de pneus, a aplicação do método proposto possui um potencial de evitar o descarte de 8,9 t de borracha para pneus em apenas um trimestre.

Palavras-chave: Eficiência energética; consumo de diesel; desgaste de pneus; seleção de equipamentos.

ABSTRACT

The main current challenges of the mining industry include aspects such leveraging the mine productivity, controlling costs and reducing environmental impacts. In most surface mining operations, overburden removal requires haulage over short distances. A comparison of different haulage options for short distances with respect to energy efficiency in open-pit mining is a key aspect for decision-making, but only a limited number of recent research efforts have considered energy efficiency as a control variable in mining projects. Loading and haulage have an energy source that is highly dependent on fossil fuels. In addition, the equipment involved in these operations use tyres as an important input. There are many studies relating the fuel consumption and tyre wear to several performance indicators, but a methodology that identifies and prioritizes higher-impact variables under each specific operating condition is not available. This research proposes new methods using alternative equipment simulations for fuel consumption and tyre wear management. Such methods include multiple regression analysis, stochastic simulation and specialized software routines in order to identify and control operational performance variables related to diesel consumption, tyre wear and selection of new alternatives equipments. Considering alternative scenarios of equipment models, the results of the proposed method include a 14% reduction in specific fuel consumption and a 16% increase in productivity. Regarding the fuel management method, the reduction of diesel consumption reached 10%. For the tyre wear management method, the results indicated a potential to save up to 8.9 t of tyre rubber in only one quarter.

Keywords: Energy efficiency; diesel consumption; tyre wear, simulations; alternative equipments.

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1. GENERAL INTRODUCTION

In the majority of mining companies that apply surface mining methods, loading and haulage operations are performed by loaders and trucks. Among all of the operations performed in open pit mining, haulage has the highest specific cost. In the last years, this operating method has been discussed widely due to the significant increase in costs. This is justified on the basis of inputs such as diesel oil and tyres. Case studies have indicated that haulage operations account for 46% of the mining operating costs (Bozorgebrahimi et al. 2003). Fuel supplies and tyres take the top positions in the cost structure.

In this scenario mining projects seek to reduce their operating costs by controlling the consumption of these inputs. Hence, the evaluation of variables that influence the fuel consumption and tyre wear becomes essential to ensure competitiveness in the industry. However, a methodology with the ability to select and measure the operational aspects that have a greater influence on fuel consumption and tyre wear is not yet available. Filling the gaps is an objective method of management and control of haulage costs. Effective control of the fossil fuel consumption and products of petroleum, such as the rubber of tyres, also brings improvements to the environmental performance of mining companies by reducing their greenhouse gas emissions.

Some mining methods are known for using haulage operations over short distances, ranging from the cut in the mining face to the dumping point. The mining method that uses this kind of haulage the most is strip mining, during the overburden removal operation. The environmental impacts and mining costs are lower than those of the open pit mining method, because the method has the same level of economic efficiency with a high strip ratio (SR) due to reduced haulage distances for waste. Furthermore, environmental recovery occurs at the same time as mining operations, improving the environmental performance of mining companies.

Even with various equipment options applied to this type of operation, there are many differences in energy efficiency, productivity and cost. Currently, in addition to mining projects that use the strip mining method, other surface mining operations need to perform haulage operations over short distances, for instance in-pit crushing and conveying (IPCC) in surface mining operations. Thus, it is necessary to carry out comparative analyses of different equipment options. During this analysis, parameters such as sustainability and energy efficiency have a strong influence on the identification of the best option.

The current global industry scenario requires mining companies to develop more efficient energy matrixes. This challenge has economic and environmental aspects. In the economic sphere, the strong fluctuations in mineral commodity prices are notorious. Long periods with sales prices below the usual standards of economic feasibility require many operations to make use of temporary stoppages. At such times, the main characteristic of the companies that remain in operation is reduced operating costs. Decreasing the consumption of diesel oil or replacing it with a more appropriate energy matrix is a key action to control costs. Regarding the environment, mining companies have been questioned widely by society with respect to their polluting capacity. With the increased closeness between the mining industry and communities, problems with dust, noise, vibration, water quality and emissions of greenhouse gases have been discussed extensively. As diesel oil is still the main energy matrix of open pit mining, it is the method that accounts for the largest share of the worldwide mineral production, and efficiency implies reducing emissions. This represents a gain in the coexistence of mining and society.

Products of petroleum are among the two main inputs of open pit mining operations worldwide. The literature has widely reported a high potential to generate greenhouse gases through the burning of these compounds. Considering the life cycle of tyres, there is a need to develop methods and management tools seeking rational consumption. Tyre wear control is a key tool for increasing the economic efficiency and environmental performance of opencast mining. The use of this input implies the generation of waste tyre rubber (WTR), the disposal of which is one of the major problems for society. Increasing the hauled mass per kilogram of WTR

generated by the mining industry reduces the demand for these compounds. Depending on the WTR disposal technique, the management system described in the present work can substantially reduce the emissions of greenhouse gases.

This work lists three central points for the mining industry: decreasing the consumption of inputs, reducing the environmental impacts and operational efficiency. These aspects are discussed separately in sections that address the evaluation of alternative equipment in operations, reduced fuel consumption and tyre wear management. Each of these sections corresponds to a scientific paper published in an international journal with a high impact factor. All the works have been published and are presented in full with the approval of the journals. The articles support common objectives that are achieved with different methods. The combined presentation of these solutions is an exercise that demonstrates the many possibilities of readjusting the mining industry to face the major economic and environmental challenges.

1.1. OBJECTIVES

- To evaluate equipment options used to haul over short distances and identify the most energy-efficient option.
- To build a methodology to identify and classify the operational variables that influences the fuel consumption of trucks.
- To develop a management approach able to reduce the generation of WTR through the efficient use of the tyres.

1.2. STRUCTURE OF THIS THESIS

According to the outlined objectives, the thesis were organised following the sequence bellow:

- Chapter 1: Problem presentation and objectives discussion.
- Chapter 2: Literature review, methodology, results and research analyses involving alternative equipments in mining operations.
- Chapter 3: Literature review, methodology, results and research analyses with respect to fuel consumption of haulage operations.
- Chapter 4: Literature review, methodology, results and research analyses regarding tyre wear management tools.
- Chapter 5: Conclusions of the tree studies developed and the relationship with the research objectives.
- Chapter 6: References of all studies.

2. SIMULATION OF THE IMPACT OF MINE FACE GEOMETRY ON THE ENERGY EFFICIENCY OF SHORT- DISTANCE HAULAGE OPERATIONS

2.1. INTRODUCTION

This research topic is part of a published article by the author in 2016¹. In surface mining operations, there is a frequent need to transport materials over short distances, between sites of cutting operations at mining faces and deposition areas or unloading points. The mining method that uses this type of transport most is strip mining, during overburden removal operations. According to Hartman and Mutmanský (2002), the strip mining method has a lower environmental impact and reduced mining costs compared with other mining methods. This is because the method is economical even with high waste/ore ratios (stripping ratios, SR), owing to the reduced distances through which waste needs to be transported. In addition, environmental recovery occurs concomitantly with the mining, with a favourable effect on the mining company's environmental performance. Most mining projects consider sustainable development as a central aspect in the management of their operations (Gomes *et al.*, 2015). With several equipment options being available for this type of operation, some differences remain regarding energy efficiency, productivity and costs.

Currently, in addition to companies that use the strip mining method, other surface mining operations also need to perform transport operations over short distances. An example is in-pit conveying and crushing (IPCC), in which it is necessary to transport material from mining faces to a mobile crushing machine. In these operations, it is

¹ RODOVALHO, E.C., DE TOMI, G. **Simulation of the impact of mine face geometry on the energy efficiency of short-distance haulage mining operations**, Mining Technology, v. 125, n. 4, p. 226–232, 2016. (DOI: <http://dx.doi.org/10.1080/14749009.2016.1170990>)

possible to use several types of equipment, such as excavators, front-end-loaders and haul trucks. After the material has been crushed, at points near the mining faces, transport beyond the pit boundaries to mineral processing facilities is via conveyor belts.

In the context of new surface mining operational settings, comparative analyses among different equipment options are required. There are a few studies that have compared the performances of different types of transport equipment, for short distances and under similar operational conditions. However, up-to-date comparative evaluations that indicate the option offering the greatest energy efficiency, greatest productivity and lowest costs are not yet available. Following equipment selection, it is necessary to define a methodology to indicate the optimal geometric configuration, considering the specific conditions of each surface mining operation. Practice validation is essential to ensure reproducibility of the results obtained from industrial-scale simulations. This subject has not often been explored in the literature, despite the strong demand for it in the mineral industry.

The aim of the research reported here was to evaluate the equipment options used in short-distance transport, identify the option giving the greatest energy efficiency and establish the most productive geometry, considering specific operational conditions of surface mining. A mine using the strip mining method was considered and the operational efficiency of haul trucks, excavators and dozers in overburden removal operations was evaluated. The practical tests were performed in a large bauxite mine located in the state of Pará (Brazil). The evaluation criteria were energy efficiency, productivity and operating costs. Through simulation rounds, with the use of fleet sizing software, it was possible to identify the optimal geometry for a given operational condition. After the simulation was performed, the results were validated on an industrial scale using the parameters adopted in an active mine.

The main contribution of this study is the definition of a methodology that is able to identify operational settings that consider energy efficiency as one of the main parameters in the operationalization of a mine. With the selection of more energy-efficient equipment, mining becomes more sustainable without abandoning

productivity standards. The possibility of increasing production and consuming less fuel makes mining a less damaging activity for the environment. In addition, the practical application approached in this study can be replicated and adapted to any surface mining operation where transport over short distances occurs.

2.2. METHODOLOGY

The development of a simulation model requires the collection of a vast amount of information and the analysis of a similar amount of output data. In addition, aspects such as proficiency in operating computational tools and the costs involved need to be considered (Nader *et al.*, 2012). This study was divided into two phases. The first was developed in an operational environment. Considering the results obtained from an operating mining company, three different overburden removal techniques were comparatively evaluated. After data collection, it was possible to identify the option with the greatest energy efficiency. The second phase occurred in a computing environment. With fleet sizing software, it was possible to predict the performance of overburden removal operations for different geometric configurations. From analysis of the results, a more efficient configuration for the operational conditions at the mining company studied could be identified. The study took into consideration the geotechnical characteristics of the relevant lithologies. The bauxite layer had low hardness, without faults or discontinuities, while the overburden layer was composed of friable clay and was without discontinuities. Clean production in the mining industry is currently undergoing changes in process management, with the aim of achieving greater energy efficiency (Hilson, 2003).

The optimal configuration must be validated through an industrial-scale application. The simulation routines described in this study, followed by an industrial-scale validation, represent a novel approach. The results obtained will be subject to further analysis later.

2.2.1. OVERBURDEN REMOVAL OPTIONS ASSESSMENT

To assess the equipment options used for transport over short distances, a mining company operating the strip mining method was considered. Overburden removal was performed with 34 m³ blade dozers, 4 m³ bucket excavators associated with 20 m³ capacity haul trucks, and 13 m³ bucket excavators associated with 57 m³ haul trucks. The three options were followed for 12 months using the standard geometric configuration used in similar mines.

Figure 1 shows the cutting sequence required to release a 25 m-thick ore strip. Each strip has a length of 200 m. The dozers perform the cutting and push the material up the waste stack. All other options require cutting with excavators and a fleet of haul trucks for transport to the waste stack. Simultaneous operations of the three overburden removal techniques under the same operating conditions allow an appropriate comparative analysis of energy efficiency. Equipment selection strongly influences mine design and mining costs (Bozorgebrahimi *et al.*, 2003). This is because both mining optimization and operationalization depend on equipment features. Haul trucks and excavators used for waste haulage require loading areas, haul roads and dump areas following geometric settings that provide safety and productivity. In contrast, the use of dozers avoids the need for these ancillary operations.

Figure 1 – Cut sequence and overburden removal layout

Source: Personnel file

All the equipment options used in overburden removal require diesel oil as an energy source. Norgate and Haque (2010) claim that worldwide, even with the use of electrically powered excavators, 87% of the energy consumption for material handling can be attributed to the burning of fossil fuels. This percentage considers loading and transport operations in bauxite and iron mining around the world. Li et al. (2011) state that the transport distances between loading points and mineral processing plants tend to grow with mining development, leading to increasing CO₂ emissions for each ton produced. McLellan et al. (2012) highlight that CO₂ emissions are proportional to the payload and the average transport distance covered by haul trucks. This trend further strengthens the need to identify more efficient and productive options. Table 1 shows the productivity and the consumption profile of each equipment option used in overburden removal. This collection of data refers to 12 months of operation. Fleet A is made up of small equipment, fleet B comprises large equipment and fleet C only uses dozers. The classification into small or large equipment is based on the capacity of trucks and excavators. According to Hartman

and Mutmansky (2002), the use of dozers to transport material over distances up to 150 m, considering downhill cuts and transport pushing material, can be an advantageous option regarding mining cost. Although the main raw material of this type of mining operation is diesel oil, their view is confirmed by table 1, which shows that dozers provide greater energy efficiency for overburden removal operations.

Fu et al. (2014) claim that despite the flexibility provided by the use of haul trucks in overburden removal, this involves high operating costs. In addition to the high fuel consumption, this option also implies costs associated with haul roads. These structures must be able to ensure the productivity and safety of the process. For short-distance haulage operations with dozers, these costs can be disregarded.

Table 1 – Specific consumption and hourly productivity of each type of equipment used in overburden removal

Fleet		A		B		C
Equipment		Truck A	Excavator A	Truck B	Excavator B	Dozer
Capacity/m³		20	4	57	13	37
Hourly consumption/L h ⁻¹	fuel	17.03	40.16	73.8	139.5	112
Hourly productivity/m³ h ⁻¹		88.1	220	340	1020	490
Specific consumption/L m ⁻³	fuel	0.19	0.18	0.22	0.13	0.23
		0.37		0.35		

Source: Personnel file

During the data collection period, an operational costs control was performed. These costs include all expenses required to maintain operations, including inputs, headcount and maintenance. Figure 2 shows operating costs (US\$/m³) for fleets A, B and C during the 12-month period. From an analysis of the chart, it can be seen that fleet C had lower operating costs than fleets A and B. Regarding energy efficiency, fleet B achieved better results than fleet A, although its operating costs were higher. The excavators of fleet B have high energy efficiency, but their maintenance requires specialized services and expensive components.

Figure 2 - Operational costs for fleets A, B and C during overburden removal operations.

Source: Personnel file

2.2.2. SIMULATION

After implementation of the first phase, it can be seen that fleet C has the greatest energy efficiency and economy. Consequently, the second phase of the methodology focused on operations with dozers to transport material for short distances. This phase included a geometric parameters simulation, aiming to identify the configuration providing the greatest energy efficiency, greatest productivity and lowest costs. According to Bozorgebrahimi et al. (2003), the identification of an optimized geometry promotes high standards of efficiency and productivity from the selected equipment. Rodovalho and Cabral (2014) claim that the possibility of estimating key performance indicators for mining operations makes projects more realistic. Through this routine, it is possible to determine the effect of operational restrictions inside each mine. Another advantage is the possibility of prior targeting of resources and controls for potentially favourable configurations.

The testing area was a mine using the strip mining method. Therefore, the computer simulation had to comply with the principles of that method. The geometry of the mining faces had to be compatible with the specifications of the mining equipment. Figure 3 shows the main dimensions of an overburden removal operation using dozers. These parameters were taken as input data for the simulation using fleet sizing software. The simulation tool, DozSim, was developed by Caterpillar and used during this study (Caterpillar, 2007). In this case, the width of the strips was 20 m. To simulate operations with other widths, the same pattern was considered for the layout preparation. According to figure 3, the waste material is carried to the waste deposit in a specific position. The overburden removal may be continued until the bauxite layer or a certain thickness of waste is reached. Particular types of equipment are appropriate for use in the final stages of overburden removal. Some mining companies use excavators to remove the last 4 m thickness of waste, until the bauxite layer has been reached. The selection of equipment and the optimal layout depend on an economic and operational analysis.

Figure 3 - Geometry of the layout for simulation of 20 m-wide mining strips

Source: Personnel file

The fleet sizing software DozSim uses some input information to generate the productivity and estimate costs. For this study, the input variables were material type,

material density in the cutting, bulking factor, cutting distance, cutting thickness, cutting slope, carrying distance, blade type and visibility. It would be possible to add other variables if required. For this study, the productivity response was considered. This variable analysis is sufficient to identify the optimal geometry. Field tests provided energy efficiency data and costs. This information will be discussed later.

According to Hustrulid et al. (2013), the mine design must be compatible with the dimensions of the equipment used in the mining unit operations. The productivity simulation, by varying the strip width, considered the subsequent operational characteristics. After removal of the overburden, the bauxite was mined using haul trucks with 20 m³ capacity. This equipment requires an operational area with a minimum width of 19 m, which allows two-way traffic and loading manoeuvres. Figure 4 shows the simulation results as the strip width was varied between 19 and 31 m. The effect of overburden thickness on productivity was also evaluated for thicknesses between 12 and 16 m. From analysis of the simulation results, it was found that the maximum productivity in overburden removal was obtained for strips of 19 m width. As the strip width and overburden thickness increase, productivity decreases. Considering the overburden thickness as a constant at the value of 16 m, field tests can validate only this curve.

Figure 4 - Overburden removal productivity as a function of strip width for different overburden thicknesses.

Source: Personnel file

The simulation tool also allowed us to assess the overburden removal performance for different cutting angles. Figure 3 shows an angle of 17°; however, other cutting angles were also simulated. Dozers have wide performance variations depending on whether they are pushing material on flat terrain, downhill or uphill. In the present study, the cut occurred only downhill. Only in flat locations or uphill is transport of material required. Figure 5 shows the results obtained using DozSim only for downhill cuts with a 16 m thickness of overburden. As this round of cutting angle assessment considered only downhill cuts, without transportation on flat ground or uphill, high productivity was observed. The results form a cloud of points describing a parabolic curve. The equation of this parabolic curve is shown in figure 5. Considering this equation, the maximum productivity was found for 17° cuts. Cuts with inclinations higher than 17° lead to reduced productivity and may also increase the risk of damage to some dozer components. This damage reduces equipment availability because of the resulting need for maintenance.

Figure 5 - Definition of the most productive cutting angle using simulation tools.

Source: Personnel file

2.3. PERFORMANCE TESTS

Analysis of the simulation results indicated that cuts with a 17° inclination in 19 m-wide strips led to the maximum productivity. To ensure safety during the tests involving loading and haulage operations, a 20 m-wide strip was adopted. The addition of the extra 1 m reduced the probability of blockages and imperfections along the road, which could lead to accidents with tyres. This adoption of a 20 m width reduced the frequency of stops to allow road maintenance and therefore avoided the consequent drop in operational performance.

The purpose of the tests was to compare dozer performance in overburden removal for different geometries. The first geometry tested had 25 m-wide strips, without any marking of the cutting inclination. The second had 20 m-wide strips and a 17° cutting

angle. The first configuration represents the traditional technique based on the configurations used by other similar companies.

It is important to highlight the advantage of drawing up projects, strategic plans and detailed simulation before implementing any mining operation. According to Frändegård et al. (2013), this systematic approach reduces uncertainties and possible mistakes during implementation of operations on an industrial scale. Validation of the simulated operations was done in a bauxite mine. This uses the same equipment as that considered in the simulation. The mine's topography and geology work teams were made available to monitor the tests. This schedule aimed to guarantee the same operating conditions for all tested areas.

The test consisted in operating with 25 m-wide strips for three months in the entire mine area. During the three subsequent months, all these strips started overburden removal with 20 m-wide strips under the same conditions. The topography team performed a topographic survey of all areas before and after overburden removal, with the aim of measuring the displaced material volume. During the last three months of testing, the topography team also started to check the cut inclination of 17°. Mine operation teams were responsible for measuring the number of hours used in each area. The geology team checked the lithological contacts indicating the end of overburden removal. Table 2 shows the test results at six months.

Table 2 - Results of productivity tests performed in a bauxite mine using the strip mining method.

Width of cut/m	Test period	Real productivity/m ³ h ⁻¹	Average productivity for period/m ³ h ⁻¹	Productivity predicted by simulation/m ³ h ⁻¹	Variation/%
25	July	554	529.3	560	-5.5%
	August	471			
	September	563			
20	October	630	612.7	610	0.4%
	November	562			
	December	646			

Source: Personnel files

Following this procedure, it was possible to measure the hourly productivity in the 20 and 25 m-wide strips. Note that during the tests with the 25 m-wide strips, the traditional operating procedure was preserved, without marking the cutting angle. As the simulation indicated that this parameter is crucial to achieve optimum productivity, control of the cut inclination was implemented for the assessment. As the conditions are the same for both geometric configurations, it is possible to analyse the results and identify which situation is more productive.

In addition to productivity, fuel consumption control to measure the energy efficiency of each configuration was also performed. Figure 6 shows the dozers' specific consumption for different strip widths. This result relates the volume of waste removed by the dozers and the volume of fuel consumed in these operations.

Figure 6 - Control of specific fuel consumption by varying the strip width.

Source: Personnel files

2.4. RESULTS AND DISCUSSION

Innovative solutions are part of the routine of mining companies committed to energy management in their operations (Levesque et al., 2014). The results found in this study are able to fulfil this requirement regarding equipment selection and mine design. According to Norgate and Haque (2010), it is possible to improve the energy efficiency of loading and transport operations through pit optimization and mine design, reducing the need for haul trucks. IPCC is an example of an alternative that reduces the need for haul trucks (Norgate and Haque, 2013). This solution uses in-pit crushers that are fed by front-end loaders or shovels. The transport up to mineral processing is performed by conveyor belts, replacing haul trucks. However, Roumpus et al. (2014) warn that application of IPCC depends on the geometry of the mineralized body and on deposit restrictions. Some deposits do not have the conditions required for the use of IPCC, and traditional equipment is therefore necessary. Such traditional equipment includes haul trucks, excavators and dozers, as analysed in this study.

Traditional haulage options over short distances using haul trucks and excavators showed lower productivity compared with dozers. Table 1 shows that dozers had a 35% greater energy efficiency than fleet B, which achieved the best energy performance among the haul truck and excavator options evaluated. However, considering the costs, fleet B had worse results than fleet A, showing that the small equipment is not economical compared with large equipment in this type of operation. Figure 2 confirms that dozers had lower costs than fleets A and B. The results also indicate that dozers achieved 77% lower costs than fleet A. Therefore, dozers are the option with the greatest energy efficiency without accompanying increases in operating costs.

Mine design is also a decisive factor for the rational use of energy resources. The simulation rounds indicated a more productive and efficient configuration. After six months of testing, there was a validation of the simulation responses. The 20 m-wide strips and 17° cut inclination yielded 16% greater productivity than the 25 m- wide

strips without a fixed slope set. In addition, the productivity estimates from the simulation showed only small deviations from the values obtained in the field, with a maximum variation of -5.5% . Analysis of figure 6 shows the formation of a baseline in the first three months of tests, with an average specific consumption of $0.2282 \text{ L} \cdot \text{m}^{-3}$. In the last three months, this baseline was displaced to a mean value of $0.1952 \text{ L} \cdot \text{m}^{-3}$. These data indicate that there was a 14% reduction in specific consumption after the implementation of 20 m-wide strips. These results validate the simulation responses and show that the solution is suitable for implementation on an industrial scale. Therefore, it will be possible to maintain operations with high productivity using less fossil fuel.

An important aspect of this solution implemented for overburden removal in a bauxite mine is that there was no impact on subsequent operations. Ore loading and transport maintained safety standards, productivity and efficiency, since the necessary dimensions were guaranteed. Together with this, the use of the 20 m-wide strips does not imply increased costs for maintenance and roads.

3. NEW APPROACH FOR REDUCTION OF DIESEL CONSUMPTION BY COMPARING DIFFERENT MINING HAULAGE CONFIGURATIONS

3.1. INTRODUCTION

This research topic is part of a published article by the author in 2016². In large open pit mines, load and haul operations are commonly performed by haul trucks and excavators. Among the operations performed in an open pit mine, haulage has the highest operating cost. Over the past years, this method has been widely discussed due to the significant increase in its operating costs (Curry et al., 2014). This is justified on the basis of inputs such as diesel oil and tyres. According to Bozorgebrahimi et al. (2003), transport operations account for 46% of the mining operation costs. In addition, the fuel ranks first in the composition of these costs.

Against this background, mining companies seek to reduce operational costs by controlling the consumption of these inputs. By applying techniques that reduce the consumption of supplies, the mining industry can become more economical and sustainable (Gomes et al., 2015). Therefore, assessment of the variables that influence diesel consumption becomes essential to ensure the competitiveness of the mining industry. However, the mining industry lacks a methodology able to select and measure the operational aspects that have more or less influence on fuel consumption. Filling this gap would represent a tangible method of management and control of the operating costs of haul trucks. Effective control of the consumption of fossil fuels also improves mining companies' environmental performances, reducing their greenhouse gas emissions.

² RODOVALHO, E.C., LIMA, H.M., DE TOMI, G. **New approach for reduction of diesel consumption by comparing different mining haulage configurations**, Journal of Environmental Management, v. 172, p. 177 – 185, 2016. (DOI: <http://dx.doi.org/10.1016/j.jenvman.2016.02.048>)

The purpose of this paper is to build a methodology to identify and classify the operational variables that influence the fuel oil consumption of haul trucks. In addition, it aims to develop actions that reduce fuel consumption. With the use of statistical analysis and multivariate linear regression tools, which are applied to the modelling of fuel consumption behaviour, it is possible to manage the mining operation costs. After the identification and classification of these variables by degree of influence, it will be possible to use prioritization tools to establish the management actions. These actions should be applied on an industrial scale to seek to validate the management method. This study used real data from a large open pit mine. The results obtained were validated at the same open pit mine.

3.2. METHODOLOGY

In large iron mines the overburden and ore transport costs have a direct relationship with the diesel consumption. Due to the growing production demand, it is becoming necessary to use off-road trucks with increasingly large capacities, leading to increased energy consumption. Shafiee and Topal (2012) claim that the estimation, cost simulation, and operating performance analysis can be done through the use of graphical analysis of tables and equations. All of these features are intended to identify a pattern linked to a particular operating configuration. This pattern is used as a reference to estimate indicators and support decisions in similar operating conditions. In order to identify and investigate the aspects that affect fuel consumption in haulage operations is necessary to delimit a period of one year for data collection. The studies were developed in a large iron mine in the Quadrilátero Ferrífero (Brazil). After this step, prioritization tools were applied to identify actions which can reduce the diesel consumption.

The development of this methodology is not limited to addressing the economic aspects but also has great potential to promote sustainability in mining operations. The key to reducing greenhouse gas emissions and, therefore, reducing diesel

consumption begins with the development of management tools able to identify and address issues that strongly influence consumption (Levesque et al., 2014).

3.2.1. DRIVING AND HUMAN FACTORS RELATED TO FUEL CONSUMPTION

In order to understand the behaviour of fuel consumption in mine haul operations, one should not be limited to mechanical parameters (Australian Government, 2010). However, it is necessary to evaluate the influence of the human factor on the behaviour of this variable. Operators' performance is supported by their driving style. This feature differs under conditions of acceleration, breaking, cornering, speed variations, and manoeuvres. Besides these, there are other associated conditions that influence the performance of the production process, such as weather and topographic conditions (Shafiee and Topal, 2012). It is clear that all of these points are addressed in specific operational training for driving haul trucks. However, mine operation teams comprise a heterogeneous group with respect to the capability to execute each of the process steps in the most safe, economical, and productive way possible.

The first step of this study seeks to establish a method to measure the variability in fuel consumption between the teams by considering their heterogeneity regarding the experience and ability to operate equipment. This condition exists within each team or between one team and another. In addition, teams are subjected to diverse operating circumstances such as weather and haul road conditions, night shifts, visibility, and availability of resources.

A period of one year was assumed for assessment in order to consistently cover all subject teams, variables, and operating conditions. One year was considered sufficient to submit all teams to the climate seasonality that occurs during the year. An onboard system of sensors in trucks has been developed for evaluating the equipment performance and operating conditions regarding diesel consumption. A report by the Australian Government (2010) indicates that the diversity of haul road

conditions has a direct effect on fuel consumption. Figure 7 illustrates the topographic surface of the operating mining area where the studies were developed.

Figure 7 - Topographic surface with the active haul roads considered in the study.

Source: Personnel file

The lines represent the active haul roads used by trucks, with their grades, between load and dumping points. The segment formed by the points A and B forms the route AB, while the points C and D form the route CD. These routes were selected so that the influence of the operators' performance could be evaluated in a broad and representative way. The route CD represents the waste rock flow and the route AB the iron ore flow. Figure 8 illustrates the elevation profile of the route AB, while Figure 9 shows the elevation profile of the route CD. Points A and C are loading points and B and D are dumping ones. Haul route AB is considered a favourable gradient because the trucks are loaded down the ramp and gravity helps the movement. The CD profile is considered unfavourable because the loaded trucks go up the ramps. On these roads the trucks must overcome rolling resistance, generated by the friction

of the tyres with the pavement, and gradient resistance. The performance of the haul trucks depends on the design of the mine haul roads and gradient variations (Thompson and Visser, 2006). In this way all the teams and operators are subject to different types of haul roads.

Figure 8 - Detailed elevation profile of route AB.

Source: Personnel file

Figure 9 - Detailed elevation profile of route CD.

Source: Personnel file

The studied mine operation has a transport fleet of mechanical and electromechanical off-road trucks, both of which have the same load capacity. All truck drivers are able to operate both fleets' equipment. The evaluation of the human factor was performed considering mechanical trucks on routes AB and CD for one year. Descriptive statistical analysis was the first step in assessing the data generated by the five mine operation teams. Boxplot graphics were used to perform

this analysis and check for outliers. It is also necessary to evaluate whether there are significant differences in terms of absolute diesel consumption between teams. For this it is necessary to perform a normality test to assess the p-value. This standard defines the use of parametric or non-parametric methods to measure the relevance of variability between samples (Montgomery and Runger, 2007). If the variability between teams is not significant, one can consider that there is no difference in consumption between them. Thus, technical heterogeneity between operators does not correspond to different consumption patterns, which eliminates the influence of the human factor.

For the route AB, 239 measurements of the five teams were performed. Each measurement represents an absolute consumption of diesel in a six-hour shift. Figure 10 shows a graphical representation of descriptive statistics using a boxplot graph corresponding to the fuel consumption on the AB path. Figure 11 illustrates the graph referring to the route CD boxplot. In Figure 10 one can observe the absence of outliers and that the B team had the lowest median. Figure 11 also shows no presence of outliers. Outliers are points that indicate consumption above normal during the research. Each point represents a shift with consumption above normal. On this route team D showed lower variability. From the boxplot graphics one can observe the variations of the median between the teams. But it is not possible to state that the variability between the teams is relevant. According to Oskouei and Awuah-Offei (2014), further analyses such as normality tests are required to determine whether the variability is significant. After this test, it is necessary to apply parametric or non-parametric analysis to measure the significance of the variance.

Figure 10 - Boxplot graph of fuel consumption for each shift on haul route AB.

Source: Personnel file

Figure 11 - Boxplot graph of fuel consumption for each shift on haul route CD.

Source: Personnel file

The normality test for the population assessed in Figure 10 gives a p -value < 0.05 . According to Devore (2000), for p -values lower than the significance level of 5%, the null hypothesis that the data follow a normal distribution is discarded. Since the data distribution is not known, the application of parametric procedures is not recommended. The alternative is to use distribution-free procedures, known as non-parametric methods (Montgomery and Runger, 2007). However, the Kruskal-Wallis test may be applied, which is a non-parametric alternative equivalent to the F-test. With the application of this test one can check whether there is a difference between the average fuel consumption of the teams on routes AB and CD.

Through a tool of statistical analysis it is possible to consider the population studied and apply the Kruskal-Wallis test. Table 3 shows the results of application of the test relating to the haul roads AB and CD. For route AB, the test indicates a p -value equal to 0.692, which is greater than the significance level of 5%. Therefore, the null hypothesis is not rejected, meaning that the fuel consumption does not show significant variability between teams. Evaluating the results for the CD route the p -value is equal to 0.096, which is greater than the significance level of 0.05. Therefore, the null hypothesis is not rejected, meaning that the fuel consumption does not show significant variation among the teams.

Table 3 - Kruskal-Wallis test applied to analysis of the fuel consumption on routes AB and CD.

Kuskal–Wallis test of fuel consumption	
Haul route	p -value
AB	0.692
CD	0.096

Source: Personnel file

3.2.2. VARIABLE SELECTION

Between 2008 and 2009, the Australian government analysed the energy balances of 40 active mines and found that 17% of the energy comes from the burning of fossil fuels. At these units, energy consumption reduction programmes were implemented

through the application of management routines, control, and simulation. As a result of these initiatives, an average 6% reduction in fuel consumption was achieved (Australian Government, 2010). Against this background, the development of routines and methods to manage the energy consumption can lead to a good economic performance for a mining company. Therefore, it is necessary to identify, manage, and evaluate each of the variables that have an influence on fuel consumption. Shafiee and Topal (2012) state that a collection of detailed and comprehensive data is the key input of accurate and reliable estimate tools used in mining projects.

According to Motlogelwa and Minnitt (2013), fuel consumption is related to the gross vehicle weight of trucks. Thompson and Visser (2003) developed a model that relates the consumption of diesel to unfavourable and favourable gradients, truck speed, haul road conditions, and overall rolling resistance. Besides considering issues related to haul roads' infrastructure and speed, this paper seeks to relate operational management aspects and the weather seasonality with fuel consumption. The activities started by collecting data for 12 months in a large iron mine in the Quadrilátero Ferrífero region of Brazil. The choice of the period was based on the need to consider the performance of operations in the dry and wet seasons. The daily working schedule of the truck fleet is divided into four 6-hour shifts per day, 7 days per week. The selection of variables covered in this study comes from operational controls data available in fleet management systems. The studied mining company provided controls for several process variables that can exert an influence on the diesel consumption. All of these data are collected automatically and were obtained from internal reports. Besides the variables considered earlier, that is, the human factor in fuel consumption and the trucks' performance on different grades, this section will be consider some additional variables. These will be used in the construction of the model to explain the fuel consumption in a large mining operation. This model attempts to measure the influence of each variable that has a high correlation with the fuel consumption. Table 4 lists the variables considered in this study. Next to each variable is a description and the unit of measurement.

Table 4 - List of variables used to build the simulation model and the system of equations that explain the fuel consumption in haulage operations.

Investigated Variables	Description	Unit
PAVEMENT MATERIAL	Number of dumps (total mass) that were aimed at building or repairing the haul road pavement.	Dumps/week
INFRASTRUCTURE	Number of dumps (total mass) that were used for the construction of safety berms, haul roads, ramps, and fill.	Dumps/week
FI	Total mass of friable itabirites used for the haul road pavement maintenance or construction	t/week
CI	Total mass of compact itabirites used for the haul road pavement maintenance or construction	t/week
LATERITE	Total mass of laterite used for the haul road pavement maintenance or construction	t/week
MOTOR GRADERS	Total number of hours of motor grader operation for haul road maintenance	Hours/week
WHEEL TRACTORS	Total number of hours of wheel tractor operation for haul road maintenance	Hours/week
RAINFALL	Average weekly precipitation in the mine area	Millimetres/week
TRAFFIC VOLUME	Weekly average number of cycles to a destination, starting from a loading point and going via a certain path to a dumping point.	Dumps/hour
UD	Weekly total distance on unfavourable grades (against the load)	Meters
FD	Weekly total distance on favourable grades (with the load)	Meters
AHD	Average haul distance (per week)	Meters
US	Weekly average speed of unloaded vehicles	Kilometres/hour
LS	Weekly average speed of loaded vehicles	Kilometres/hour
FUEL CONSUMPTION	Total volume of fuel consumed per week	Litres

Source: Personnel file

Considering the large number of variables involved in the process and the long period of data collection, it was necessary to use a statistical analysis tool. For this, Minitab16 was used. This software is able to select the variables according to significance level and is also used in modelling of the investigated scenarios. As the focus of the research is the absolute fuel consumption in litres, this variable is called the response variable and all other variables are called predictors. To select the predictor variables, the stepwise regression method (forward and backward) was used, where the analysis is started using all variables and then they are successively excluded in order of increasing correlation. The selection is completed when a satisfactory correlation equation is reached. This method is suitable when there are a large number of predictor variables that have some level of correlation with the response variable.

Table 5 shows the result of applying the variables selection technique by the stepwise regression method. This application corresponds to the fleet of mechanical trucks on the haul road AB. In step 4 only variables with p-values smaller than 0.15, among all those listed in Table 4, are selected by the tool. With the evaluation of this parameter in each round, step 4 is the stepwise regression final model. Thus, all variables with compatible p-values are provided in the model. Table 5 shows the values of the adjusted coefficient of determination (R^2_{adj}), which is useful to compare models with different numbers of predictors. The definition of the adjusted coefficient of determination is represented by equation (1) (Montgomery and Runger, 2007). The higher R^2_{adj} value, the better the model fits the data. The same technique was applied to mechanical trucks on all active paths of the mine.

$$R^2_{adj} = 1 - \frac{(1-R^2)(n-1)}{n-p-1} \quad (1)$$

Where:

R^2 = sample R-square

n = Total sample size

p = number of predictors

Table 5 - Stepwise regression for mechanical trucks on haul road AB.

Response		Fuel Consumption			
Step	1	2	3	4	
Constant	231.5	2630.3	1508.9	-1384	
Variables		Coefficients			
Traffic volume	15100	15173	15009	15790	
Pavement material		-10.7	-13.5	-16.9	
FI			0.078	0.084	
Rainfall				36	
R ² _{adj}	88.15	88.96	89.76	90.70	

Source: Personnel file

3.2.3. DEVELOPMENT AND VALIDATION OF THE MODEL

Considering the results shown in Table 5, step 4 sets out the parameters which best explain the fuel consumption on the haul road AB using equation (2). All the multivariate analyses that generate these equations have errors associated with the estimation. The next step is the application of a residual plot analysis. Thus, it is necessary to verify the presence of autocorrelation in the residuals of the regression analysis performed. The Durbin-Watson statistic and analysis of Cook's distances are the most efficient tools for this analysis. In eq. (2), the value of the Durbin-Watson statistic obtained is equal to 1.52, indicating that the residuals are independent and there is no autocorrelation. Cook's distances analysis indicates no influential point. Both analyses show the consistency of the model describing the fuel consumption on the haul road AB.

$$\text{Fuel Consumption} = -1384 + 15790 \text{ Traffic volume} - 16.9 \text{ Pavement material} + 0.084 \text{ FI} + 36 \text{ Rainfall} \quad (2)$$

For additional verification of the model, one should apply graphic residual analysis. For this routine it is necessary to certify that the residuals follow a normal distribution,

have constant variance, and are independent, as assumed in a multiple linear regression model. In Figure 12, the normal probability graph shows that the points follow the line of theoretical normal probability, with p-values > 0.15 , so it can be assumed that the residuals do not deviate significantly from a normal distribution. Figure 13 shows the graph of residuals versus fitted values, where the constant variance assumption is not broken because the residues are randomly distributed around zero and have approximately the same dispersion for all adjusted values. No outlier is present. Figure 14 shows the graph of residuals versus observation order; the points do not have any trend, and thus it is assumed that the errors are independent. In Figure 15 the histogram displays information compatible with a normal distribution. Thus, all the elements necessary to validate the model are satisfactorily fulfilled. Therefore, Equation (2) is able to explain the absolute diesel consumption on the haul road AB appropriately.

Figure 12 - Normal probability graph for the haul road AB.

Source: Personnel file

Figure 13 - Graph of residuals versus fitted values for the haul road AB.

Source: Personnel file

Figure 14 - Graph of residuals versus observation order for the haul road AB.

Source: Personnel file

Figure 15 - Histogram analysis for the haul road AB.

Source: Personnel file

For all other haul roads, the same procedure was applied considering the fleet of mechanical trucks. Eq. (3) describes the fuel consumption of mechanical trucks on all active haul roads of the studied mining company. On the other hand, eq. (2) presents a specific analysis of a sector of the mine (haul road AB) where the largest ore production flow occurs. By analysing all active haul roads, it is possible to identify the variables that have a global influence.

$$\text{Fuel Consumption} = -23519 + 11561 \text{ Traffic Volume} + 197 \text{ Motor graders} - 60.4 \text{ Pavement material} + 1.28 \text{ Laterite} - 0.301 \text{ CI} \quad (3)$$

From eq. (3), an adjusted coefficient of determination (R^2_{adj}) of 93.8% is obtained, which shows a good model fit regarding the data. From eq. (3), a value of the Durbin-Watson statistic of 1.66 is obtained, indicating that the residuals are independent and there is no autocorrelation. The analysis of the Cook's distances does not indicate any influential point. In the graphical analysis of the residuals, the theoretical normal distribution is followed with no significant deviations. The other charts also indicate

that there is no inconsistency in the model. Therefore, eq. (3) is able to explain the absolute fuel consumption of the mechanical truck fleet for all haul roads properly.

3.3. PRACTICAL APPLICATION

The model developed in order to know the diesel consumption behaviour has two sections. The first is a statistical analysis that measures the impact of the human factor, while the second brings a system of equations able to identify the variables that have the greatest influence on a specific haul road or all haul roads. When evaluating the results obtained in the statistical analysis it is observed that the performance of the operators, considering different skill levels, does not promote significant changes in diesel consumption. However, the system of equations indicated a group of variables with the greatest degree of influence on fuel consumption. This group changes when analysing a specific haul road or a complete set of active haul roads of a mine. Nevertheless, both equations show that fuel consumption is sensitive to haul road conditions and the fleet's management system. Management tools can be applied to evaluate practical actions related to the identified variables in equations. These actions seek to reduce the influence of factors that may increase the diesel consumption.

In an open pit mine, the road design, trafficability, and conditions of the roadway surface affect the diesel consumption (Australian Government, 2010). There are several operating conditions that can be modified in order to increase energy efficiency in mine haul operations (Nader et al., 2012). Table 6 shows the feasibility matrix, which aims to identify actions that can be taken to improve the short-term results and do not require large investments. The practical matrix actions are proposed according to analysis of equations (2) and (3). These equations report that the variables pavement materials and CI are inversely proportional to fuel consumption. According to Thompson and Visser (2000), the selection of appropriate wearing-course material for structural design and road surface, following maintenance routines, promotes reduction of mining costs due to increased energy

efficiency in haulage. This is supported by equations and the data shown in Table 6. The other variables are directly proportional to fuel consumption. Therefore, the actions related to these variables must block the influence on fuel consumption.

Table 6 - Feasibility matrix applied to identify opportunities for the reduction of fuel consumption

Variable	Practical actions	Feasibility	Justification
TRAFFIC VOLUME	Traffic restrictions: preferred operation on more efficient haul routes	Feasible	Restrictions: Fleet management system
PAVEMENT MATERIAL	Improve the regravelling frequency	Unfeasible	Operational restrictions: fleet and headcount
MOTOR GRADERS	Levelling in low-traffic periods	Unfeasible	Operational restrictions: fleet and headcount
FI	Reduce the friable itabirite mass in the regravelling. An excessive amount generates dust / poor visibility	Unfeasible	Suitable material for regravelling / high availability
LATERITE	Reduce the laterite mass in the regravelling.	Unfeasible	Reduces the generation of dust / high availability
CI	Increase the compact itabirite mass in the regravelling.	Unfeasible	Low availability
RAINFALL	Improve the drainage	Unfeasible	Long-term return

Source: Personnel file

The identification of variables and practical actions is the result of the analysis of equations (2) and (3). The feasibility of the actions relies on technical and economic aspects. This study prioritizes actions that do not constitute new investments and that use available materials and tools. In addition, emphasis is placed on actions that generate returns in the short term. The application of the feasibility matrix identifies only one action in accordance with these criteria. The action indicated by the matrix restricts the traffic of trucks through the fleet management system. Equations (2) and (3) indicate that the traffic volume is the main factor contributing to the diesel consumption. The pit operationalization aims to maximize ore exploitation with less

waste removal and the shortest haul distance between the mining faces and destinations (Sousa et al., 2012). In the mining company studied, both pit development and the ore bench faces are concentrated in a few areas. Regarding the position of the mining areas, many exploitation faces use the same haul road. Haulage is carried out via the haul road that provides the shortest distance to the point of dumping. The application of this rule leads to heavy traffic by trucks in some places during the production cycle. The main paths of ore flow and waste flow are, respectively, the haul roads AB and CD. Thus, these paths represent the roads that have the highest traffic volume. Therefore, as can be seen in Figure 7, point B is surrounded by the main ore faces and point C, the main waste removal area. The fleet management system promotes dynamic allocation of haul trucks by controlling queue times, load equipment idleness, and other variables. This system is also able to consider restrictions for haul operations. These restrictions must follow some criteria where the objective is to restrict some of the haul trucks to certain mining faces and thus reduce the traffic volume without reducing productivity. The current study analysed the fuel consumption behaviour of mechanical trucks. However, the mining company studied also has electromechanical trucks. Both fleets operate at all mining faces. As these haul trucks have different constructive aspects regarding energy consumption, it is necessary to measure whether these characteristics justify a variation in performance under specific conditions. If different results are detected for each fleet, the analysed condition can become a constraint. So it is possible to achieve reduced consumption by reducing the traffic volume and the allocation of haul trucks under the most favourable conditions.

3.4. RESULTS AND DISCUSSION

The registration of a restriction by the fleet management system needs to be validated by technical criteria. It is necessary to identify the operating conditions that have an advantage in the energy performance of each of the transport fleets. The fleets of mechanical and electromechanical trucks are of similar size and age. The payload and gross vehicle weight show variations between 1% and 2%. Therefore,

both truck types have been considered to have similar capacities for the scope of this study. This feature applies to individual trucks or groups of equipments. Electromechanical trucks have a system that transforms part of the mechanical energy into electrical energy. This electrical energy is converted back into mechanical energy to assist the diesel engine in equipment traction. Mechanical trucks have traction generated only by burning of diesel. Considering the constructive differences between the two fleets, tests subjecting them to each existing grade condition in the mining area were carried out. Based on the test result, there is the possibility to design a restriction through the dispatch system.

The roads AB and CD, illustrated in Figures 8 and 9, represent the most commonly used routes in the mining area. The road AB connects one of the main ore faces to the primary crushing, while the road CD is the route of one of the main areas of waste removal. The road AB has favourable ramps because the loaded trucks go down. The road CD requires trucks to travel on unfavourable ramps. During this route, the loaded trucks must to rise up the ramp. Table 7 shows the specific fuel consumption of different truck fleets submitted to different ramp conditions. Measurements were performed for two weeks and used 11 trucks from each fleet.

Table 7 - Performance test on the haul roads AB and CD.

Truck type	Load point	Dump	Production (t)	Fuel consumed (l)	Specific fuel consumption (l/t)
Mechanical mining trucks	A	B	79336	24914	0.314
	C	D	57984	21747	0.375
Electromechanical trucks	A	B	79560	26547	0.333
	C	D	60480	20984	0.347

Source: Personnel file

Table 7 shows that the mechanical and electromechanical trucks move similar masses of ore and waste. Over 240 cycles were performed for each route, representing a significant population for assessment. The tests relied on strict control of traffic segregation through the fleet management system with the aim of reducing or eliminating simultaneous traffic of both fleets on the same route. This means that

during the performance measurements of a fleet on route AB, the other fleet has travelled only on route CD. The results indicate that specific fuel consumption for mechanical trucks on route AB is 5.8% lower. The ramps of route AB were favourable for the two fleets. On the other hand, the electromechanical trucks on route CD, where the ramps are unfavourable, achieved 7.4% lower fuel consumption. The results show that the electrical energy generated by electromechanical trucks assists on unfavourable ramps. Because the equipment uses this extra component in its traction, the diesel engine has reduced consumption. Mechanical trucks do not store energy for use on harsh profiles but have more efficient engines on favourable ramps. The results are satisfactory and should be implemented as a permanently active restriction in the fleet management system. This demand is required for validation of the good results obtained in tests on an industrial scale. Thus, within two months the restriction was registered in the fleet management system. That means the system gave priority to programming routes with favourable profiles for mechanical trucks. On the other hand, the system also prioritized the programming routes with unfavourable profile for electromechanical trucks. Table 8 shows the results obtained during the first two months of operation restrictions on the fleet management system. A background was adopted for the average monthly consumption and the average monthly production of the last 12 months, which generates the standard specific consumption for the evaluated fleets. The standard specific fuel consumption of each fleet was compared to that of the two following months.

Table 8 - Fuel consumption after the activation of the restriction at industrial scale.

Truck type	Period	Fuel consumption (l)	Production (t)	Specific fuel consumption (l/t)	Reduction (%)
Mechanical mining trucks	Monthly average	384350	1142653	0.336	
	First month	376291	1169307	0.322	- 4.2%
	Second month	504447	1668003	0.302	- 10.1%
Electromechanical trucks	Monthly average	448595	1162437	0.386	
	First month	409271	1108061	0.369	- 4.4%
	Second month	579441	1561935	0.371	- 4.0%

Source: Personnel file

The results obtained after activation of the restriction in the fleet management system confirmed the reduction achieved in the tests. According to Shafiee and Topal (2012), operational routines of proven efficiency can be automatically applied with software development solutions. The first month of operation represented a period of adjustment, checking, and monitoring of the fleet management system. The monitoring routine should be extended for another month with information shift by shift. During the second month the system applied the restriction with stability and the dynamic allocation of trucks worked automatically. After the adaptation period, the reduction of diesel consumption by mechanical trucks exceeded the test results and reached 10%. Reduction of fuel consumption by electromechanical trucks remained stable at around 4% during the two months of assisted operation.

The acknowledgment of the gains from segregation strengthens the validity of the statistical analysis dedicated to measuring the influence of the human factor. Performance tests have controlled conditions and suitable operators who can perform the tests in accordance with the scope of the study. In an operational environment, operators with various skill levels are observed in simultaneous activity,

the cycle breaks occur for several reasons. At industrial scale, multiple events can interrupt a cycle, such as unscheduled maintenance, weather conditions, and operational assistance. Even at increased scale, the results were confirmed and validate that the influence of the human factor on fuel consumption is insignificant.

No variable linked to road conditions appears as the main component influencing fuel consumption. However, there is a strong correlation between road conditions and fuel consumption. In the studied mine the traffic volume was identified as the main factor contributing to the diesel consumption. This is supported by Table 5, where the stepwise regression identified high correlations in the first round. However, diesel consumption is satisfactorily explained only when considering hours of road surface maintenance, material type, and mass of wearing-course materials for road maintenance and construction. The materials most frequently used on the surfaces of roads are hard gravel, crushed rock, and mixtures of different lithologies with complementary characteristics (Thompson and Visser, 2006). Analysing equations (1) and (2), the variables CI, FI, and Laterite confirm the use of lithologies such as compact itabirites, friable itabirites, and laterites in the road surface. This practice depends on the availability of these materials near the mine in order to control costs and ensures appropriate conditions for traffic (Thompson and Visser, 2006).

4. REDUCING ENVIRONMENTAL IMPACTS VIA IMPROVED TYRE WEAR MANAGEMENT

4.1. INTRODUCTION

This research topic is part of a published article by the author in 2016³. The reduction of the generation of waste tyre rubber (WTR) in mining operations is a major challenge for the mining industry. The main tyre consumer is the automotive industry but the mining industry also uses a considerable number of tyres. Imyim et al. (2016) state that this production system results in a growing generation of WTR. In this context, it is necessary to develop waste management techniques to control pollution from industry around the world (Kwon et al., 2015). In the US, 300 million discarded tyres are generated annually (Kwon et al., 2015). It is estimated that the mining industry accounts for 8% of WTR worldwide, which is higher than agriculture and aviation (Cutler, 2012). According to Rodovalho et al. (2016), tyre consumption ranks second in the costs of open pit mining operations that use trucks for haulage. In this context, the number of tyres consumed in mining is significant and imposes the need to include tyre wear management techniques in mining operations.

Large open pit mines adopt different operating procedures according to the prevailing climatic variations of each season. Tyre wear is an aspect of mine haulage that is strongly influenced by climatic conditions. According to the Australian Government (2010), the lowest tyre wear rates are associated with dry season. The same report also states that in the rainy season there is increased rolling resistance. Thomson and Visser (2006) state that rolling resistance is a measure of the force required to overcome the friction between the tyres and the road surface. The authors also relate

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the tyre flexion and penetration on the road surface with tyre wear. Both aspects have a strong relationship with the load carried by trucks.

Many mines around the world require operational controls that investigate the causes of the premature discarding of tyres (Thompson and Visser, 2003). These causes are associated with specific operational factors related to trafficability conditions. Kagogo (2014) proposed a management system applied to a uranium mine, which achieved positive results. However, the author evaluated the durability and failure modes only at the time of disposal. Furthermore, the actions aim to block the specific causes of disposal and involved no evaluation of these causes throughout the tyre life, considering climatic variations. In the literature there is no description of a management system that is able to monitor tyre wear considering the seasonality and operating condition variation. In addition, there are no studies that describe mine scheduling methods that allow for the management of tyre wear during operation.

Considering the described gaps, this study aims to elaborate a quarterly mining schedule that allows tyre wear management in order to reduce the WTR. Therefore, it is necessary to evaluate the Overall Equipment Effectiveness (OEE) throughout one year, considering complete cycles of dry and rainy seasons. This assessment includes selection of events that have the greatest impact on haulage hourly productivity under different conditions. The OEE evaluation also includes utilisation and mechanical availability but excludes operational costs. The identification of the statistical behaviour of each event favours the construction of simulation models (Nader et al., 2012).

According to Kagogo (2014), the variable tonnes kilometre per hour (TKPH) measures the tyre use efficiency. The approach of using TKPH with other haulage variables applied to quarterly mining plans is novel. This innovative tyre-wear management approach can ensure maximum productivity of tyres with minimal WTR generation. This represents a cleaner production strategy for application in the mining industry.

4.2. METHODOLOGY

In order to illustrate the various aspects that affect the tyre consumption in a mine, this study considered a large iron mine as a case study. This mine is located in the south-eastern region of Brazil and its assessment was carried out for one year. Levesque et al. (2014) claim that the way to improve sustainability performance for an industrial process is to develop management tools that are able to identify and prioritise aspects that influence the input consumption. Therefore, this study seeks to define a quarterly mining scheduling method that considers variables related to tyre consumption. Thus, tyre wear is managed simultaneously with the execution of mining plans.

Operational data generated in the year 2012 were used in multiple linear regression analysis. The tyre-wear management system and quarterly mining scheduling of 2013 were grounded on multiple regression analysis. The adoption of the database generated in 2012 covers a complete cycle of dry and rainy seasons. The relationship between key performance indicators of haulage operations and seasonality of the previous year is the reference for the tyre-wear management system of the following year. In the mine studied in this research there are approximately 250 discarded truck tyres annually. The actual amount of WTR in 2012 was 814,740 kg. Considering the total haulage production in 2012, the rate of WTR generation was 0.0116 kg.t^{-1} . The development of systems to optimise the tyre usage, which are adapted to the operating conditions of each mine, can increase cleaner production in the mining industry. Variables that do not have high correlation with the haulage system productivity are considered secondary. In general, the present study uses the expression *ceteris paribus* to keep economic and operational efficiency constant.

4.2.1. SYSTEM DESCRIPTION AND BOUNDARIES

The present methodology adopts statistical tools in order to reduce the level of uncertainty in decision support. Considering that mining operations can be modified

with time, a continuous decision support process is needed. In this regard, Herrmann et al. (2013) proposed a method for evaluating uncertainty in the decision support process named “the Statistical Value Chain” (SVC). The SVC is applied through stages of plan, do, check and act, repeatedly. This approach follows a fundamental principle of the Deming cycle. Figure 16 shows each step to be followed in the present investigation based on the SVC method and the principle of the Deming cycle. The application of these concepts allows for the replication of the present methodology, thus supporting cleaner production for another operation or period.

Considering that the main contribution of the present study is a tyre management system, it is necessary to define the system boundaries. In this context, only variables that exhibit high correlation with the productivity of the mining haulage system were evaluated. This type of analysis is justified because it allows for assessing whether the tyres are generating the expected production before being disposed. This is a cleaner production strategy that indicates whether the tyre consumption pattern is suitable. Therefore, this research did not address operational conditions that generate premature disposal of tyres. Accidents involving side cuts and mechanical shock are the main reasons for premature tyre disposal. With regards to mine design and mine planning, only short-term plans will be considered. This type of plan, limited by periods of up to one year, has a strong impact on tyre consumption patterns and mine haulage operations.

Figure 16 - Cycle of activities detailing each step in order to employ a tyre-wear management system in a mining haulage system.

Source: Personnel file

4.2.2. ASSESSMENT OF OEE WITH RESPECT TO ANNUAL CLIMATE SEASONALITY

Quarterly mining scheduling involves dividing an annual plan into four periods. Considering an iron mine, each period must address a specific quality specification and quantity of materials (Benndorf and Dimitrakopoulos, 2013). The execution of each period depends on the climatic variation that influences the process performance. Rodovalho and Cabral (2014) claim that hourly productivity is an essential parameter for the development of mining plans. However, many maintenance failures and operational inefficiencies are not manageable by hourly productivity. Thus, it is necessary to evaluate a more comprehensive performance

indicator. This type of project should also contemplate dry and rainy seasons over a compatible period.

The OEE is calculated as a multiplication of mechanical availability, operational utilization and hourly productivity. Hence, the evaluation of OEE is more suitable for the project. A boxplot graph allows for a descriptive statistical analysis of the different populations of OEE for the haulage fleet as shown in figure 17. There are differences between dry and wet periods over a year. The dry period is characterised by greater stability of the production system, as evidenced by the reduced dispersion. In addition, the dry period reached a median OEE that was 14.4% higher than the rainy season. The rainy season has a greater variability of the OEE, which is proven by the increased interquartile distance. Therefore, the strong dispersion observed in the rainy season indicates a possible relationship between rainfall and haulage OEE.

Figure 17 - Boxplot graph of haulage OEE in wet and dry seasons during 2012. The dispersion in wet period is higher than dry period.

Source: Personnel file

In order to assess the variability of haulage OEE among wet and dry season populations it is necessary to perform a statistical analysis. The first step is to check if the population of haulage OEE for a year follows a normal distribution. The normality test consists of evaluating the p-value and determines which statistical test is best to examine the variability of the population (Oskouei and Awuah-Offei, 2014). Graphical analysis of the normality test measures the population adjustment as shown in figure 18. The null hypothesis is accepted whether p-value is greater than the significance level of 0.05. The acceptance of null hypothesis means that the OEE follows a normal distribution. The adjustment degree is measured by the p-value, which is considerably lower than 0.05. Thus, the null hypothesis is rejected, meaning that the OEE does not follow a normal distribution. According to Montgomery and Runger (2007), to evaluate the relevance of the variability among populations that do not follow a normal distribution it is necessary to use non-parametric tests. This study applies the Kruskal–Wallis test, which is a non-parametric alternative to the F-test.

Figure 18 - Normality test for haulage OEE. The y-axis represents the normal probability (percent) and the x-axis represents the values of OEE for each point. The points do not follow the line of theoretical normal probability.

Source: Personnel file

The Kruskal–Wallis test can be applied using statistical analysis software. The results of this test are used to evaluate whether the haulage OEE shows a significant variation in relation to rainfall. The result of the Kruskal–Wallis test for OEE haulage related to a period of one year is presented in table 9. This period covers both the rainy and dry seasons, so the analysis is shown to be appropriate. If the p-value is greater than the significance level of 0.05, the null hypothesis is accepted. The acceptance of null hypothesis means that the OEE has no significant relationship with the variation of the rainfall. The test result indicates a p-value of 0.916, which is greater than 0.05. This result does not reject the null hypothesis. This indicates that other factors, besides rainfall, influence the variation of the OEE.

Table 9 - Kruskal–Wallis test applied to analysis of the haulage OEE during the wet and dry seasons.

Kruskal–Wallis test of haulage OEE	
Index	<i>p</i> -value
Haulage OEE	0.916

Source: Personnel file

4.2.3. VARIABLE SELECTION AND DEVELOPMENT OF THE SIMULATION MODEL

According to Hadi et al. (2016), the number of discarded tyres around the world is increasing systematically. In the mining industry, the volume of WTR is directly proportional to the mineral production. However, the variables that influence the consumption of tyres in mining operations are different from those observed in the automotive industry. Thompson and Visser (2003) conducted studies in mines in various countries and found that only operational aspects influence the tyre consumption. Therefore, this study adopts the hourly productivity as a response variable for the simulation model because the variables that influence the production cycle in mine haulage operations are measured by hourly productivity. This response addresses both the preparation of quarterly mining plans and the need to develop tyre wear management tools. In order to complement the input data of a quarterly plan it is necessary to know the number of maintenance hours and operational stoppages for the equipment. This information can be obtained from equipment maintenance plans and through headcount management tools.

To consider complete cycles of dry and wet periods, the database includes 12 months of data. The data generated by the off-road haulage fleet owned by a large open-pit mine were analysed. These data were collected from the fleet management system. The evaluated trucks are all of the same size, payload and age and operate under the same operating conditions. The studied mine operates 24 hours per day, divided into six-hour shifts, seven days a week. Rainfall, evaluated in the previous section, will be considered in the development of the simulation model. In addition to

this data, other variables were evaluated. Table 10 lists the variables that have a significant influence on hourly productivity for the quarterly periods.

Table 10 - List of variables used to build the simulation model and the system of equations that explain the hourly productivity in haulage operations.

Investigated Variables	Description	Unit
AHD	Average haul distance: distance between each load point and each dump point weighted by the planned mass for each load point	Kilometres
CT	Cycle time of trucks: total time of truck production activities	Hours
FED	Full / empty distance ratio: Relation between full haul distance and empty haul distance	
HP	Hourly productivity: relation between total production and effective hours.	t. h ⁻¹
LT	Load time: average time of loading	Hours
MT	Manoeuvring time: average time of manoeuvring	Hours
OD	Operational delay: shift relay and fuel supply (controlled events)	Hours per shift
TKPH	Tonnes kilometre per hour: relation between the trucks' payload and speed.	t.km.h ⁻¹

Source: Personnel file

Besides the variables listed in table 10, many other variables influence the productivity of mining processes, such as queuing time, downtime and dump time. This group also considers the rainfall that was assessed in the previous section. Not all the variables have a significant influence. To measure the degree of influence and correlation with the response variable it is necessary to use a statistical analysis tool. For this, Minitab 16 was used. This software provides tools for variable selection according to the level of significance and is also used to model the evaluated scenarios. In all models generated in this study, the response variable is the hourly productivity. The other variables are called predictors. To identify predictors, the stepwise regression method (forward and backward) was used. This kind of analysis

allows for the inclusion and exclusion of variables during each stage of the analysis, seeking to increase the correlation with the response variable. The selection ends when the maximum correlation is identified for the equation.

Table 11 shows the result of applying the variable selection technique by the stepwise regression method for the dry season. This application corresponds to the hourly productivity of the haulage fleet during the dry season. In stage 6, only variables with p-values smaller than 0.15, among all those listed in table 10, are selected by the tool. With the evaluation of this parameter in each round, stage 6 is the stepwise regression final model. Thus, all variables with compatible p-values are provided in the model. Table 11 shows the values of the adjusted coefficient of determination (R^2_{adj}), which is useful to compare models with different numbers of predictors. The higher the R^2_{adj} value, the better the model fits the data. The same technique is applied to the haulage fleet during the wet season as shown in table 12. However, the group of variables identified in table 11 is different from those identified in table 12. Not only the group of variables but also the significance order has changes from the dry season to the wet. This demonstrates that between the wet and dry seasons there is an operational rearrangement.

Table 11 - Stepwise regression for haulage fleet related to a dry season.

Response		Hourly productivity				
Stage	1	2	3	4	5	6
Constant	573.9	589.9	536.1	410.9	390.9	380.3
Variables		Coefficients				
CT	-575	-544	-670	-47	-42	-38
OD		-3.52	-4.03	-5.31	5.34	-5.28
TKPH			0.064	0.239	0.246	0.248
AHD				-95.3	-96.6	-96.8
MT					656	642
LT						127
R^2_{adj}	49.99	57.09	64.81	96.69	96.9	96.91

Source: Personnel file

Table 12 - Stepwise regression for haulage fleet related to a wet season.

Response		Hourly productivity				
Stage	1	2	3	4	5	6
Constant	549.6	491.9	379.1	412.9	394.1	376.3
Variables		Coefficients				
CT	-553	-721	4	15	31	-29.1
TKPH		0.078	0.286	0.283	0.287	0.234
AHD			-121.7	-120.9	-122.7	-102
OD				-5.06	-5.09	-5.05
MT					627	-261
FED						2.9
R^2_{adj}	34.35	47.71	87.24	94.9	94.95	95.03

Source: Personnel file

4.3. QUARTERLY MINING SCHEDULING

Mining scheduling is an important tool that brings long-term information to short-term and operational routines. Hustrulid et al. (2013) state that mining scheduling aims to meet qualitative and quantitative specifications of a project. Therefore, each period of a schedule matches a mining plan that corresponds to a given geometry. The mining geometry corresponds to polygons that limit the active load points in each period. Thus, there are preliminary parameters that limit the dimensions of each mining face. Figure 19 shows the topographic surface of the mine studied in the quarterly scheduling for one year. In the figure, seven load points (LP) and four dump points (DP) are discriminated. All these points remained active during the study. The mining polygons projected onto topographic surfaces generate solids. This volume is calculated from a preliminary OEE obtained from the annual financial report. However, this data is used only as reference to draw the haulage profile and calculate the AHD. After this routine, the simulation model is used to determine the dimensions of the mining solids. In order to estimate the amount of WTR in 2013, the

WTR of 2012 is used as a baseline. This study refers to the expression *ceteris paribus* to keep the rate of WTR generation ($0.0116 \text{ kg. t}^{-1}$) constant in 2013.

Figure 19 - Topographic surface with the quarterly mining polygons, haul roads, load points and dump points

Source: Personnel file

4.4. RESULTS AND DISCUSSION

Considering the results shown in table 11 and table 12, stage 6 sets out the parameters that best explain the hourly productivity in the dry and wet seasons. Eq. (4) describes the hourly productivity for dry seasons and eq. (5) explains this response for wet seasons. Applying a residual plot analysis, it is possible to verify the presence of autocorrelation in the residuals of the regression analysis performed. The Durbin–Watson statistic and analysis of Cook’s distances are the most suitable tools for this analysis. In eq. (4), the value of the Durbin–Watson statistic obtained is equal to 1.69. In eq. (5), the value of the Durbin–Watson statistic obtained is equal to 1.92. These results indicate that the residuals are independent and that there is no autocorrelation. Cook’s distances analysis indicates no influential point. Both analyses show the consistency of the model describing the hourly productivity for dry and wet weather. In addition, both equations reached an R^2_{adj} higher than 90%, according to tables 11 and 12. This coefficient confirms a good model fit regarding the data.

$$HP = 380.3 - 38 CT - 5.28 OD + 0.248 TKPH - 96.8 AHD + 642 MT + 127 LT \quad (4)$$

$$HP = 376.3 - 29.1 CT + 0.234 TKPH - 102 AHD - 5.05OD - 261MT + 2.9 FED \quad (5)$$

Table 13 shows the AHD calculation for the first quarter based on the plan presented in Figure 19. The distance between each load point and each dump point is calculated. These values are weighted by the mass required to generate the value of AHD. Each mining solid has a different ore mass, waste mass, stock material and location. Thus, each quarter has a distinct AHD. This variable changes with the operating conditions and influences the haulage productivity. The value obtained for each quarter is inserted into the simulation model to estimate the hourly productivity.

Table 13 - AHD calculation for first quarter

		Load points							
Dump points		LP1	LP2	LP3	LP4	LP5	LP6	LP7	Total
Mass (kt)	DP1		355.6	2518.6	592.6	177.8	237	9.7	3891.2
	DP2			207.4		533.3	1896.3	393.3	3030.4
	DP3			88.9	1185.2	1066.7	237	1611.9	4189.7
	DP4			148.2	592.6				740.8
	Total		355.6	2963	2370.4	1777.8	2370.4	2014.8	11852
Distance (km)	DP1	5	4.8	4.7	3.5	1.4	2.2	1.5	4.2
	DP2	6.1	6	5.8	5.1	3.8	3.9	4	4
	DP3	5.4	5.2	5.1	4.5	2.8	3.2	2.9	3.4
	DP4	5.1	5.4	5.2	3.7	5	5.4	5.6	4
	Total								

Source: Personnel file

The simulation model is used after setting the AHD and other parameters for the dry and rainy season. Raghavendra Rao et al. (2010) state that the use of simulation tools in mine planning increases the efficiency of haulage operations management. In the technical literature there are some successful examples of operations management; however, the use of simulations applied to a mining schedule that allows tyre-wear management and productivity estimation is novel. Table 14 shows the parameters used in the productivity equations and the simulation results for the rainy season. Table 15 shows the results for the dry season. The simulations were based on the 2012 data and the real data was collected from 2013 operations. In both tables there is a deviation of each parameter and productivity in each quarter. The productivity values for the four quarters reached a maximum variation of 3.6%. This deviation occurred in the third quarter.

Table 14 - Simulation results for quarterly plan related to the wet season

		Constant	CT	TKPH	AHD	OD	MT	FED	HP (t/h)
	Coefficients	376.3	-29.1	0.234	-102	-5.05	-261	2.9	
Simulation	1 ST quarter		0.32	1433	3.1	10	0.023	0.887	331.9
	4 TH quarter		0.31	1443	2.9	10	0.02	0.895	356.1
Real performance	1 ST quarter		0.321	1431	3	9.7	0.024	0.886	343
	4 TH quarter		0.312	1432	2.9	9.8	0.02	0.894	354
Variation (%)	1 ST quarter		0.4	-0.14	-3.33	-3.09	0.41	-0.02	3.2%
	4 TH quarter		0.13	-0.77	0	-2.04	0.5	-0.01	-1%

Source: Personnel file

Table 15 - Simulation results for quarterly plan related to the dry season

		Constant	CT	OD	TKPH	AHD	MT	LT	HP (t/h)
	Coefficients	380.3	-38	-5.28	0.248	-96.8	642	127	
Simulation	2 ND quarter		0.34	9.2	1405	3.2	0.017	0.06	376.93
	3 RD quarter		0.31	9.2	1250	2.7	0.018	0.061	388.15
Real performance	2 ND quarter		0.341	9.2	1405	3.2	0.018	0.06	376
	3 RD quarter		0.313	9.1	1195	2.71	0.018	0.06	374
Variation (%)	2 ND quarter		0.5	0.01	0.01	0.03	-0.16	0.15	0.2%
	3 RD quarter		0.9	-0.11	-4.56	0.37	0.55	-0.16	-3.6%

Source: Personnel file

The tool developed in this work allows for the assessment of each equation parameter and productivity. Figure 20 shows the deviation graph between the

parameters used in the simulation and the actual parameters of the third quarter. The actual data were obtained from the fleet management system. The graph shows that the main factor that explains the productivity below the forecast was the TKPH. During the third quarter, the TKPH was 4.56% below the forecast. Analysis of the speed controls of the fleet management system showed that there are many speed reduction events on the haulage roads between LP1, LP2 and LP4 and the DP1. These routes presented failures of the road surfaces between the months of July and August. There are many turns in most routes and road maintenance activities contribute to speed reduction. The permanence of maintenance equipment performing roadworks requires the fleet to operate in safe mode, resulting in reduced traffic speed.

Figure 20 - Deviations between simulation and real performance for the third quarter

Source: Personnel file

The quarterly scheduling procedure, considering the variables in tyre consumption control, is an innovative practice. The use of multiple linear regressions allows for the selection of only those variables that have a strong influence on haulage operations. After selecting the group of variables, which have varying levels of impact on

productivity, the equations explain the haulage process under different weather conditions. The simulation tool developed in this work proves to be effective to explain the haulage process because it has high R^2_{adj} for both the dry and rainy seasons. In both seasons R^2_{adj} is above 95%. Validation is attributed to the difference between the simulation results and the actual results of hourly productivity. The results in tables 14 and 15 present deviations below 5%, which validate the tool in the development of quarterly mining plans.

Even with positive results for the hourly productivity estimation, it is necessary to assess the reasons for greater deviations. The greatest variation is attributed to the third quarter when the deviation was 3.6%. Figure 20 shows the TKPH as the main reason for the reduced productivity. However, it is not possible to state whether this difference is due to a normal variation of the system or is related to a specific event. To assess whether during the third quarter there was a variation due to a specific event, it is necessary to use X-bar and R-chart control charts. The X-bar control chart controls the average quality, whilst the variability of the process is controlled by an amplitude graph called the R-chart (Montgomery and Runger 2007). According to these authors, if any point is beyond the 3-sigma limits in at least one of these control charts, it means that the process variation is outside the acceptable standards. Figure 21 shows the X-bar control chart related to the previous 20 months. The 3-sigma limit corresponds to three standard deviations and is represented by the upper control limit (UCL) and the lower control limit (LCL). The X-bar chart shows that the test failed at point 19. This point corresponds to the month of August when the TKPH reached the value of $1102.2 \text{ t.km.h}^{-1}$. Even with no failures in the R-chart graph, point 19 represents a TKPH that is lower than acceptable. Use of this tool clarifies the need for action on the causes of problem. As the TKPH variable is directly linked to tyre consumption, values below the acceptable value indicate that in August the tyres were under-used. This means that there was tyre wear but that productivity was lower than standard.

Figure 21 - X-bar control chart for TKPH with a negative deviation in 19th month.

Source: Personnel file

The negative deviation of TKPH implies a deficit of 3.6% of hourly productivity and additional WTR generation. This productivity deviation represents a production of 775,342 t. In order to reach the third quarter production targets, more trucks are required in the haulage operation. Considering the WTR generation rate of 0.0116 kg.t⁻¹, the additional amount of WTR for the third quarter is 8,993 kg. The WTR generated in the studied mine is burnt in cement kilns as the rubber is used as fuel for clinker production. According to Downard et al. (2015) the burning of 8,993 kg of WTR generates approximately 25.7 t of CO₂ emissions.

By identifying the problem, it is possible to investigate and propose more accurate preventative actions. As stated earlier, there was a high braking frequency in some areas of the mine. Considering table 13, DP 3 and DP 1 are the destinations with the highest tonnages and the largest volume of traffic. To unload at these destinations, the trucks must use routes with several curves in sequence. Analysing figure 19, there are successive low radius curves. This type of route implies frequent braking events and stretches of speed reduction. This operating behaviour tends to increase

tyre wear and WTR generation as shown by the negative variation of TKPH in figure 20. From analysis of these control charts, speed reduction is not a normal event and represents a loss for the process. In this case, the loss not only affects productivity, but the efficient use of inputs is also harmed. Some actions could normalise the speed of the trucks and make tyre use more efficient. Review of the haulage road design is one of the main actions. This review includes calculating the curve radius, road grade and materials employed on the haulage road surface. The implementation of these actions allows tyres to be used to their full capacity, avoiding excessive demand on this input. Demand built on efficient use is also able to control the generation of WTR. Haulage road design and maintenance are routine procedures for mining companies and do not involve any new investment.

The management system proposed in this work can be considered a useful tool for mines that seek to reduce the generation of WTR through optimum tyre usage. However, this study has some limitations and uncertainties. Tyre disposal due to accidental failures were not considered. The main causes of accidental failures are cuts, impact breakages and tread/belt separations; however, there are tyre recovery and recycling procedures. The effectiveness of these techniques in the mining industry can be evaluated in terms of WTR reduction.

Training and education of the staff is also a decisive factor in reducing WTR. The evaluation of the human factor in WTR generation was not evaluated because it requires the collection of specific data. Equations that estimate the WTR generation based on haulage variables were also not evaluated due some uncertainties. In order to directly relate these variables it would be necessary to obtain information on tyre pressure, internal temperature, braking frequency and haulage road conditions for each truck and each cycle. There are online measuring systems for these variables but the frequency of measurements is incompatible with equipment cycles. The limitations and uncertainties listed in this section may be investigated in further research.

5. CONCLUSIONS

The conclusions of the research involving alternative equipment in mining operations follow. After the completion of the industrial-scale tests, deviations of up to 5.5% were observed between the practical results and those estimated in the simulation. For six months, the productivity and fuel consumption of the evaluated geometrical configurations were controlled. The optimal geometric configuration indicated by the simulation achieved a productivity increase of 16%. The process also had greater energy efficiency. For the displacement of 1 m³ of waste, 14% less diesel oil consumption was required.

Owing to the complexity of the production process and the presence of numerous factors influencing the results of a mining operation, this deviation is considered to be low. The evidence of increased energy efficiency without abandoning productivity, safety and economy standards indicates compliance with the main objective of this work.

The development of a new technique that is capable of reducing fossil fuel consumption in the mineral industry is the main contribution of this study to the research on sustainable mining. The method described here can be applied to other mines with the same geometry and geotechnical characteristics of the ore and overburden. However, changing any of the variables could affect the performance even while still using the strip mining method. In addition, if the configuration is changed to a different one from that adopted in this study, the dozers may no longer turn out to be the best option.

Other types of equipment can be employed in such cases, such as wheel tractor–scrapers and draglines. Further studies may evaluate their performance under the same operating conditions. This continuity in research is based on geometrical analysis and mine design with the aim of reducing the waste volume necessary for the release of the ore. With such a reduction in the volume of waste removed, the

mineral industry will require smaller areas for the installation of waste piles, thereby reducing its environmental impact and improving the industry's relationship with society.

The conclusions regarding the development of the fuel consumption of haulage operations follow. The application of statistical analysis tools and modelling techniques to mining proved to be an effective alternative in the management of operational costs. The developed model identified critical points in the production process and ranked each variable in order of priority. This result optimizes the resources and efforts to lock deviations and losses in the process. In an economic environment in which the control and reduction of operational costs is becoming key to organizations' ability to remain in the market, this method provides a relevant contribution. Because fuel consumption is directly related to cost control in the mining industry, the goal of this study has been reached with the validation of the model. The implementation of this method in the mining operation routine using the available resources and without large investments also represents a breakthrough for the industry.

Among the results achieved is the reduction of the fuel consumption by mechanical and electromechanical haulage trucks, which reached 10% for the fleet of mechanical trucks and 4% for the electromechanical trucks. This is a reduction greater than that achieved by other mines cited during the study, where the application of similar techniques represented an average 6% reduction in fuel consumption. This advantage is mainly attributed to the efficiency of the fleet management system covering all the mining equipment. The method proved to be valid and applicable to other mining enterprises of all sizes, since it is a suitable tool for the identification and prioritization of points that are critical for operating costs. The basic requirement for the implementation of this model in other mines is the availability of data for modelling. A fleet management system is recommended, because it provides the study with greater precision. In addition, each mine has a variable group with the greatest influence on fuel consumption.

Complementing this research, a regular reassessment of such results is necessary to check the behaviour of the variables across the depreciation of the fleet. Over time the equipment may show changes in performance standards. Another aspect that must be assessed is the applicability of alternative equipment to mining operations. As the mineral production volume has shown successive increases in recent years, some enterprises seek to increase the size of the equipment to dilute the costs. However, this practice is labour-intensive and can generate safety hazards in operations. Nevertheless, there is a need for further studies of alternative equipment and processes in mining operations. The aim of the new studies is to maintain the production levels with increased productivity, energy efficiency and safety and to improve the environmental performance.

The conclusions related to tyre wear management are represented by the following comments. The application of this method requires mining companies to invest in management tools. However, the benefit is not only limited to the potential cost reduction and increased productivity, as the mining haulage operations can also be more environmentally responsible. The implementation of the procedure proposed in the methodology was effective in the development of a quarterly mining schedule. The models developed using the variables that have the most influence on productivity explained the haulage operation appropriately. The high R^2_{adj} demonstrated the quality of the models for both climate scenarios. For both wet and dry conditions, the R^2_{adj} was greater than 95%. TKPH was identified as a relevant variable in productivity estimation for both models. This result shows that there is a strong relationship between the tyre consumption and the productivity of mining processes.

The application of simulation tools described in this study indicated that the deviation between the simulated and the real data was below 5%. Nevertheless, the use of quality tools is decisive in determining whether the deviation is normal or represents a failure. The use of control charts is a practice that avoids unnecessary actions in situations of normal process variations. The graphical analysis clearly distinguishes the normal oscillations of particular variables or occasional operational failures. The control chart for TKPH indicated an operational failure that significantly reduces the

tyre efficiency. This failure causes increased generation of WTR and CO₂ emissions. The application of the model showed the potential for reducing the emissions of greenhouse gases. In the studied mine, the potential for WTR reduction reached 8,993 kg in one quarter. Considering the destination of WTR, the application of the proposed model means that the emission of 25.7 t of CO₂ in the same period could have been avoided. This kind of evidence permits safe decision making and justifies actions to block the causes of failure. With these results the present work meets the objective of developing mining schedules that enable the proper management of tyres. Thus, the application of the methodology contributes by enabling the mining industry to consume tyres rationally and responsibly.

The continuation of this research will be guided by the identification and implementation of actions that are able to rationalise the use of tyres in the mining industry. In Figure 19 it is possible to identify points with sharp curves. Furthermore, these curves are successive and present a high grade. During road maintenance the haulage operation remains in safe mode, wearing the tyres without the concomitant production of ore. Further studies can evaluate the impact of the mine design on tyre wear. Another factor that must be evaluated is dust control actions and their impact on environmental and operating performance. The present study and future work aim to develop mining processes that are more committed to sustainability without departing from productivity standards.

REFERENCES

- AUSTRALIAN GOVERNMENT, Department of Resources, Energy and Tourism, **Analyses of Diesel for mine haul and transport operations, a case study**, Australia, 2010. Available in: <<http://eex.gov.au/files/2014/06/Analyses-of-Diesel-Use-for-Mine-Haul-and-Transport-Operations.pdf>> Accessed in: 08 Apr. 2016.
- BENNDORF, J., DIMITRAKOPOULOS, R. **Stochastic long-term production scheduling of iron ore deposits: Integrating joint multi-element geological uncertainty**. Journal of Mining Science, v. 49, n. 1, p. 68 – 81, 2013.
- BOZORGEBRAHIMI, E.; HALL, R.A.; BLACKWELL, G. H. **Sizing equipment for open pit mining – a review of critical parameters**. IMM Transactions Mining Technology Section A, v. 112, p. A 171 - A 179, 2003.
- CATERPILLAR. **DozSim Quick-calc software®**, Track-Type Tractors Division, Caterpillar Inc., Peoria, IL, USA, Personal communication, 05 Nov. 2007.
- CURRY, J. A.; ISMAY, M. J. L.; JAMESON, G. J. **Mine operating costs and the potential impacts of energy and grinding**. Minerals Engineering, v.56, p. 70-80, 2014.
- CUTLER, T. **EM Tyre supply shortage – How it is affecting us**. 8th Australian Institute of Mining and Metallurgy Open Pit Operators' Conference, Australia, 2012. Available in: <<http://www.ausimm.com.au/openpit2012/presentations.asp>> Accessed in: 22 Aug. 2016.
- DEVORE, J. L. **Probability and statistics for engineering and the sciences**, Duxbury, 5^a ed. California, USA, 775 p., 2000.
- DOWNARD, J., SINGH, A., BULLARD, R., JAYARATHNE, T., RATHNAYAKE, C.M., SIMMONS, D.L., WELS, B.R., SPAK, S.N., PETERS, T., BEARDSLEY, D., STAINER, C.O., STONE, E.A. **Uncontrolled combustion of shredded tires in a landfill - part 1: Characterization of gaseous and particulate emissions**. Atmospheric Environment, v. 104, p. 195 - 204, 2015.
- FRÄNDEGÅRD, P.; KROOK, J.; SEVENSSON, N.; EKLUND, M. **A novel approach for environmental evaluation of landfill mining**. Journal of cleaner production, v. 55, p. 24 – 34, 2013.
- FU, Z., TOPAL, E. AND ERTEN, O. **Optimization of a mixed truck fleet schedule through a mathematical model considering a new truck-purchase option**. Mining Technology, v. 123, n. 1, p. 30 – 35, 2014.

GOMES, R. B., DE TOMI, G. AND ASSIS, P. S. **Impact of quality of iron ore lumps on sustainability of mining operations in the Quadrilátero Ferrífero area**, Minerals Engineering, v. 70, p. 201–206, 2015.

HADI, P., YEUNG, K.Y., GUO, J., WANG H., MCKAY, G. **Sustainable development of tyre char-based activated carbons with different textural properties for value-added applications**, Journal of Environmental Management, v. 170, p. 1 – 7, 2016.

HARTMAN, H. L.; MUTMANSKY, J. M. **Introductory Mining Engineering**, 2nd edition, Wiley, 2002, 570 p.

HERRMANN, I.T., HENNINGSEN, G., WOOD, C.D., BLAKE, J.I.R., MORTENSEN, J.B., SPLIID, H. **The statistical value chain - a benchmarking checklist for decision makers to evaluate decision support seen from a statistical point-of-view**. International Journal of Decision Science, v. 4, n. 2, p. 71 – 83, 2013.

HILSON, G. **Defining “clear production” and “pollution prevention” in the mining context**. Minerals Engineering, v. 16, p. 305 – 321, 2003.

HUSTRULID, W.; KUCHTA, M.; MARTIN, R. **Open Pit Mine Planning and Design**, 3rd edition, Taylor and Francis, 2013, 1004 p.

IMYIM, A., SIRITHAWEEESIT, T., RUANGPORNVISUTI, V. **Arsenite and arsenate removal from wastewater using cationic polymer-modified waste tyre rubber**. Journal of Environmental Management, v. 166, p. 574 – 578, 2016.

KAGOGO, T.S. **A critical evaluation of haul truck tyre performance and management system at Rössing Uranium Mine**. Journal of South African Institute of Mining and Metallurgy, v. 114, n. 4, p. 293 – 298, 2014.

KWON, E.E., OH, J., KIM, K. **Polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) mitigation in the pyrolysis process of waste tires using CO₂ as a reaction medium**. Journal of Environmental Management, v. 160, p. 306 - 311, 2015.

LEVESQUE, M.; MILLAR, D.; PARASZCZAC, J. **Energy and mining – The home truths**, Journal of Cleaner Production, v. 84, p. 233 – 255, 2014.

LI, Y.; CORDER, G. D.; McLELLAN, B.C. **Transport in the mineral industry-contribution to greenhouse gas emissions and potential for mitigation**. Minerals Engineering, v. 24, n. 13, p. 1430 – 1439, 2011.

McLELLAN, B. C; CORDER, G. D.; GIURCO, D. P.; ISHIHARA, K. N. **Renewable energy in the minerals industry: A review of global potential**. Journal of cleaner production, v. 32, p. 32 – 44, 2012.

MONTGOMERY, D. C.; RUNGER, G. C. **Applied statistics and probability for engineers**, John Wiley & Sons, 4th ed., 2007, 490 p.

MOTLOGELWA, O.G.; MINNITT, R.C.A. **Optimization of diesel usage at Uitvlugt Mine**, The Journal of the South African Institute of Mining and Metallurgy, v. 113, n. 4, p.345 – 349, 2013.

NADER, B., DE TOMI, G. AND PASSOS, A. O. **Key performance indicators and the mineral value chain integration**, REM: Revista Escola de Minas, Ouro Preto, v. 65, n. 4, p. 537–542, 2012.

NORGATE, T.; HAQUE, N. **Energy and greenhouse gas impacts of mining and mineral processing operations**, Journal of cleaner production, v. 18, p. 206 – 274, 2010.

NORGATE, T.; HAQUE, N. **The greenhouse gas impact of IPCC and ore-sorting technologies**. Minerals Engineering, v. 42, p. 13 -21, 2013.

OSKOU EI, M. A.; AWUAH-OFFEI, K. **Statistical methods for evaluating the effect of operators on energy efficiency of mining machines**, Mining Technology, v. 123, n. 4, p. 175 – 182, 2014.

RAGHAVENDRA RAO, S., COOK, C., BAAF, E., PORTEOUS, R. **Design and simulation of roadway development operations to improve productivity**. Mining Technology, v. 119, n. 2, p. 79 – 87, 2010.

RODOVALHO, E.C.; CABRAL, I. E. **Estimate of hourly productivity applied to elaboration and implementation of mining plans**, REM: Revista Escola de Minas, Ouro Preto, v. 67, n. 2, p. 221 - 227, 2014.

RODOVALHO, E.C., LIMA, H.M., DE TOMI, G. **New approach for reduction of diesel consumption by comparing different mining haulage configurations**, Journal of Environmental Management, v. 172, p. 177 – 185, 2016.

ROUMPOS, C.; PARTSINEVELUS, P.; AGIOUTANTES, Z.; MAKANTASIS, K. **The optimal location of the distribution point of the belt conveyor system in continuous surface mining operations**. Simulation Modeling Practice and Theory, v.47, p. 19 - 27, 2014.

SHAFIEE, S.; TOPAL, E. **New approach for estimating total mining costs in surface coal mines**, Mining Technology, v. 121, n. 3, p. 109 – 116, 2012.

SOUSA, L. M. L. S.; FILHO, W. L. O.; LIMA, H. M. **Haul roads structural design in open pit mines**, REM: Revista Escola de Minas, Ouro Preto, v. 65, n. 2, p. 279 – 284, 2012.

THOMPSON, R. J.; VISSER, A. T. **The functional design of surface mine haul roads**, The Journal of the South African Institute of Mining and Metallurgy, v. 100, n. 3, p.169 – 180, 2000.

THOMPSON, R. J.; VISSER, A. T. **Mine haul road maintenance management systems**, The Journal of the South African Institute of Mining and Metallurgy, v. 103, n. 5, p.303 – 312, 2003.

THOMPSON, R. J.; VISSER, A. T. **Selection and maintenance of mine haul road wearing course materials**, Mining Technology, v. 115, n. 4, p.140 – 153, 2006.