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Reducing GHG emissions through efficient tire consumption in open pit mines

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ABSTRACT

The waste management practices currently applied by the mining industry have been widely questioned regarding safety and efficiency. It is not by chance that the mining industry is considered one of the sectors with less integration in circular value chains. The present work is aimed at identifying the specific blend of lithologies applicable to haul road wearing coarse materials with the objective of increasing tire efficiency and reducing of waste tire rubber generation. The methodology includes the physical characterization of waste lithologies as the first stage to evaluate applications for environmental and economic performance improvement. Simulation models generated through multiple linear regression can identify the impact of waste rock application on tire performance. In addition, methods and practical applications that consider the use of wastes as a construction material for haul roads to reduce tire wearing is a novelty. Regarding a 5-year mine scheduling context, the combination of the simulation model applied to tire wear management and the new haul road maintenance method reached a reduction of 30.2 kt per year of waste tire rubber in an open pit mine. Considering the burning of these tires in cement kilns, this result also implies a reduction of 86.1 t of CO_2 emissions per year. These practices are aligned with sustainable mining concepts and can contribute to the maintenance of social licenses of the mining industry.

1. Introduction

Waste reduction and sustainability have been the subject of frequent discussion among various industrial segments of the world's major economies in the first decades of the 21st century. During this period, many industrial sectors developed productive chains in line with the concept of circular economy. As each industrial segment has different characteristics, the concepts of the absorption and adjustment process of the value chains is also not uniform. However, the mining industry stands out in relation to the other industrial segments because of the low assimilation of circular economy concepts. The main factor driving this sector away from circular supply chains is waste management practices. Except for specific examples, mining projects still generate a lot of waste, tailings, and other residuals like tires that are fully disposed in the environment. Responsible mining concepts are based on waste and greenhouse gas (GHG) emissions reduction which allows a better integration between new mining projects and society (Pimentel

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et al., 2016). In order for a mining project of any size to integrate into a community, it is necessary to consider the enterprise sustainability because it represents a key aspect to ensuring the social license. Inserting tailings, wastes, and other enclosing rocks into productive chains optimizes the use of natural resources and represents a greater synergy with circular economy concepts (Liu et al., 2019).

Considering open pit mining projects, all enclosing rocks with no economic value are classified as waste. The handling of this material represents an operational cost to the enterprise and may still require vegetal suppression. In addition, if proper environmental control procedures are not applied, water and air quality may be affected (Hawley and Cunning, 2017). There are other residuals and environmental impacts related to mining operations, such as GHG emissions from fossil fuel combustion and waste tire rubber (WTR). These combined items represent an important issue because they account for almost 25% of an open pit mining costs (Lewis and Steinberg, 2001). Due to the great demand for the various mineral goods, the disposal of mining tires is increasing and exceeds 8% of the world WTR (Cutler, 2012). The WTR and overburden removed during mining operations are the main solid wastes, according to the current production model applied by the mining industry (Rodovalho and De Tomi, 2017). Materials with no economic value are stacked in waste piles, which are structures that take up large areas and heavily modify topography (Hawley and Cunning, 2017). On the other hand, the WTR is intended for burning in some industrial processes. These procedures generate GHG emissions related to mining, which seeks to reduce these emissions as a long-term strategy for maintaining social licenses (Nakousi et al., 2018).

The tire consumption in a mining operation depends on the degree of wear during haulage operations. Many operational variables influence tire wear and most of these are related to the iteration between tires and the haul road surface (Topal and Ramazan, 2010). Thompson and Visser (2006) claim that the state of the art of mining haul roads construction and maintenance is based on the application of empirical methods without considering the characteristics of each material. The authors present a haul road maintenance management system that describes a material selection method and the frequency of maintenances capable of reducing haulage costs. In addition to the controlled operating costs, it is necessary to consider other aspects related to the mining sustainability in order to maintain the social license. Pascual et al. (2017) developed a methodology that addresses the tire production chain from suppliers to mining companies through economic and environmental aspects. The authors relate investments in haul road maintenance with the extension of tire life and the reduction of environmental impacts. Several other papers also relate concepts of circular economy, reduction of environmental impacts in mining and control of tire wear (Patterson et al., 2017; Liu et al., 2018, 2019; Pascual et al., 2019). To complement these investigations, this study has an important contribution: it measures the amount of waste saved due to the application of a tire wear control methodology.

Another key contribution to be discussed in this work is the waste rocks insertion in mining operations' value chain. Employing wastes to be used as haul roads construction material reduces the need for new waste piles, decreasing the environmental impact of mining operations. In an open-pit mine, the availability of enclosing rocks with different physical characteristics is very common. As a mine develops, these different materials become available in the mining faces to be employed in haul road maintenance and construction. However, there is no method that indicates which physical characteristics should be investigated or the proportion of these materials. The relationship of these materials combined with tire wear also represents a gap in the literature. It is important to emphasize that the physical characterization of wastes or low economic value lithologies, aimed at reducing tire wear, is also a novelty. In recent years, the mining industry has been blamed for serious environmental and human disasters involving waste (Cruz and Rodovalho, 2019). Therefore, society requires the application of updated techniques of mining that assist the integration of this sector into circular supply chains. The application of procedures and techniques capable of introducing wastes into value chains and at the same time reducing tire consumption is a necessity of society and industry. Considering this scenario, the present work seeks to answer the following research question: How to reduce the tires consumption in mining and, consequently, GHG gas emissions, using wastes for haul road maintenance? In a mine of metallic minerals there are different materials that have no significant economic value. The present work aims to identify the lithologies that can be used as construction material and to measure the optimum proportion to be applied in haul road surface to reduce the tire consumption. As these materials were inserted into haul road maintenance operations, the need for new waste piles or tailings dams was reduced. At the same time, WTR generation decreased due to reduction of abrasion wear. The present work also considered a practical application in an operating mine during some semesters.

2. Methodology

In order to evaluate the relationship between haul road surfaces with different compositions and tire wear, this study considered a large iron mine in Brazil. At this industrial unit there was data collection, an application of mobile equipment management tools, and a performing of field tests. The present study used historical data between 2012 and 2015 to establish a tire consumption background. The practical application of the method, which includes the haul roads suitability and the tire wear evaluation, occurred between 2015 and 2016, over 18 months. Between 2016 and 2017, the operational conditions and performance indicators were monitored throughout the haul roads network of the studied mine. The data collection on loading and haulage operations should be sufficient to identify standards and measure the efficiency of the implemented actions (Rodovalho and Cabral, 2014). The authors state that these industrial processes present natural oscillations of performance, which implies the need for a more extended data collection. Therefore, the present study considered data generated over 5 years. This period includes the operational background, period of application of the methodology, and results validation.

Many large-scale open-pit mining projects adopt continuous improvement concepts to investigate the process by application of quality tools and standardization of procedures. For this work, this model was applied to tire wear management integrated with haul road maintenance. This type of industrial process allows the application of the statistical value chain (SVC) combined with the fundamental principle of the Deming Cycle (PDC). The SVC method allows us to evaluate and identify uncertainties in the decision process (Herrmann et al., 2013). Fig. 1 shows the cycle of activities following the SVC method aimed at integrating haul road maintenance and tire wear management. This cycle presents sectors dedicated to analyzing the industrial process, practical applications, validation of the results, and standardization, according to the basic assumption of the Deming cycle. This approach allows that the events described in the SVC can be adjusted as needed. In mining operations, changes in the behavior of variables and operating conditions are common. This is due to weather, geological aspects, economic aspects, consumer market and others. The laboratory tests, statistical tools used in each step, and practical applications will be detailed in the following sections.

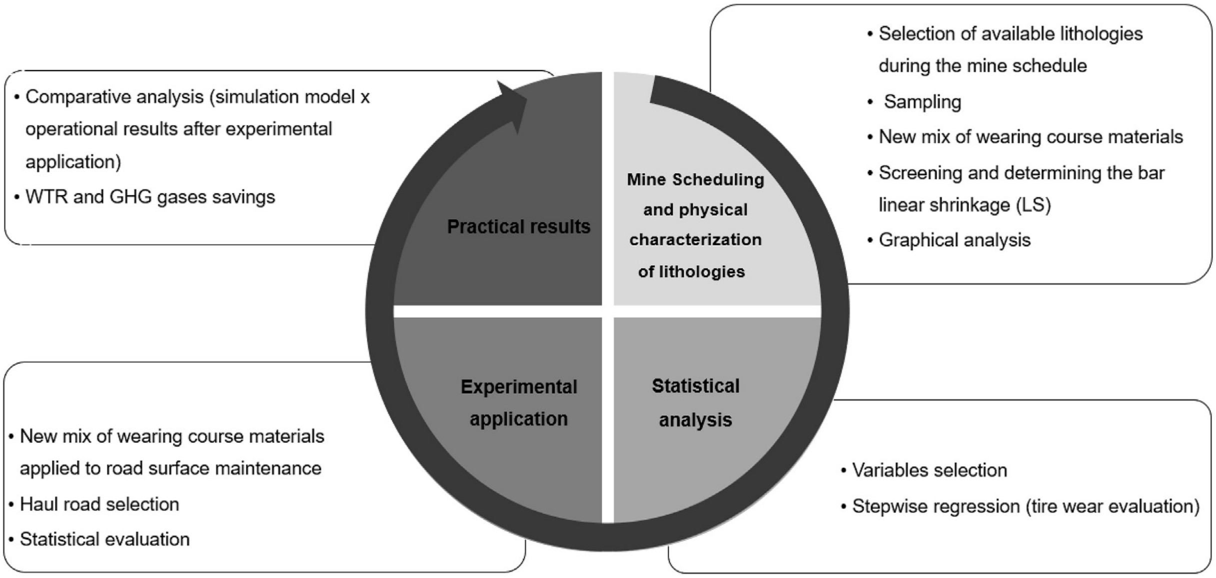

Fig. 1. Cycle of tire-wear management system detailing each stage in order to reduce the WTR generation and GHG emissions during mining haulage operations.

2.1. Mine scheduling and physical characterization of lithologies

The mine scheduling is developed by optimization tools, mathematical programming, and specific algorithms. The purpose is to identify a possible solution that balances production targets and operational constraints. The results of mine scheduling make it possible to know the position, volume, and geometry of mining cuts devoted to ensuring the production according to previous specifications. Most mining projects consider this type of study as a key reference for short-term mining plans and mining operations. Based on the geometry of the cuts associated with each period, the lithologies that will be mined are identified. In addition, this information can be combined with the quality and quantity of each lithology. Gravel and crushed stones represent the most suitable materials for application in haul road surfaces (Thompson and Visser, 2006). According to the authors, it is necessary that the materials be resistant and have specific physical characteristics that allow a predictable, safe and economic performance of the trucks. The authors also state that the haulage cost influences from 10% to 50% of the total mining costs. This variability is directly related to the distance travelled by the trucks between the origin and destination of the productive cycles. Hence, it is fundamental to know the availability and the characteristics of the materials near the mining faces. As the mining scheduling has the assumption of concentrating operations in certain areas, it is possible to know this availability in advance. This possibility reduces the need for excavators' relocations, which favor the safety and cost-effectiveness of operations.

Considering the studied mine, the lithologies that have the greatest resistance and compatibility for application as wearing coarse material are the low-grade iron ore formations. These materials are stacked in waste piles or low-grade ore piles, without integration into the value chains. The lithologies identified as low-grade iron ore formations, to be used as wearing coarse material were compact itabirite (CI), friable itabirite (FI), and ferruginous laterite (FL). In order to investigate the physical characteristics and suitability of each material, granulometry analysis and measurement of linear shrinkage (LS) were performed in the laboratory. The objective of these tests was to know the grading coefficient (GC), Shrinkage product (SP) and the Dust ratio (DR). Equations (1)–(3) define the variables GC, SP and DR, respectively. The variables P265, P475, P2, P425 and P075 mean the percentage of passing in sizes 26.5 mm, 4.75 mm, 2 mm, 0.425 mm and 0.075 mm, respectively. Each of the equations has experimental references that define the range of ideal conditions (Thompson and Visser, 2006). In this way, it is possible to evaluate if a score meets the ideal traffic conditions. The relationship between GC and SP scores are directly related to the susceptibility of haul roads' structural problems that cause increased rolling resistance, dust generation, increased fuel consumption, and premature tire wear (Thompson and Visser, 2006). The relationship of both variables was performed through graphic analysis, where there was a delimitation of ideal conditions for trafficability.

$$GC = ((P265 - P2) * P475)/100 \qquad \text{Ideal conditions: } 25 \leq GC \leq 32 \tag{1}$$

$$SP = LS * P425 \qquad \text{Ideal conditions} : 95 \leq SP \leq 130 \tag{2}$$

$$DR = P075/P425 \qquad \text{Ideal conditions} : 0.4 \leq DR \leq 0.6 \tag{3}$$

Table 1 presents the laboratory tests results and values for GC, SP, and DR, considering 5 different scenarios. The particle size analysis was performed by vibration screen tests for each scenario separately. A sample of each blend is needed to carry out the screen tests. After this procedure, the dry mass sorted by each deck is measured. Based on these results, the relation between the mass sorted by each deck and the total sample mass provides the particle size analysis. Scenarios A, B, and C consider 100% of each lithology available in mine scheduling and are also compatible for application as wearing coarse material. These scenarios are not recommended for practical application because their individual availability is constrained by mine scheduling and implies an increase of haulage distance in the long term. Moreover, this practice restricts the insertion of low economic value lithologies into value chains. However, this physical characterization is important because it generates the GC, SP, and DR scores of each individual lithology. This information is used to investigate operational problems related to inappropriate mixes applied in haul road

Table 1
Results of laboratory tests for CI, FI, and LF lithologies and their blends.

Blend Scenarios		A	B	C	D	E
Rock type (% of mass)	CI	0	100	0	50	10
	FI	100	0	0	40	70
	FL	0	0	100	10	20
Particle size analysis (% passing)	P075	27.1	16.78	4.68	15.57	21.58
	P425	80.51	30.98	14.88	29.37	62.43
	P2	88.44	41.6	28.39	40.28	71.75
	P475	92.71	60.02	43.2	58.34	79.54
	P265	100	93.9	85.79	93.09	99.58
Bar linear shrinkage (mm)	LS	5.28	3.58	3.37	3.56	4.73
Material parameters (Scores)	GC	10.7	31.4	24.8	30.8	22.1
	SP	425.1	110.9	50.1	104.6	295.3
	DR	0.34	0.54	0.31	0.53	0.35

surfaces. Scenarios D and E are technically feasible mixtures and may be recommended for practical application. The recommendation depends on the results of SP, GC, and DR scores. This result combines the mineral resources optimization, operational, and economic performance. It is important to highlight that none of these blend scenarios were taken into consideration previously.

The results of Table 1 indicate significant differences between the available lithologies detailed by the mine schedule. The lithology FI, which makes up 100% of blend A, has more than 80% of particles with a diameter below 0.425 mm. This result shows that it is a very fine material, with a high potential for dust generation, if it is applied in the haul roads. This hypothesis is confirmed by the result of DR that is out of ideal specifications. On the other hand, the blend B has more than 50% of particles with a diameter greater than 4.75 mm. This means that lithology CI is a coarse material similar to crushed rock that is recommended by some authors as the main component of haul road surfaces. This implies that roads coated by mixture C may present structural problems. Therefore, an ideal solution is to have a blend with different lithologies to overcome these challenges.

Fig. 2 shows a graph for the comparative analysis of the 5 evaluated mixtures. Blend C is located below the gray area which limits the ideal conditions, which is implied in corrugations and excessive deformations of the haul road surface (Thompson and Visser, 2006). Haul road surfaces filled by plastic materials, such as blend C, can increase rolling resistance due to the penetration of these structures into the road (Tonkovich et al., 2012). In addition, truck traffic on this type of road is also directly related to the increase in fuel consumption and can lead to tire damage (Soofasteli et al., 2016). In Fig. 2, there is a gray area that bounds the ideal conditions for roads surface composition based on the analysis of GC and SP results. Only mixtures B and D are contained in this area and meet the operational assumptions for truck traffic. This implies that blends B and D are suitable for application in industrial scale tests. These compositions provide structural conditions capable of reducing tire wear due to low road penetration.

2.2. Statistical analysis

Before the development of the present work, the studied mine did not have a standard for haul road surface composition. In this context, the most varied traffic conditions were present. Among the most frequent problems are deformations, poor wet skid resistance, poor dry skid resistance, increased loose stones and dustiness. Considering the previous operational performance as reference, it is necessary to evaluate and measure the influence of the Ton Kilometer per hour (TKPH) on the haulage hourly productivity (HP). TKPH is an expression of the working capacity of a tire related temperature, load, and speed (Meech and Parreira, 2013). This is the leading indicator for tire performance and wear management. TKPH monitoring is applied to the studied mine for this purpose and also to avoid tire damage. Other variables, which also influence productivity, were investigated. Table 2 shows the list of the main influencing factors of road conditions. These data were used in a multiple linear regression analysis using Minitab 18. In this analysis, the response variable is the hourly productivity and the others are predictor variables. This method makes it possible to evaluate the degree of influence of each predictor with the response variable. Thus, it is possible to measure the wear of the tires and the production associated with any oscillations.

The data collection is done from a fleet management system that records events, position and equipment times in real time. The trucks evaluated in the present study have the same size, nominal payload, and age and operate under the same conditions. The work schedule adopted by the studied mine is 24 h a day, divided into 6-h shifts, 7 days a week.

Each of the variables described in Table 2 have different degrees of influence on hourly productivity. In addition, other variables such as queue time and downtime are related to truck performance. However, the two examples cited above have a low influence on the haulage productivity in the investigated mine. In order to select the variables that have the greatest influence on and correlation with hourly productivity, the stepwise regression method (forward and backward) was used. This method considers the significance level to select variables capable of explaining the productive performance of haulage operations. In each round, the method performs the insertion or withdrawal of variables seeking the systematic increase in correlation. At the end of this process, the predictors are identified by maximum correlation with the response variable. When the equation reaches a maximum correlation, the selection ends.

Table 3 presents the final configuration of a model generated after application of the stepwise regression method. The reference database for building the model covers the behavior of predictor and response variables between 2012 and 2015. When using an extensive database, the models address the oscillations of operating conditions, such as climatic variations and human factors. The models resulting from this practice are more accurate and adherent to reality. From the first stage of the analysis, TKPH were included in every stage until the variable selection. The objective was to build a model adapted to the tire wear management. Stage 8 considered only the variables with a p-value less than 0.15. Therefore, stage 8 represents the final model for stepwise regression where positive signals indicate direct proportionality with productivity, and the negative sign indicates the inverse. The other seven stages are used to calculate the value of the eighth stage and are not further

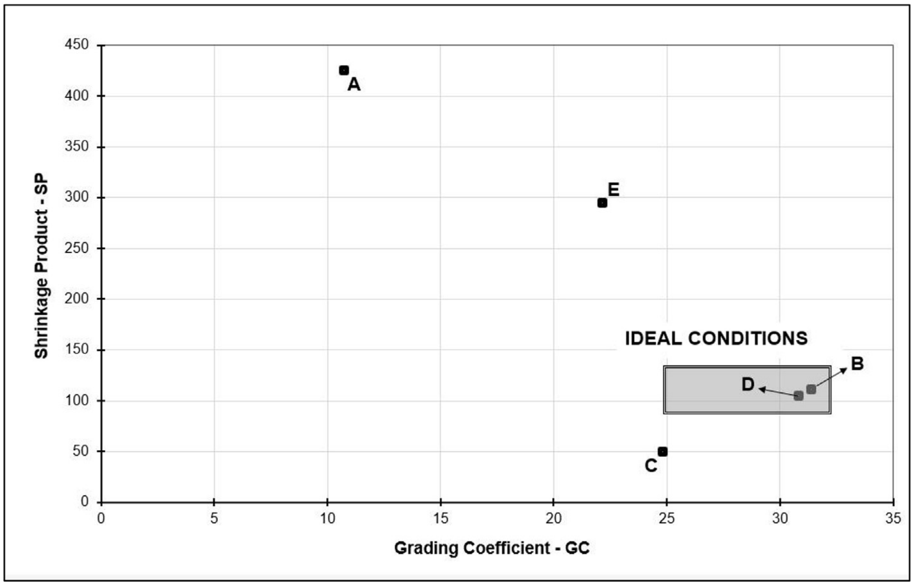

Fig. 2. Graphical analysis in order to identify ideal conditions of operational haul road surface.

Table 2
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
TKPH	Tonnes kilometer per hour: relation between the trucks' payload and speed.	$t.km.h^{-1}$
P	Payload of truck: total production of each cycle measured by on-board weighing scale	t
FED	Full/empty distance index: Relation between full haul distance and empty haul distance	
HP	Hourly productivity: relation between total production and operating hours.	$t.\ h^{-1}$
LT	Load time: average time of loading	Hours
ML	Maneuvering time for loading: average time of maneuvering before loading	Hours
DT	Dump time: average time of dumping	Hours
TE	Average time of haulage empty (no load)	Hours
TF	Average time of haulage loaded	Hours

Table 3
Stepwise regression (forward and backward) for haulage fleet.

Response	Hourly productivity							
Stage	1	2	3	4	5	6	7	8
Constant	543.9	805.9	1272.7	1030.6	1097	1125.2	1138.1	596.8
Variables	**Coïficients**							
TKPH	0.0437	0.0333	−0.0048	0.0170	0.0236	0.0260	0.0283	0.0236
TE		−1944	−1881	−1539	−1551	−1554	−1565	−1577
TF			−1930	−1620	−1619	−1576	−1521	−1595
FED				33.1	33.6	32.4	31.5	29.6
LT					−2186	−2292	−2166	−2177
DT						−2103	−1979	−1980
ML							−2673	−2649
P								2.41
$R^2{}_{adj}$	54.94	61.09	71.19	75.82	80.32	84.86	86.99	87.64

considered. The last line of Table 3 shows the adjusted coefficient of determination (R^2 adj), which indicates the evolution of data adjustment.

For additional verification of the model, residual plot analysis was performed. 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 type of analysis (Montgomery and Runger, 2007). The Durbin–Watson test is a measure of autocorrelation in residuals from regression analysis. To perform this test, the population of residuals from a multivariate regression analysis is needed. Regarding the equation of the eighth stage, the value of the Durbin–Watson statistic obtained is equal to 1.75, indicating that the residuals are independent and there is no autocorrelation. Cook's distances analysis indicates no influential point. The last verification procedure is the multicollinearity analysis by the variance inflation factors (VIF). Multicollinearity is when there is a correlation between predictors in a model, which affects the regression results. The VIF estimates how much the variance of a regression coefficient is inflated due to multicollinearity in the model. All variables reached VIF between 1.02 and 1.99 indicating no multicollinearity. All three procedures have demonstrated the consistency of the proposed model describing the hourly productivity of haulage fleet.

3. Practical application

Some scenarios presented in Table 1 have technical feasibility regarding the studied mine scheduling. Therefore, the present practical application aims to verify if an application of scenario D assumptions is able to modify tire performance. Scenario E was not considered in the practical tests due the DR score out of the appropriated conditions. The application of this blend implies in environmental and safety impacts as dust generation and poor visibility (Thompson and Visser, 2006). Fig. 3 shows the routes for the industrial scale tests of mixtures for road surfaces maintenance. Route 1 represents the standard procedure adopted by the studied mine for road surfaces. Route 2 follows the ratio defined by blend D, as shown in Table 1. Throughout route 1, road maintenance and construction were applied according to the usual mixture practiced empirically by the infrastructure team. Route 2 adopted mix D, a scenario that represents the ideal conditions of trafficability. The adjustment period of routes 1 and 2 occurred simultaneously over 6 months. After the adjustment, the period of tests with normal truck traffic was started. Table 4 shows the mass of each lithology applied in each route. During the adjustment period, there was a great availability of FI, which justifies the great application of this material in the traditional mix. However, excessive use of this material can cause problems, such as dust and poor dry skid resistance, which impairs tire performance and haulage operations.

Considering the waste mass directed to the practical tests, route 1 and 2 combined demanded 5.05 million t. This mass matched to 10% of the total waste rocks removed in the studied mine over 1 year. The period of roads adjustment was 6 months. Permanent actions tend to absorb an even larger amount of waste rocks removed at the mine. This type of action integrates materials without any commercial application in value chains. It is important to note that many roads of the studied mine under evaluation do not even receive a specific wearing coarse material, only a leveling. The mixture applied in route 1 represents the current practice when there is any maintenance of haul road surface.

3.1. Analysis of operational tests

The 12 months that followed the period of roads adjustment represented the follow-up of performance tests of the trucks. During this period the truck performance data were generated under controlled operating conditions. Therefore, it was sought to ensure compliance with the assumptions described in the methodology as verification of the age, size, and operational conditions of the trucks employed in the test. At the end of the 12 months of testing, the performance data of routes 1 and 2 were collected through a fleet management system. As the research objective is related to tire wear management, the first phase of statistical analysis will be dedicated to TKPH. This variable measures the tires usage efficiency and is related to operating conditions (Meech and Parreira, 2013).

The first step of statistical analysis of the results reached by the practical application had the objective to investigate if there were significant differences between the TKPH of routes 1 and 2. The initial procedure were the comparative box plot evaluation between the routes regarding TKPH. Fig. 4 shows the Box plot for route 1 and 2. In this graph, it is possible to evaluate, comparatively, the interquartile distance, dispersion, and position of the median of each population. Considering the period of 1 year of data collection, the populations have contributions of all climatic patterns present in the region during alternating dry and rainy periods. This assumption ensures a more accurate and representative assessment. However, longer collection periods imply the presence of outliers in the population due to incomplete cycles and failure in the notes. In order to eliminate the outliers from the analysis, a 95% confidence interval was adopted, eliminating discrepant data present at the ends of the box plot. Therefore, the graph of Fig. 4 shows no outliers and indicates that the population of route 2 has a median of 1132.74 $t.km.h^{-1}$ while route 1 has a median of 974.3 $t.km.h^{-1}$. Hence, this analysis is not sufficient to confirm whether this difference is significant or is a natural oscillation of the system.

To confirm if the difference between the populations of routes 1 and 2 is significant regarding TKPH, it is necessary to verify if the

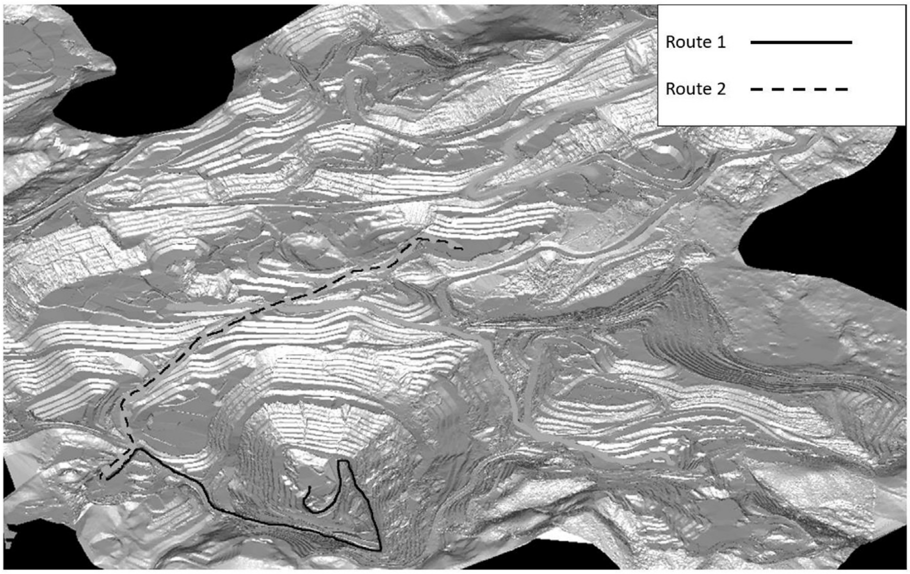

Fig. 3. Haul roads selected to perform the tests according empirical procedures and theoretical blends.

Table 4
Wearing coarse material blend applied to haul roads surface as a practical application.

Rock Type	CI		FI		FL		Total Mass (kt)	Length (km)
Route	Mass (kt)	(%)	Mass (kt)	(%)	Mass (kt)	(%)		
1	1480.4	45	1402.4	43	396.5	12	3279	2.90
2	884.7	50	679.3	38	210.1	12	1774	2.35

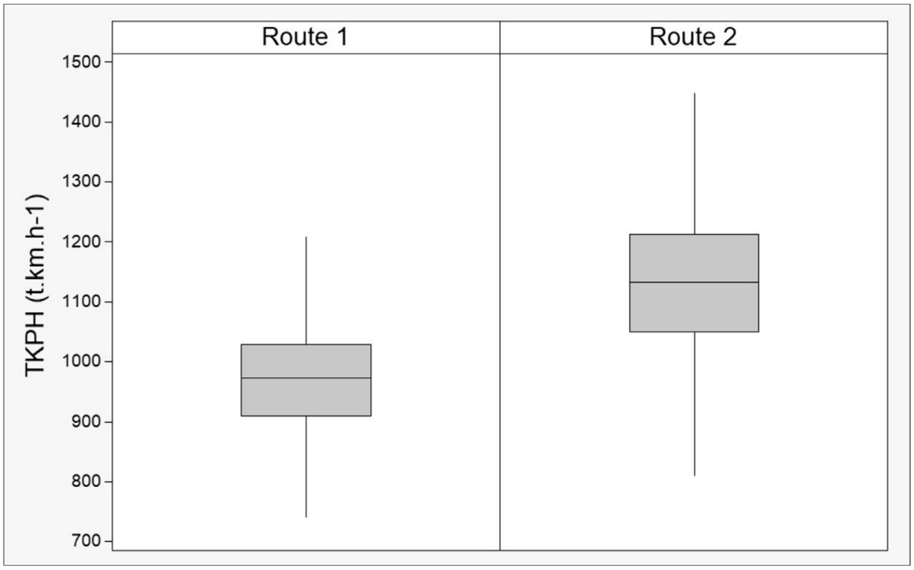

Fig. 4. Boxplot comparing TKPH of route 1 and route 2 during the test period.

data adjusts to a normal distribution. Fig. 5 shows a normality test to verify that the data follows a normal distribution. The diagonal line of the graph represents the reference related to the dispersion of population points. The results beside the graph indicate that the p-value is greater than 0.05, so the null hypothesis is not rejected. A p-value greater than the alpha level (0.05) implies that the data population follows a normal distribution (Montgomery and Runger, 2007). Knowing that the population follows a normal distribution, parametric tests were applied to assess the relevance of variability. This study applied the One-way ANOVA test, using the Tukey method, based on a confidence level of 0.05. Table 5 presents the results of the One-way ANOVA test by the Tukey method, where the

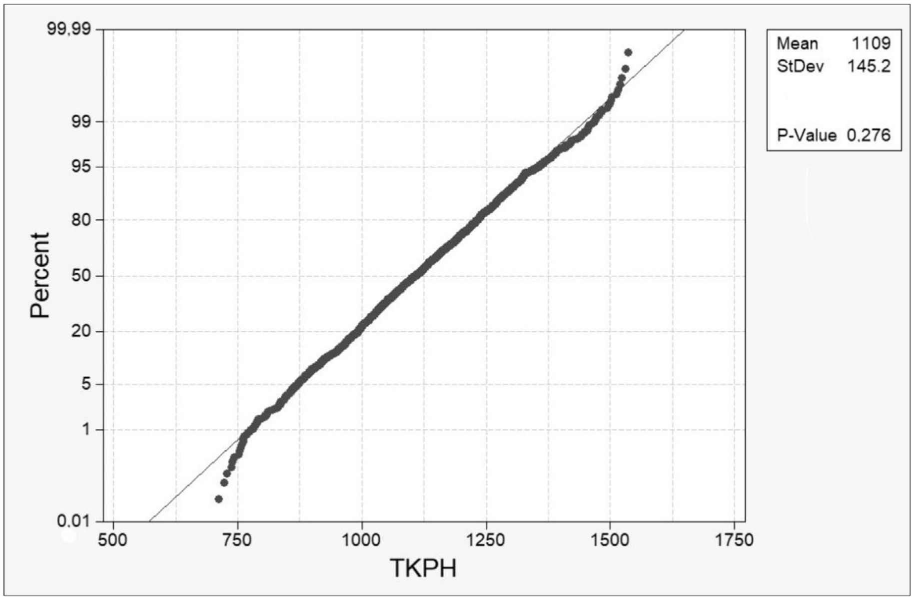

Fig. 5. Normality test for haulage TKPH. The y-axis represents the normal probability (percent) and the x-axis represents the values of TKPH for both routes. The points follow the line of theoretical normal probability.

difference between the data population is confirmed. The letters (a) and (b) in Table 5 indicate that populations have significant variations. This is implied in the different wear and performance of tires on route 1 and 2 over the testing period of 12 months. This difference can be assigned to the haul road surface since it was the only distinct operational variable between the two routes.

4. Results and comparisons

After the evaluation of populations of TKPH results, through one-way ANOVA Tukey method tests, the variability between the populations of routes 1 and 2 is significant. In order to measure the impact of the TKPH on the hourly productivity of haulage operations, the simulation model defined in Table 3 was used. Equation (4) highlights the round 8 of Table 3 that represents the equation that explains the hourly productivity of transport in the studied mine. This equation reached R^2 adj = 87.64%, which indicates a satisfactory adjustment of the data. Nonetheless, this coefficient is not sufficient to measure the quality of the equation with respect to the accuracy of the estimates. For this, a second round of validation for the proposed simulation model was applied. If the model has a variation up to 5% between simulated and real data, it means that equation (4) explains the hourly productivity of the haulage operations.

$$HP = 596.8 + 0.0236*TKPH - 1577*TE - 1595*TF + 29.6*FED - 2177*LT - 1980*DT - 2649*ML + 2.41*P \tag{4}$$

The validation procedure of equation (4) consists of collecting the values of each variable and estimating the value of HP. Mean values of these variables were considered throughout the test period. Table 6 presents the estimated and real productivity results for routes 1 and 2. This analysis considers 2269 complete cycles of trucks. The variation between simulation and real results for productivity was less than 5% in both routes. This result finishes the second stage of validation successfully, indicating that the model is able to estimate the performance of the productive system studied with satisfactory accuracy. Considering the results by route, route 1 is the operational reference because it represents the standard conditions of the studied mine. Route 2 differs from route 1 only by having an ideal blend for haul road surface. Route 2 achieved real productivity 2.5% higher than route 1. Simulation models obtained through multiple linear regressions, such as equation (4), make it possible to measure the influence of each variable on hourly productivity.

Table 6 also shows the positive and negative oscillations for each of the variables. TE and TF are the variables that present the highest impact in the hourly productivity of haulage. However, these two variables are closely related to local traffic and operation conditions. TKPH, on the other hand, is a variable that impacts hourly productivity significantly and it is closely related to tire wear behavior. Since the TKPH is a function that relate payload, speed and tires temperature; the tire wear management is carried out by analysis of this variables. In addition to TKPH, the variable TE, FED, ML, and TF reached variations above 10%. The TE and TF variables are related to mine traffic and road conditions because access in poor traffic conditions increases travel times. The FED is related to the dynamic allocation and prioritization needs of the studied mine that affects the truck travels. ML is related to the conditions and geometry of mining faces. TKPH is directly related to tire performance, where higher values indicate a higher working capacity of these structures. Under suitable road conditions, there is a TKPH trend of increase due to the reduction of speed oscillations during the truck travels (Meech and Pereira, 2011). Fig. 6 shows the impact on $t.h^{-1}$ of each variable in the productivity according to the simulation model. The graph measures the influence of each variable on increasing or decreasing hourly productivity in relation to the standard conditions of route 1. The combination of all variables results in the productivity difference between route 1 and 2 of 111.45 $t\,h^{-1}$. Of this total, the TKPH, a variable influenced only by the relation between the tires and the road surface, accounts for 23.7% of the difference.

Table 5
One-way ANOVA test applied to analysis of the TKPH of route 1 and 2 using Tukey method.

One-way ANOVA: TKPH versus Haul road/Tukey Method			
		Haul road (Route)	*p*-value
	1	2	
TKPH	969.8 ± 90.7 $_{(b)}$	1131.1 ± 125.4 $_{(a)}$	<0.001

Table 6
Combined analyses between routes 1 and 2 regarding real and estimated results.

Variables	Coefficients	Route 1	Route 2	Variation (%)
Constant	596.8			
TKPH	0.0236	975.1	1213.3	24.4%
TE	- 1577	0.136	0.108	- 20.3%
TF	- 1595	0.165	0.139	- 15.5%
FED	29.6	0.873	1.047	19.8%
LT	- 2177	0.043	0.041	- 5.1%
DT	- 1980	0.023	0.025	6.4%
ML	- 2649	0.013	0.0162	16.7%
P	2.41	241	240.8	- 0.07%
HP simulation (t/h)		655.8	767.3	16.9
HP real (t/h)		624.1	751.9	20.4
Variation (%)		- 5.1%	- 2%	

The measurement of tire durability should only consider TKPH as it is the only indicator that is not influenced by other operational aspects. The other indicators are related to the road surface and tire performance but are also influenced by other aspects mentioned above. Considering these results, the tires subject to the operational conditions of route 2 produce an additional 26.4 t at each hour of operation compared to the conditions of route 1. The durability of the tires was not affected during the study, considering that these structures resist about 4500 h (Bellamy and Pravica, 2011). Regarding the studied mine, this durability corresponds to 6 months of continuous operation. With the adoption of a road surface under the ideal conditions defined by Fig. 2, the mining company can reach the expected production in the mining schedule with a smaller number of tires. In 2016, after identifying these results, the studied mine expanded the pattern applied in route 2 to the other roads of the mine. Fig. 7 shows the reduction of WTR generation related to the mine production. In order to estimate the amount of WTR over the studied period, a baseline comparing the mine production with consumed tires was adopted. Each discarded tire is labeled and weighed since 2012. The mass of discarded tires divided by the mine production provide the WTR values. The graph shows two consumption patterns where the updated standard indicates that the WTR generation was 41% lower. The mine under study has a fleet of 31 off-road trucks. Considering the operational efficiency of the fleet and work schedule, it is possible to measure the additional production assigned to the application of this methodology. Table 7 presents the results of additional production per year and WTR savings for the same period, based on the previous standard for WTR. Considering that the mass of 30.2 kt of WTR is burnt in cement kilns because the rubber is used as fuel for clinker production, there are CO_2 emissions associated with it. The

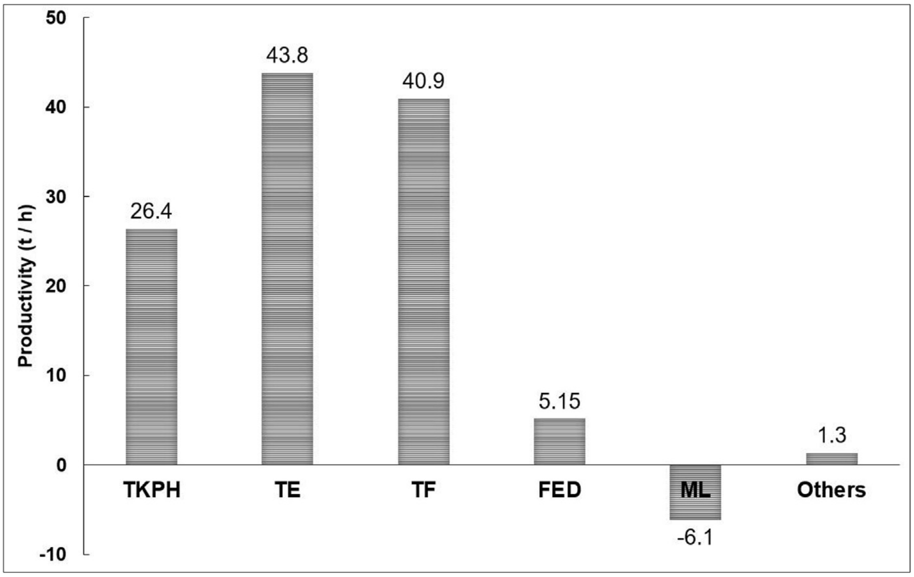

Fig. 6. Hourly productivity impact of haulage variables.

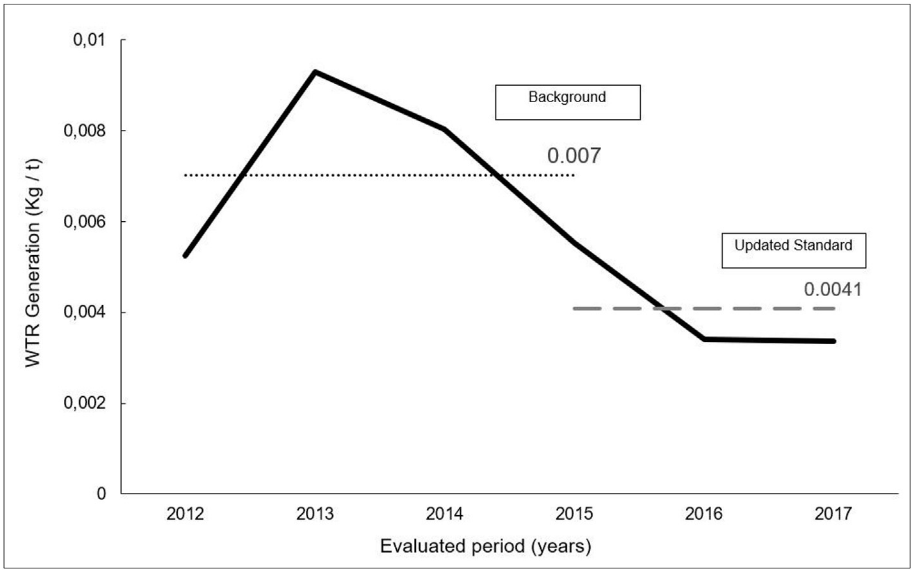

Fig. 7. WTR generation during the project.

Table 7
Results after haul road surface composition standardization following blend D.

Results of Standardization	
Additional production (t/year)	4,301,510
WTR savings (t/year)	30,202
CO_2 emissions savings (t/year)	86.1

burning of 30.2 kt of WTR generates approximately 86.1 t of CO_2 emissions (Downard et al., 2015).

5. Conclusions

The analysis of mine scheduling related to ore characteristics is a usual procedure applied in the mining industry, but using this same study to evaluate possible applications for the waste rocks is a novelty. This practice can be implemented by mining companies of any size and represents an action aligned with circular economy concepts. The proposed procedure in the methodology was implemented and the predicted improvement in tires performance was confirmed after practical application. The methodology indicated that lithology CI, if applied as wearing coarse material, would be one of the ideal alternatives. Nevertheless, this practice limits the use of geological resources and threatens the gains from increased tire performance because the availability of CI is restricted at times through the operations. Hence, the alternative, applied on an industrial scale, needs to follow the availability of materials described in the mining schedule. The mixture that met this assumption was scenario D. During the 6 months of road adjustments, 10% of all waste removed in a whole year was applied. With the adoption of this standard, the potential for waste insertion into productive chains may be even greater. New research is being conducted to evaluate this practice and measure the reduction of this type of waste in mining.

The system of simulation and estimation of performance through multiple linear regression reached R^2 adj = 87.64%, which represents a high index of adjustment of the data. In addition, the same system was validated by the practical application with deviations of less than 5% related to real data. Based on the accuracy and reliability of the simulation model, the tire performance gains were identified. The impact on hourly productivity, attributed to TKPH, was 23.7%. This increase in the efficiency of these structures justifies the reduction of 41% in WTR generation between 2016 and 2017. This result is based on increasing the efficiency of the tires that started to produce more within the same useful life. This implies that there is a reduction of the need to purchase tires to meet a particular production plan. Considering an additional production of over 4.3 million t attributed to greater tire efficiency, WTR savings reached 30,202 t. This practice may avoid the emission of 86.1 t CO_2 per year. The results of tire consumption reduction, GHG emission and waste applications; indicate that the objective of this work was successfully fulfilled. Therefore, the methodology of the work answered the research question raised in the introduction.

This type of research is fundamental for the dissemination of sustainable mining techniques and circular value chain integration. The reuse of materials that are industrial process wastes is a necessity of the current mining industry. Society no longer lives with this type of enterprise and demands applications of updated industrial management techniques. Mining companies that do not follow this reality will certainly have problems related to social license. Large mining projects may fit into the results and methods presented in this paper, but future research will be based on small-scale mining projects.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.120185.

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