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Overall Drilling Effectiveness: key performance indicator adapted for rock drilling

Efetividade Global da Sondagem: indicador de performance chave adaptado para a perfuração de rochas

Eficacia General de la Perforación: indicador clave de rendimiento adaptado para la perforación de rocas

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Abstract
OEE (Overall Equipment Effectiveness) is a key performance indicator (KPI) widely used in performance analysis in the mining industry. The present study develops the ODE indicator (Overall Drilling Effectiveness) adapting OEE concept for the reality of diamond drilling. The product of availability, utilization and quality rates in the drilling process calculates ODE. Quality is defined by the quotient between recovered drill core metreage and total drilling advance metreage. ODE consists of a management numeric tool when confronted with productivity results and drilling equipment cost. In this case study of Pilar Mine, property of Jaguar Mining Inc., the 21% rate portrays the minimum acceptable ODE value considering the enterprise operational reality according to its geological, logistical and financial particularities. When the ODE rate approaches or exceeds this value, productivity increase and cost reduction per drilled metreage are noted. The adaptation of OEE concept and elaboration of ODE as a new performance indicator, intended directly for diamond drilling process, displays as a useful performance control tool. The utilization of ODE as a KPI provides the opportunity to manage operational productivity and financial performance simultaneously.
Keywords: Overall equipment effectiveness; Key performance indicator; Rock drilling; Geology.

Resumo
OEE (*Overall Equipment Effectiveness* ou Efetividade Global do Equipamento) é um indicador de desempenho amplamente utilizado em análises de performance na indústria de mineração. Este artigo desenvolve e introduz o indicador ODE (Efetividade Global da Sondagem) adaptando o conceito do OEE para a realidade da sondagem diamantada. O indicador ODE é calculado através do produto entre as taxas de disponibilidade, utilização e qualidade no processo da sondagem. A qualidade é definida pelo quociente entre a metragem perfurada recuperada nos testemunhos de sondagem e a metragem de avanço total. ODE representa uma ferramenta numérica de gerenciamento quando confrontada com os resultados de produtividade e custo operacional. O presente trabalho utiliza o estudo de caso da Mina Pilar, de propriedade da Jaguar Mining Inc., para demonstrar que a taxa de 21% de ODE consiste no valor mínimo aceitável de efetividade das sondas, considerando a realidade operacional da empresa, de acordo com suas particularidades geológicas, logísticas e financeiras. Quando a taxa de ODE se aproxima ou atinge esse valor, a produtividade aumenta e o custo por metro perfurado reduz. A adaptação do conceito de OEE e a elaboração da ODE como um novo indicador de desempenho, aplicado diretamente para o processo de sondagem diamantada, mostra-se como uma potente ferramenta de controle de performance. A utilização da ODE como um KPI fornece a oportunidade de gerenciar simultaneamente produtividade operacional e desempenho financeiro.
Palavras-chave: Efetividade global do equipamento; Indicador de performance chave; Sondagem; Geologia.

Resumen
OEE (*Overall Equipment Effectiveness* o Eficacia General del Equipo) es un indicador de rendimiento ampliamente utilizado en el análisis de rendimiento en la industria minera. Este artículo desarrolla e introduce el indicador ODE (*Overall Drilling Effectiveness* o Eficacia General de la Perforación), adaptando el concepto OEE a la realidad de la perforación diamantina. El indicador ODE se calcula a través del producto de las tasas de disponibilidad, uso y calidad en el proceso de perforación. El indicador se define por el cociente entre el metraje perforado recuperado de las muestras de perforación y el metraje total de avance. ODE consiste en una herramienta de gestión numérica frente

a los resultados de productividad y costo operacional. El presente trabajo utiliza el caso de estudio de Mina Pilar, propiedad de Jaguar Mining Inc., para demostrar que la tasa de ODE del 21% representa el valor mínimo aceptable de efectividad de los equipos de perforación, considerando la realidad operativa de la empresa, según sus condiciones geológicas, logísticas y económicas. Cuando la tasa ODE se acerca o alcanza este valor, la productividad aumenta y se nota la reducción del costo por metro perforado. La adaptación del concepto OEE y el desarrollo del ODE como un nuevo indicador de rendimiento, aplicado directamente al proceso de perforación diamantina, demuestra ser una poderosa herramienta de control del rendimiento. El uso de ODE como KPI brinda la oportunidad de administrar simultáneamente la productividad operativa y el desempeño financiero.
Palabras clave: Eficacia general del equipo, Indicador clave de rendimiento, Perforación de roca, Geología.

1. Introduction

The recent evolution of key performance indicators, as rightly pointed out by Batista et al. (2022), can be noticed through the emerging range of publications in the last decade related to the topic (Caldeira, 2012; Costa, 2015; Dauber & Bendrat, 2014; Nader et al., 2012; Parmenter, 2015). Indicators associated with production (Brasil & Candia, 2020), human factors (Ribeiro, 2022), environment (Helleno et al., 2017; Lamjahdi et al., 2021) and equipment maintenance, for example, are increasingly common. The growing demand for the elaboration, development and use of such indicators is justified by the need to monitor, control and manage processes and mechanisms in the mineral production chain with greater assertiveness. Proposing suitable solutions for the continuous improvement, productivity increase and cost reduction are essential tasks in the current market context (Heberle, 2020). This is the demand that sustains the growth and applicability of key performance indicators (KPI's).

Overall Equipment Effectiveness is a commonly key performance indicator in the industrial productive chain. Well-stablished in academic studies, OEE is widely used in productivity and performance analysis in the mining industry, mainly intended for drilling, ore load and transport equipment, such as drill rigs, trucks and loaders. The interest in this indicator has been growing significantly in the last years. Typically linked to studies in maintenance and production, the application of OEE is gradually embracing other fields, such as process optimization and cost reduction (Corrales et al., 2020).

Overall Equipment Effectiveness is a simple tool, used in equipment management and effectiveness estimation (Elevli & Elevli, 2010). Originally introduced by Nakajima (1988) as a quantitative measure of equipment maintenance, OEE went through various adaptations in the last decade, transforming into a performance analysis tool able to identify and stablish process losses origins in a productive chain (Pintelon & Muchiri, 2008).

According to Nakajima (1988) studies about Total Productive Maintenance (TPM), six great losses divided into three categories directly affect the productive process and have influence on the calculation of OEE (Table 1).

Table 1 - Six losses and its categories.

Category	Losses
Availability	1 - Time and quality losses due to big stoppages caused by failures or equipment breakage.
	2 - Time losses due to setup and adjustments caused by parameters changed according to operations necessity.
Performance	3 - Idle time when a machine is inactive or due to short stoppages when production is interrupted by a malfunction.
	4 - Low speed due to differences between project speed and operational speed.
Quality	5 - Reduced efficiency from setup equipment until stabilization.
	6 - Unsatisfactory quality and rework.

Source: Nakajima (1988).

Considering the evolution and innovation of OEE applicability, the present study proposes the introduction of ODE, adapting the concept of OEE for the reality of diamond drilling in the mining industry. The redesign of OEE and the elaboration of ODE aim for the development of a simple but robust indicator, which presents operational performance in an objective manner. The main goals of this indicator elaboration are to: (i) establish which methods are necessary for the implementation and automatization of ODE calculations and (ii) demonstrate its efficacy and applicability.

2. Methodology

The presented data originates from a pioneer case study of the diamond drilling fleet from Pilar Gold Mine, property of Jaguar Mining Inc., located in the city of Santa Bárbara, Minas Gerais state, Brazil. The study period comprises between January 2021 and March 2022.

The following equation calculates OEE:

$$OEE = Availability * Performance * Quality$$

Whereas that the performance concept refers to the relation between real production and production capacity, utilization rate (UT) displays as an ideal indicator to represent diamond drills production.

Thus, the following equation defines ODE:

$$ODE = Availability\ (AV) * Utilization\ (UT) * Quality\ (Q)$$

Where, availability (AV) is the equipment's physical availability, calculated by the equation below:

$$AV = (t - t_{MAINT}) / t$$

Where t is the total scheduled production time and t_{MAINT} the total maintenance time during that specified time. There will always exist the relation of $t \geq t_{MAINT}$.

Utilization (UT) is the equipment's physical utilization, calculated by the equation below:

$$UT = [(t - t_{MAINT}) - t_{UNP}] / (t - t_{MAINT})]$$

Where t_{UNP} is total unproductive time, defined by the sum of programmed operational delays on the available time frame, complying with the relation of $(t - t_{MAINT}) \geq t_{UNP}$. Routine security inspections, drill core surveying and infrastructure adjustments at the drilling place are some examples of programmed operational delays.

Quality (Q) is the diamond drilling process quality rate, numerically defined by the percentage of sample recovery during drilling. The equation bellow calculates quality:

$$Q = Rec = M_{REC} / AT$$

Where recovery (Rec) is the quotient between the total recovered drill core metreage (M_{REC}) and the total drilling advance metreage (AT).

Table 2 presents the proportion relation between all variables that composes availability, utilization and quality rates.

Table 2 - Interrelationship and proportion between calculating variables of AV, UT and Q.

<table>
<tr><td colspan="5">Total time (t)</td></tr>
<tr><td colspan="2">Unavailable hours</td><td colspan="3">Available hours (AV)</td></tr>
<tr><td colspan="2">Maintenance (t_{MAINT})</td><td colspan="2">Productive (UT)</td><td>Manageable unproductive (t_{UNP})</td></tr>
<tr><td rowspan="3">Preventive</td><td rowspan="3">Corrective</td><td colspan="2">Meters drilled (A_T)</td><td rowspan="3">Scheduled operational delays</td></tr>
<tr><td>Recover (M_{REC})</td><td rowspan="2">Lost data</td></tr>
<tr><td>Quality (Q)</td></tr>
</table>

Source: Authors.

Through the historical and statistical variability analysis of AV, UT and Q indicators of a specific operational process, it is possible to stablish the minimum target of each to achieve the company planned or demanded productivity. Therefore, it is possible to define the ODE minimum target value based on AV, UT and Q targets. The ideal values of AV, UT and Q may vary according to operational reality of each operation.

The following minimum targets were considered in the Pilar Mine case study, based on historical results:

$$AV = 0.75, UT = 0.30, Q = 0.95$$

Thus:

$$ODE = 0.75 * 0.30 * 0.95 \cong 21\%$$

The 21% rate represents the global effectiveness minimum value of the diamond drilling process at Pilar Mine. ODE values above this rate reached during the operational cycle directly refers to the achievement of the minimum required productivity.

Diamond drilling production database handling through VBA-Excel environment automates ODE calculation. Operational codes utilized on diamond drilling reports are categorized and combined into groups in order to constitute the specified time to feed the equations for calculation of AV, UT and Q.

From operational code categorization on the database, employing filtering and data segmentation tools, the value of ODE for a determined period of time and for a specific equipment or for a group of equipment can be achieved automatically. It is perfectly possible to use this method in other data base analysis software as well, such as Microsoft Access or Power BI.

Regardless of the software or scripts used to automate the ODE calculation, the variables AV, UT and Q must be present in the composition of operational database. It is of fundamental importance to allow the ODE automation and the construction of a robust and complete database.

3. Results

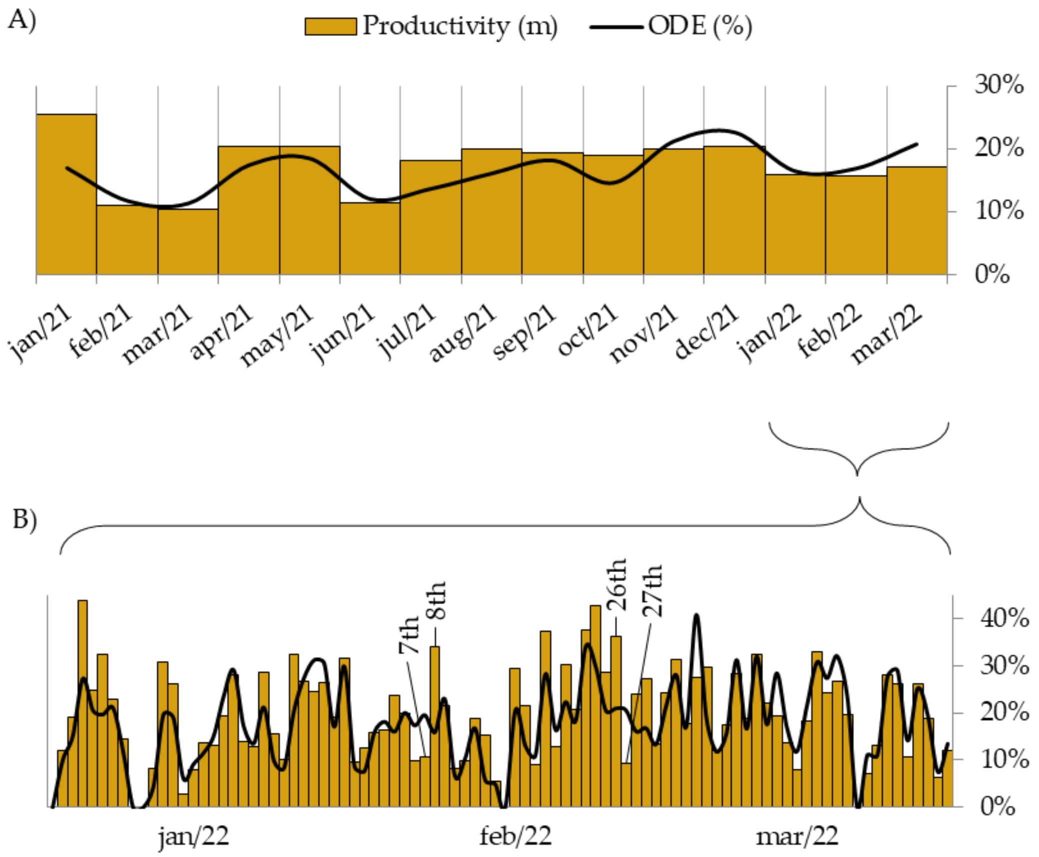
Once the ODE calculation and monitoring are stablished, it is possible to compare global effectiveness values with productivity and operational cost indicators. It is important to mention that sensitive data presented in the case study, such as the operating cost absolute values and equipment productivity numbers, were hidden in order to preserve corporate information.

3.1 Productivity

The relation between ODE and operational performance indicates that an enhancement in effectiveness converts directly into productivity. An increase in ODE indicators values (AV, UT and Q) certainly boosts productivity. The monthly analysis (Figure 1A) and the daily analysis of 2022 first trimester (Figure 1B) presents this relation.

In addition to the direct correlation between effectiveness and productivity, factors that go beyond those predicted on the ODE calculation can cause punctual oscillations on diamond drilling performance. The daily analysis graph of the 2022 first trimester shows a few outliers, where the punctual proportionality between ODE and drilled metreage is not respected. It is the case of days 7th, 8th, 26th and 27th of February (Figure 1B), when the drilled metreage showed an abrupt oscillation of the ODE curve in a 24 hours' period. It is possible to observe that there are other points of disagreement. However, the days mentioned were picked just as samples, aiming to exemplify some disagreement and lead the discussion.

Figure 1 - Directly proportional relationship between ODE and productivity. (A) Monthly sequency among January 2021 and March 2022. (B) Daily sequency for 2022 first quarter.



Source: Authors.

Those oscillations mainly occur due to drilling speed variation during operation (Table 3). As the speed rises, productivity also increases, even if availability, utilization and process quality remain similar. External equipment factors, such as advance pressure variations imposed by different operators and rheology changes of the rock mass are the main responsible for the speed variations during drilling.

Other factors are also responsible for the performance oscillation and negatively influence the drilling process. Certain operational cycle activities (i.e., installation of equipment on the diamond drill, drill core surveying, geomechanical contention application and drilling maneuvers) directly decrease effective drilling time and bring down drilling performance. In addition, the equivalence between the numbers of drill rig's operators and available equipment must also be taken into account. When the operational team is smaller than the fleet of available equipment, the drill rig's utilization rate is reduced.

Table 3 - Comparison between drilling days and its variables.

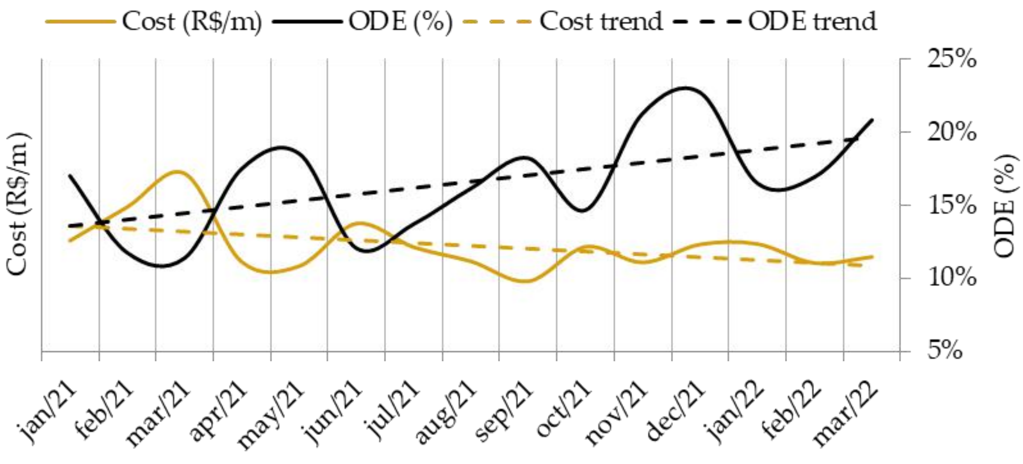
Day	AV (%)	UT (%)	Q (%)	ODE (%)	Meters	Rigs	Time (h)	Velocity (m/h)
Feb 7th	98	23	86	19.65	23.65	3	11.00	2.15
Feb 8th	100	17	96	16.00	75.90	2	17.58	4.32
Feb 26th	99	23	95	21.06	80.55	3	26.50	3.04
Feb 27th	100	22	93	20.66	20.40	2	13.92	1.47

Source: Authors.

3.2 Cost

When compared to operational cost (Figure 2), ODE acquires an inversely proportion relation. The tendency lines illustrate an increase in effectiveness values resulting in production cost reduction. When the ODE rate approaches or exceeds the minimum ideal value of 21%, or when it shows a relative rise when compared to the past period, the cost per drilled metreage decreases.

Figure 2 - Comparison between ODE curve and drilling operational cost.

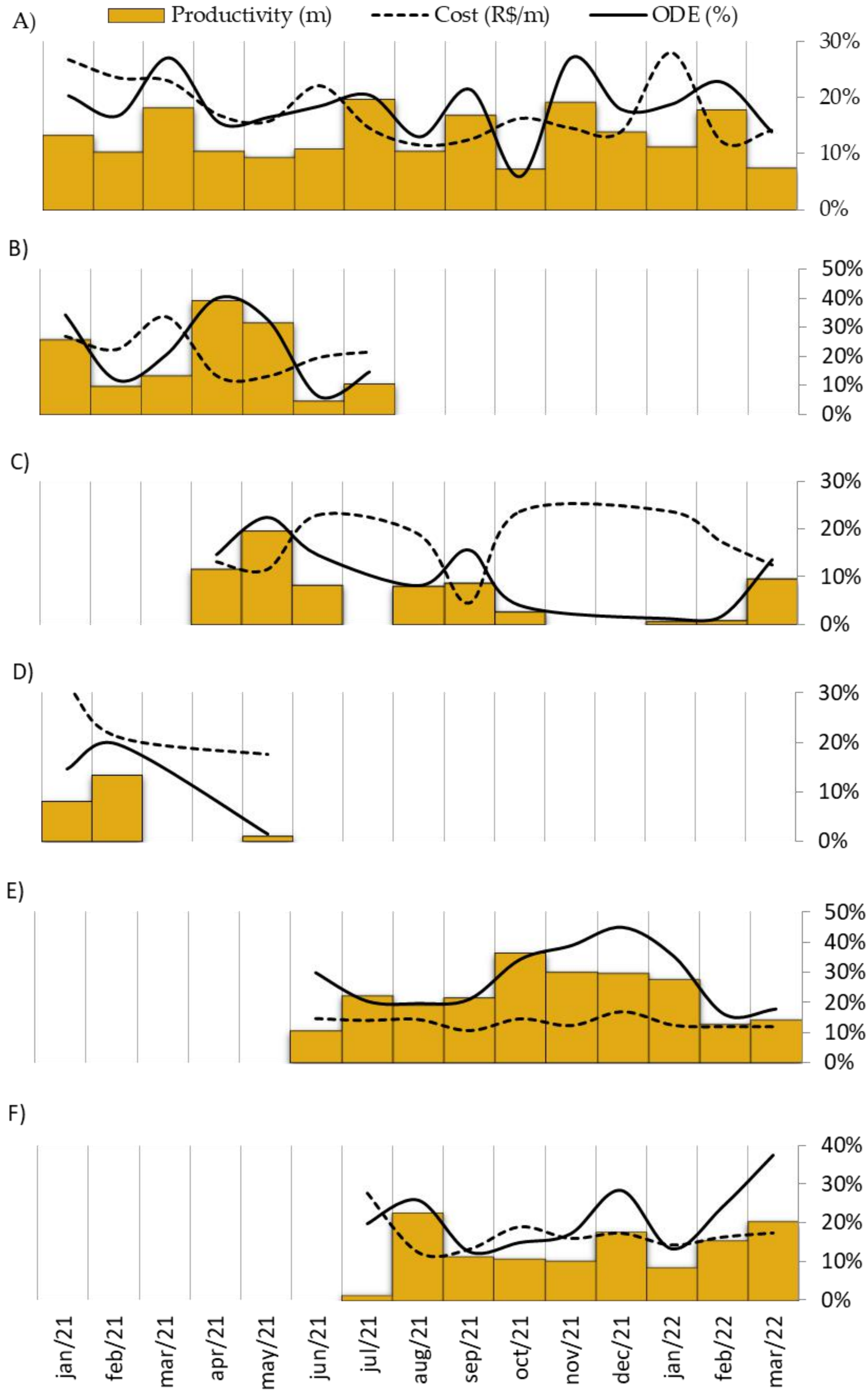


Source: Authors.

The simultaneous observation of cost and productivity for each diamond drill confirms the described relations (Figure 3). The blank intervals represent when the drills were not operating. Only diamond drill A operated during the whole study time. Diamond drill B and D were paralyzed 2021 mid-September, same period that diamond drills E and F started operations.

ODE indicator guides the diamond drills operational performance oscillations, tangential to peaks and valleys on productivity bars illustrated by the graphs on Figure 3. ODE also reflects operational cost variations. Whereas the global effectiveness increases, the performance improvement reduces and dilutes cost. The peak of ODE directly translates into productivity and results in expenses dilution, exhibiting an inversely proportion relation to operational cost.

Figure 3 - Relation between cost, productivity and ODE for operational drill rigs (A, B, C, D, E and F) at Pilar Mine.



Source: Authors.

4. Discussion

The adaptation of OEE concept and development of a new key performance indicator ODE (Overall Drilling Effectiveness) specifically for the reality of diamond drilling in the mining industry constitutes in a pioneer study in management and planning. ODE presents itself as a valuable tool for performance indicators control. There are several published studies that present similar adaptations, endorsing the malleability of OEE according to the operational reality of productive chains and industrial sector in context (Corrales et al., 2022; Pintelon & Muchiri, 2008).

In spite of being a robust key performance indicator, ODE does not consider certain variables. Both productivity and diamond drilling cost depend on factors that go beyond those predicted on the ODE calculation. Diamond drilling management should consider external agents, such as drill rig's brand, mechanical conditions, lifespan for each equipment components (Carter-Journet, 2014) and the subjectivity of each operator drilling methods.

For that matter, the importance of standardizing the drilling speed during operation is emphasized. It is fundamental to stablish operational criteria that define an advance pressure range during drilling, complying with the ore body's geological and structural factors. Therefore, drilling speed variability is attenuated, minimizing performance and effectiveness outliers, Corrective maintenance time and non-programmed operational stoppages reduce as a result of operational stability and the losses caused by parameters adjustments are mitigated.

Although AV, UT and Q target definitions were based on Pilar Mine's operational fulfilment historical results, it is not possible to stablish an ideal universal value for all effectivity indicators (Dal et al., 2000). The 21% rate was adopted as an ideal value for Pilar Mine's specific context, but it is crucial to consider geological, logistical and financial particularities of each enterprise in order to achieve operational compatible and adequate targets.

5. Final Considerations

As pointed by Gackowiec et al. (2020), the actual mining enterprises challenge is to monitoring and control critical elements in process management. To make that, it is essential to identify the key performance indicators (KPIs) that is relevant to the analyzed processes.

Low equipment efficiency, defined by low rates of AV, UT and Q, can endanger the operation success and discourage management and worker involvement (Fourie, 2016). Presented results exhibits how the utilization of ODE on monitoring diamond drilling production and operational cost can be effective. The control of this indicator provides the opportunity to manage diamond drill's operational productivity and financial performance simultaneously.

This research was funded by Jaguar Mining Inc. The authors declare that sensitive data used and presented in the case study, such as the absolute value of operating cost and equipment productivity, were hidden in order to preserve Jaguar Mining corporate information. The authors intend that this data omission does not affect the technical content and discussions arising from the work in question. The funders had no role in the design of the study; in the collection, analyzes, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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