Scientific Article

FOREST EXTRACTION MANAGEMENT WITH THE INDICATOR OF OVERALL EFFICIENCY OF FOREST MACHINES (OEFM)

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ABSTRACT – Performance indicators are tools capable of exposing measurable characteristics and generating relevant information on forest operations, thus being considered pillars for managers to make agile and assertive decisions. Forest extraction with a *forwarder* must be improved, understanding the factors that affect the costs of this machine, such as productivity (PR), fuel consumption (FC), operational efficiency (OE), and quality of operation. Thus, the objective of this study was to evaluate the implementation of the Overall Efficiency of Forest Machines (OEFM) indicator in the management of forest extraction data using *forwarders*. Data were collected during forest harvesting from five operating fleets, in commercial eucalypt plantations, in full-tree and coppice regimes, in the states of Bahia and Espírito Santo. The indicator was expressed as a percentage calculated by OEFM = ((4*PR)+(3*FC)+(3*OE))/10. The performance of the machines was evaluated by a stochastic model of dynamic simulation of systems in eight scenarios, proposing improvement for the average individual volume harvested, fuel consumption, and mechanical or operational stops. Analyzes were performed using PowerSim Studio 9 software. The OEFM of two fleets was higher than the established target of 95.17%, with 95.72% and 97.44%. The OEFM indicator proved to be useful in the management of forest extraction with adequate and easy-to-understand information from a large amount and variety of data. The stochastic simulation model was efficient to study the impact on the global efficiency and the flow of wood extraction by the *forwarder*.

Keywords: Productivity analysis; *Forwarder*; Performance.

GESTÃO DA EXTRAÇÃO FLORESTAL COM O INDICADOR EFICIÊNCIA GLOBAL DE MÁQUINAS FLORESTAIS (EGMF)

RESUMO – Os indicadores de desempenho são ferramentas capazes de expor características mensuráveis e gerar informações relevantes das operações florestais, sendo considerados pilares para uma tomada de decisão ágil e assertiva por parte dos gestores. A extração florestal com ***forwarder*** *deve ser aperfeiçoada, compreendendo os fatores que afetam os custos desta máquina, como produtividade (TP), consumo de combustível (TC), eficiência operacional (EO) e qualidade da operação. Dessa forma, o objetivo estudo foi avaliar a implementação do indicador Eficiência Global de Máquinas Florestais (EGMF) na gestão dos dados da extração florestal com uso de* ***forwarders****. Os dados foram coletados durante a extração florestal de cinco frotas em operação, em plantios comerciais de Eucalipto, em regimes de alto fuste e talhadia, nos estados da Bahia e Espírito Santo. O indicador foi expresso em percentual, calculado por: EGMF = ((4*TP)+(3*TC)+(3*EO))/10. O desempenho das máquinas foi avaliado com um modelo estocástico de simulação dinâmica de sistemas em oito cenários, propondo melhorias no volume médio individual colhido, consumo de combustível e paradas mecânicas ou operacionais. As análises foram realizadas com o software PowerSim Studio 9. O EGMF de duas das cinco frotas estudadas foi maior que a meta estabelecida de 95,17%, com 95,72% e 97,44%, respectivamente.*

O indicador EGMF se mostrou útil na gestão da extração florestal com informações adequadas e de fácil entendimento a partir de uma grande quantidade e variedade de dados. O modelo de simulação estocástico foi eficiente para estudar o impacto na eficiência global (EGMF) e no fluxo de extração de madeira pelo ***forwarder****.*

Palavras-Chave: Análise de produtividade; ***Forwarder****; Performance.*

1. INTRODUCTION

The forestry sector has a prominent position in the Brazilian economy, with more than 9 million hectares of commercial forest plantations and expressive numbers in the economy, representing approximately 1.0% of GDP, tying high productivity, incorporated technology, and good forest management practices (IBÁ, 2021). The sector aims to grow more by investing in new operations, planting areas, new products, and improvements in the processes of the wood production chain.

Among these processes, forest harvesting stands out, which can be defined as a set of operations that aim to prepare and extract the wood to the transport location using established techniques and standards, to transform it into the final product (Cassiano et al., 2021). Forest harvesting is an expensive, complex activity, subject to several variables, which affect the productivity of the machines used, and, consequently, operating costs (Santos et al., 2017; Shadbahr et al., 2021), which turns fundamental planning essential to improve this stage in operational and economic terms (Gomes et al., 2021).

In Brazil, the cut-to-length system is the most used in harvesting the Eucalyptus for the pulp industry (Camargo et al., 2021). In this system, the tree is processed at the harvest site by the harvester and extracted to the roadside by the forwarder (Bont et al., 2022). Forest harvesting with a forwarder must be improved to understand the factors that affect the productivity and costs of this machine. The costs for forest harvesting operations are high, accounting for a significant part of the sector's budget. Thus, it is necessary to constantly evaluate the performance and quality of operations.

Performance indicators are developed in this sense, which are tools capable of exposing measurable characteristics of forest harvesting operations. To continuously monitor and track the effectiveness of operations, the Overall Equipment Effectiveness (OEE) indicator is one of the best measurement techniques (Settanni et al., 2021). This indicator has a simple and direct form and can say how effectively the equipment has been used, comparing it to the amount that the equipment can produce (Dobra and Josvai, 2021), based on data on fuel consumption, productivity, and quality of operation

There is a need for company managers to prepare themselves with tools and methodologies to generate valuable information from the large amount and variety of data that are generated (Singh et al., 2021). This information is a pillar for a more agile and assertive decision making, guaranteeing a shorter response time to positive or negative variations in the process. Thus, the objective of this study was to evaluate the implementation of the Overall Efficiency of Forest Machines (OEFM) indicator, created based on the OEE, in the management of forest extraction data using forwarders and to simulate improvements and recommend the refinement of the quality control of this operation.

2. MATERIALS AND METHODS

2.1. Characterization of the study area

Data were collected during forest extraction operations with a forwarder in commercial Eucalyptus plantations in high bole and coppice regimes located in Bahia and Espírito Santo, Brazil. The spacing of the plantations was 3 x 2 m, with a density of 1,667 plants ha^{-1}, individual mean volume (IMV) between 0.020 m^3 $plant^{-1}$ and 0.204 m^3 $plant^{-1}$, according to the reality of each location. The logs extracted varied between 3.0 and 6.6 meters. The predominant soil type in the region is the Red-Yellow Latosol, and the relief is flat (up to 25° of slope) to soft-wavy (over 25° of slope). The characteristic climate of the region is the super-humid tropical hot (Af, Am and Aw types, according to Köppen), with an average annual temperature of 24.4°C. The average annual rainfall in the region is 1,054.9 mm.

2.2. Characterization of the evaluated fleets and machines

This study analyzed five different operating fleets, which worked in 3 shifts, two at Espírito Santo

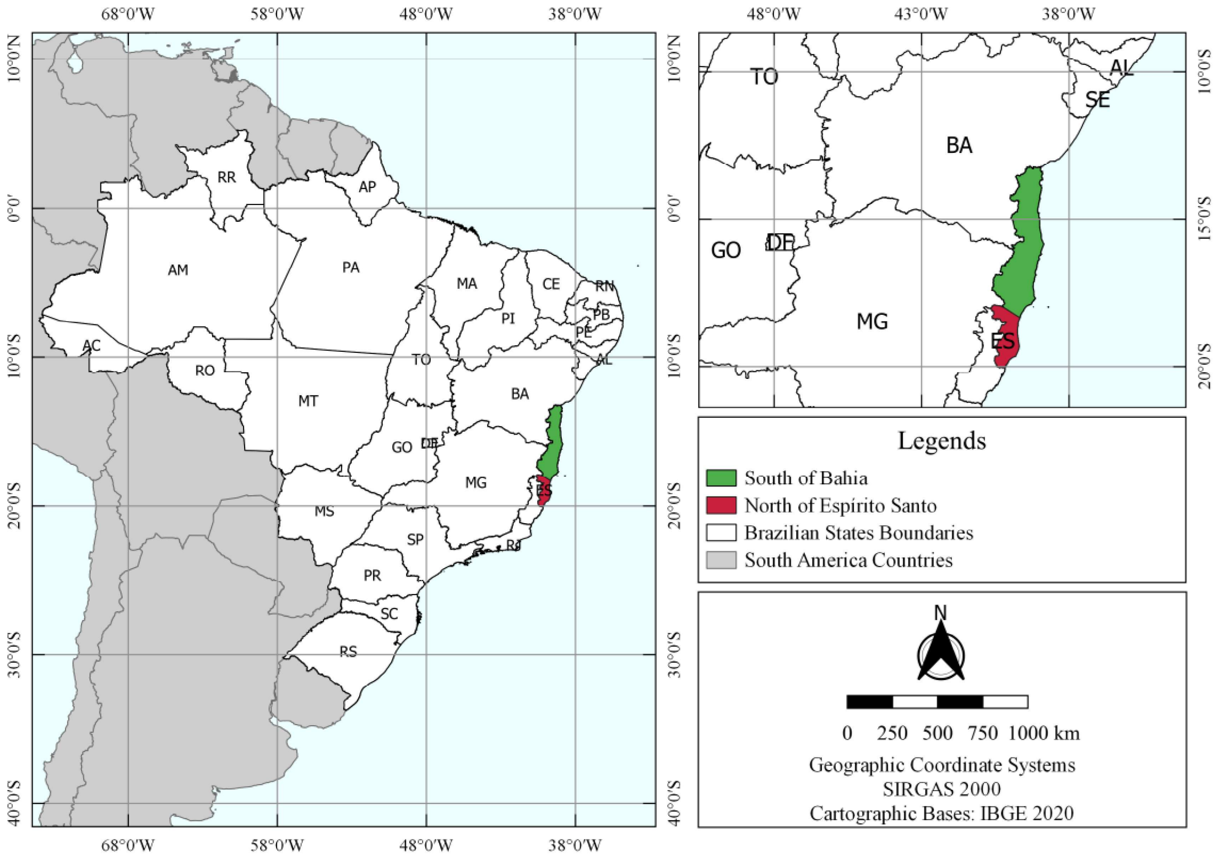

Figure 1 – Location of data collection areas in northern Espírito Santo and southern Bahia.
Figura 1 *– Localização das áreas de coleta de dados para o estudo, no norte do Espírito Santo e sul da Bahia.*

and three at Bahia. All operators had the same level of training and knowledge of the operation after reaching the level of learning required by the company for the position. The amount of 5 machines per fleet was considered in this study, being Komatsu brand forwarders, model 890.3, with 6x6 traction, 74 CTA Tier 3 engine, and power of 204 HP. The machines analyzed had the highest number of hours operated at the end of the research, up to the maximum limit of two years of use.

2.3. Data Collection and Analysis

Data were collected and registered as follows: operation productivity, reported by the machine's onboard computer; mechanical and operational stops, informed by the operators through the timing on the machine's onboard computer; quality of the operation, outsourced company on the first level and supervisors of the operation on the second level. Data analysis was performed Microsoft Excel Microsoft Power BI software.

Operating productivity was determined according to the following equation:

$$\text{Op. Prod.} = (\text{Nl} * \text{IMV})/\text{Eh} \qquad \text{Eq. 1}$$

In which: Op. Prod. = operation productivity (m^3s/c/h); Nl = number of logs processed (ud); IMV = individual volume per individual (m^3/tree.); Eh = effective working hours, without interruptions.

The productivity rate (PR) was based on actual versus planned productivity, according to the following equation:

$$\text{PR (\%)} = (\text{Op. Prod./Plan. Prod.}) * 100 \qquad \text{Eq. 2}$$

In which: PR (%) = productivity rate; Op. Prod. = operation productivity (m^3s/c/h); Plan. Prod. =

planned productivity according to IMV values (m^3s/c/h).

The fuel consumption calculation considered the volume of fuel (diesel oil) placed in the tank of the machines. The supply information was provided by the operation manager daily. The hourly consumption of each machine was calculated according to the following equation:

Hour. Cons.= (Adep./Eh) Eq. 3

In which: Hour. Cons. = hourly diesel fuel consumption (l/h); A_{dep}. = amount of fuel deposited in the equipment (liters); Eh = effective working hours from the fuel depot.

The fuel consumption rate was calculated according to the following equation:

FC (%)= (Hour. Cons./Plan. Cons.) * 100 Eq. 4

In which: FC = consumption rate in relation to the stipulated target (%); Hour. Cons. = hourly diesel fuel consumption (l/h); Plan. Cons. = planned hourly consumption of diesel oil, being 20 l/h the company's goal (l/h).

Operational efficiency was based on the percentage of time of activities that effectively resulted in production, disregarding mechanical and operational stops, according to the following equation:

OE (%)= 1 - (Hm + Ho/Ht) * 100 Eq. 5

In which: OE = operational efficiency (%); Hm = downtime for maintenance and repairs (hours); Ho = time in operational downtime (hours); Ht = time worked (hours).

The quality of the operation is another crucial parameter in the evaluation of the forwarder's performance (Jacovine et al., 2005), with the evaluation of the following variables: load occupancy rate, wood remaining in the stands, formation of the base of the piles ("mattress"), disposition of the logs in the piles ("mirroring"). Adapted from the OEE - Overall Equipment Effectiveness indicator (Settanni et al., 2021), the value of the OEFM indicator was calculated according to the following equation:

OEFM (%) = (4 * PR (%) + 3* FC (%) + 3* OE (%))/10 Eq. 6

In which: OEFM = Overall efficiency of forest machines; operation productivity (PR), fuel consumption (FC), and operational efficiency (OE). The weighted average of the variables was used because the productivity of the operation has a greater impact on the process regarding the demand of the factory and the costs involved.

The performance of forwarders concerning the volume extracted from wood, with proposed improvements to the individual mean volume (IMV), fuel consumption, mechanical stops, and operational stops, was evaluated through a stochastic model to simulate the dynamics of the systems – Mathematical Formulation of Stock and Flow. This model presented several random input variables, leading to outputs considered as quantitative estimates related to the volume of wood extracted. The following scenarios were evaluated: Scenario 1 – Low IMV (0.020 – 0.081 m^3/ind.); Scenario 2 – Medium IMV (0.082 – 0.143 m^3/ind.); Scenario 3 – High IMV (0.144 – 0.204 m^3/ind.); Scenario 4 – Medium IMV, 5% decrease in fuel consumption, 10% decrease in corrective maintenance period, 10% decrease in machine inspection period; Scenario 5 – Medium IMV, 3% decrease in fuel consumption, 10% decrease in corrective maintenance period, 20% decrease in machine inspection period; Scenario 6 – Medium IMV, 5% decrease in fuel consumption; Scenario 7 – Medium IMV, 20% decrease in corrective maintenance period; Scenario 8 – Medium IMV, 20% decrease in machine

Table 1 – Total time (TT in hours), maintenance (MAIN in hours), operational downtime (OD in hours), mealtime (MT in hours), operational efficiency (OE in %), operational efficiency target (Goal OE in %).
Tabela 1 *– Tempo total (TT em horas), manutenção (MAN em horas), paradas operacionais (OP em horas), tempo em refeição (TR em horas), eficiência operacional (EO em %), meta de eficiência operacional (Meta EO em %).*

Fleet	TT	MAIN	OD	MT	OE	Goal OE
01	21,309.2	1,630.1	1,301.9	1,551.6	86.2	83.9
02	18,164.5	2,275.5	1,205.9	1,535.8	80.8	83.9
03	18,971.8	1,918.3	1,045.9	1,287.8	84.4	83.9
04	17,125.9	1,634.1	985.4	1,115.8	84.7	83.9
05	7,390.7	415.0	290.5	361.6	90.5	83.9
Average	8,2962.2	7,873.0	4,829.6	5,852.7	84.7	83.9

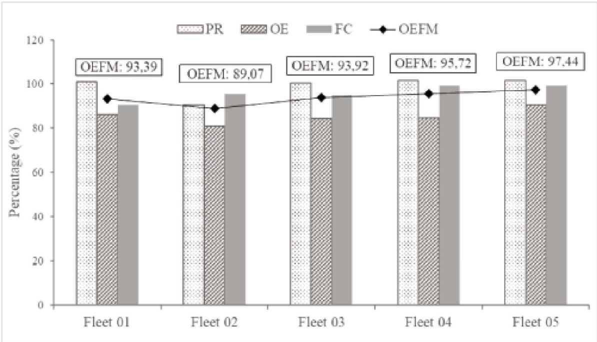

Figure 2 – Productivity (PR in %), operational efficiency (OE in %), fuel consumption (FC in %), and overall efficiency of forest machines (OEFM in %) of the analyzed fleets.
Figura 2 – *Produtividade (TP em %), eficiência operacional (EO em %), consumo de combustível (TC em %) e eficiência global de máquinas florestais (EGMF em %) das frotas analisadas.*

inspection period. The analysis of these scenarios was performed with the software PowerSim Studio 9, a robust software package used in this type of analysis (Kumar, 2014; Gunal, 2012).

3. RESULTS

The productivity of four of the five fleets in operation was higher than the target, with fleets 04 and 05 exceeding the planned productivity rate by 1,4% and 02 not reaching the target. The operational efficiency of four fleets was higher than the established target (83.9%), and fleet 02 obtained a result lower than the target (Table 1) due to the longer time spent on corrective, preventive maintenance, inspection, and transport of the machine.

Fuel consumption (diesel oil) was not satisfactory in any of the analyzed fleets, all above the stipulated target of 20 l/h. Regarding the operation quality parameters, deviations were observed in all analyzed variables. The following were found: logs of wood inside the stands, piles of wood without a formed base, and logs arranged in non-compliance with the recommendations, in addition to loaded forwarders, without maximum occupancy of the compartment. Any situation in which the percentage of non-compliance with the quality parameters of the operation was higher than the targets established in the company’s operating procedures, which varied between 90-95% of compliance, was considered a deviation. A more rigorous evaluation of the influence of these variables on the forwarder’s performance and costs in forest extraction is recommended.

The OEFM of fleets 04 and 05 were above the target (94.0%), with 95.72 and 97.44%, respectively (Figure 2).

The Overall Efficiency of Forest Machines (OEFM) and the annual wood production (deficient in 663,085.02 m³) were lower in scenario 1, working in areas with low IMV (Table 2). On the contrary, the efficiency of the operation and annual extraction of wood (surplus of 5,786,496.23 m³) were higher in areas with higher individual mean volume (IMV)

Table 2 – Overall Efficiency of Forestry Machines (OEFM in %) of the analyzed fleets and annual wood extraction (Wood Ext. in m³) in eight scenarios (Cen.).
Tabela 2 –*Eficiência Global de Máquinas Florestais (EGMF em %) das frotas analisadas e extração anual de madeira (Ext. Mad. em m³) em oito cenários (Cen.).*

Scen.	Fleet 1	Fleet 2	Fleet 3	Fleet 4	Flet 5	Wood Ext.
1	70.81	76.56	68.05	73.33	72.17	- 663,085.02
2	92.66	105.66	82.45	95.64	94.07	2,561,705.61
3	114.51	134.76	96.85	117.95	115.97	5,786,496.23
4	94.49	107.43	81.61	97.33	95.83	2,695,856.37
5	93.82	106.81	81.00	96.71	95.16	2,659,856.37
6	94.30	107.22	83.45	97.15	95.71	2,561,705.61
7	92.66	105.66	82.45	95.64	94.07	2,679,170.88
8	93.03	106.06	82.78	95.98	94.30	2,639,716.57

Scenario 1 – Low IMV (0,020 – 0,081 m³/ind.); Scenario 2 – Medium IMV (0,082 – 0,143 m³/ind.); Scenario 3 – High IMV (0,144 – 0,204 m³/ind.); Scenario 4 – Medium IMV, 5% decrease in fuel consumption, 10% decrease in corrective maintenance period, 10% decrease in machine inspection period; Scenario 5 – Medium IMV, 3% decrease in fuel consumption, 10% decrease in corrective maintenance period, 20% decrease in machine inspection period; Scenario 6 – Medium IMV, 5% decrease in fuel consumption; Scenario 7 – Medium IMV, 20% decrease in corrective maintenance period; Scenario 8 – Medium IMV, 20% decrease in machine inspection period.
Cenário 1 – Baixo VMI (0,020 – 0,081 m³/ind.); Cenário 2 - Médio VMI (0,082 – 0,143 m³/ind.); Cenário 3 - Alto VMI (0,144 – 0,204 m³/ind.); Cenário 4 - Médio VMI, diminuição em 5% no consumo de combustível, em 10% do período de manutenção corretiva, em 10% do período de inspeção da máquina; Cenário 5 - Médio VMI, diminuição em 3% no consumo de combustível, em 10% do período de manutenção corretiva, em 20% do período de inspeção da máquina; Cenário 6 - Médio VMI, diminuição em 5% no consumo de combustível; Cenário 7 - Médio VMI, diminuição em 20% do período de manutenção corretiva; Cenário 8 - Médio VMI, diminuição em 20% do período de inspeção da máquina.

(scenario 3). In scenario 4, the efficiency of the operation and the annual volume of extracted wood increased (surplus of 2,695,865.37 m^3) (Table 2).

4. DISCUSSION

Fleet 02 has a productivity rate below the target due to the operation in inclined regions (above 25° of of inclination) for most of the year, which reduced its number of trips per hour. Carrying out forestry operations in mountain regions is difficult due to the lower accessibility, slope, and roughness (Enache et al. 2016), and these conditions require greater attention from operators in forest extraction (Leite et al. 2014). An alternative to increase productivity in these conditions would be to use the cable assistance system with a winch (Kuhmaier and Stampfer, 2010; Visser and Stampfer, 2015).

The lower time spent on operational stoppages explains the operational efficiency results of the four fleets above the target (01, 03, 04, and 05), and the unsatisfactory result of the 02 fleet is due to the higher time spent on corrective, preventive maintenance, inspection, and transport of the machine. The "maintenance" and "repair" components represent 30-60% of the average total cost of operating a forwarder (Simões et al. 2010; Leite et al. 2014), so training operators and maintenance staff in machine care are essential (Lopes et al., 2016).

Fuel consumption higher than expected is a concern because this variable represents 7 to 20% of the total cost of operating the forwarders (Oliveira, 2009; Robert et al., 2018). It shows that the machines are oversized and must be compatible with the expected productivity.

The arrangement of the piles affects the performance and costs of a forestry loader (Santos et al., 2008), so positioning the logs in the piles following the requirements is essential. The load compartment occupancy rate aims at more efficient planning by operators to get as close to the compartment's capacity as possible. This variable is necessary for the costs of forest extraction since the travel time loaded corresponds, on average, to 7.7% of the total operational cycle, depending on the extraction distance traveled by the machine (Oliveira, 2009). In other studies (Eriksson e Lindroos, 2014; Carmo et al., 2015; Proto et al., 2018), the authors mention that the productivity of forwarders with greater load capacity is crucial as it reduces the final cost of wood.

The OEFM of fleets 04 and 05 above the target can be explained mainly by the lower fuel consumption (FC) in relation to the other fleets. However, still below the established target. This result confirms the possibility of obtaining greater productivity combined with lower fuel consumption, that is, greater energy efficiency (Simões et al., 2010). Obtaining fuel consumption and energy efficiency is essential for evaluating the engine efficiency, which transforms the chemical energy of the fuel into useful work. The increase in the energy efficiency of forest harvesting machines is achieved through planning operations and technological innovations, mainly in areas sensitive to the operation (Lindros et al. 2017; Štěrbová et al. 2019).

The lower volume of wood extracted in scenario 1 confirms the influence of the individual mean volume (IMV) on the performance of the forwarders, with the smaller size of the trunks increasing the time in loading and unloading the cargo (Leite et al., 2014). The greater efficiency of the operation and the annual volume of wood extracted in areas with high individual mean volume (IMV) in scenario 3 would allow reducing the number of machines in operation to supply the wood demand of the mill (Carmo et al., 2015). This result confirms the individual mean volume as the factor that most impacts forwarder productivity and operating costs (Eriksson and Lindroos, 2014).

The higher operating efficiency and annual wood volume in Scenario 4 confirm the influence of fuel consumption (Oliveira, 2009) and corrective maintenance and machine inspection times on the forwarder performance (Simões et al., 2010; Leite et al., 2014).

5. CONCLUSIONS

The forwarder's overall logging efficiency is influenced by plantation productivity, fuel consumption, and operational efficiency.

Fuel consumption was the variable that most influenced the best OEFM performance of the evaluated fleets.

The disposition of logs, woodpiles without a formed base, and forwarders loaded without maximum occupancy are the principal sources of non-compliance concerning the quality of the operation.

The stochastic simulation model was efficient to study the impact on the overall efficiency (OEFM) and the flow of wood extraction by the forwarder.

The individual mean volume (IMV) of forest plantations directly influences the overall efficiency of forwarders in forest extraction.

The OEFM indicator proved to be useful in the management of forest extraction, with quick and easy-to-understand information. This indicator must be used in the individual management of the operators' performance, and deviations must be shown and minimized to improve the process.

AUTHOR CONTRIBUTIONS

Arthur A. Silva: data analyse and text writen, Carlos C. Machado: research superfision and text review, Raiane R. Machado: research superfision and text review, Bruno L. S. Schettini: text writen, Luciano J. Minette: technical review, Ítalo L. Nunes: text review, Paulo H. Villanova: text review

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