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ORIGINAL ARTICLE

Analysis of preventive maintenance strategy in off-road trucks

Análise de estratégia de manutenção preventiva sistemática em caminhões fora de estrada

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Abstract: Preventive maintenance is an important strategy to improve physical availability, reduce downtime and extend equipment life. In the context of mining, transport fleets are large equipment and are subject to unplanned events that, in turn, interrupt operation and lead to unavailability. Therefore, the objective of this work is to analyze the main causes that influence the throughput of performance indicators of truck maintenance, focusing on the measurement of impacts caused by inefficiency of preventive maintenance. Thus, the data of 118 trucks were collected in 2022 and the performance calculated. The fleet CAT® 797F was prioritized was not adherent to the programmed, resulting in a production loss of $5{,}086{,}957\ tons$ and, for maintenance, an unavailability was $9{,}722.88h$ and $3{,}870$ failures. Two evaluation requirements were proposed focusing on evaluating the notes and analyzing the adherence to the preventive. In summary, it was found that of the 783 scheduled preventive maintenance only 607 were performed and presented problems related to compliance with the guidelines. Finally, the inefficiency of the preventive ones generated an increase of more than 819 failures and an impact in the availability of 8.16%.

Keywords: Reliability; Productive performance; Management maintenance; Mining processes.

Resumo: A manutenção preventiva é uma estratégia importante para melhorar a disponibilidade física, reduzir o tempo de inatividade e prolongar a vida útil dos equipamentos. No contexto de mineração, as frotas de transporte são equipamentos de grande porte e estão sujeitos a eventos não planejados que, por sua vez, interrompem o funcionamento e acarreta a indisponibilidade. Isto posto, o objetivo deste trabalho é analisar as principais causas que influenciam no desempenho dos indicadores de performance da manutenção dos caminhões, em particular, com foco na mensuração dos impactos causados pela ineficiência da manutenção preventiva. Desta forma, os dados de 118 caminhões foram coletados em 2022 e a performance calculada. A frota CAT® 797F, priorizada, não foi aderente em relação ao programado, acarretando numa perda produtiva de $5.086.957$ toneladas e, para a manutenção, numa indisponibilidade foi $9.722{,}88h$ e 3.870 falhas. Dois requisitos de avaliação foram propostos com foco em avaliar os apontamentos e analisar a aderência à preventiva. Em síntese, foi constado que das 783 manutenções preventivas programadas apenas 607 foram executadas além de apresentarem problemas relacionados ao cumprimento das pautas. Por fim, a ineficiência das preventivas gerou um aumento de mais de 819 falhas e um impacto na disponibilidade de $8{,}16\%$.

Palavras-chave: Confiabilidade; Desempenho produtivo; Gestão da manutenção; Processos de mineração.

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1 Introdution

For a long time, companies have focused their attention on the ability to design products that incorporate optimized features and attributes, to meet the needs and desires of customers (Corrêa & Corrêa, 2012). However, according to Fernandes et al. (2021), with a view to the production process in the mining industry, product quality is related to the content of the ore exploited, making increased production and cost reduction one of the main strategic objectives. Thus, the set of excellencies in each process represents the quality of the organization and this is the main goal of the mining companies (Fernandes et al., 2023b; Gackowiec et al., 2020).

In the Brazilian context, mineral reserve exploration, mainly of iron ore, is predominantly performed by the open pit mining method and involves activities of prospecting, exploration, development and exploitation and, after the removal of the ore, this is transported to the primary crusher in which the beneficiation step begins (Carvalho et al., 2014; Luz & Lins, 2018; Rocha et al., 2021)

Exploration activities begin with the preparation of the area to be mined so that it can be drilled and detonated. Then the excavation and loading are done by loading equipment that are allocated in front of the mine. These remove the material and load it in transport equipment, trucks, conveyor belts, wagons, among others. The transport equipment takes the material to a certain point of discharge, which may be crushers, sterile cell, or lung cell, where the operation cycle resumes (Fernandes et al., 2023a; Osanloo & Paricheh, 2020; Osanloo & Paricheh, 2020)

The company under study, is a large mining company located in southeastern Pará in which it establishes, as a responsibility for the Reliability Engineering team, identify and manage risks associated with its critical assets, classified as well as those that may cause a material unwanted event (MUE) (ICMM, 2015). In this way, an incident is an unplanned event or an occurrence that results in damage or other loss (ABNT, 2014) and, in turn, the failure is an incident that interrupts the operation and leads to the unavailability of the equipment (ABNT, 1994).

In this sense, asset management should guide the way organizations seek excellent operational performance, efficiently integrating Operational Planning and Control (OPC) and Maintenance Planning and Control (MPC) (Pascual et al., 2016; Qiao et al., 2017).

In the scope of process management, the primary function of the operation is to ensure the realization of management plans without impacting the goals of production plans (Slack et al., 2013). Otherwise, the operation plays a crucial role in achieving production results, and a failure can directly impact the expected results. Therefore, ensuring the reliability of physical assets, managing risks and minimizing failures are integrated activities between OPC and MPC (Zampolli, 2019).

In addition, to play a strategic role, maintenance needs to be aligned with the organization's business results, mainly by ensuring the availability of equipment for operation, reducing the likelihood of unplanned production shutdowns, minimizing the need for Corrective Maintenance (CM), and prioritizing Preventive Maintenance (PM).

Preventive maintenance is an important strategy to improve the Physical Availability (PA) of a system or equipment, reduce downtime and extend the life of the equipment. However, although this type of maintenance is an important tactic to reduce the frequency of system failures, there may be cases where PM may interfere or impair equipment availability, where the maintenance runtime is longer than the planned time in the prevention plan.

The implementation of an optimal maintenance policy, optimal in the sense of reducing the total expected cost of maintenance, is a problem that has been addressed by several authors and is based on systems that operate under a maintenance strategy, in which PM are performed in predetermined and CM in the occurrence of failures between PM. (Doyen & Gaudoin, 2004; Gilardoni & Colosimo, 2007; Toledo et al., 2016).

A second approach is that the planning of PM does not necessarily imply deterministic times, that is, the periodicity of PM can be changed due to a Reliability-Centered Maintenance plan (RCM) or by adopting a maintenance policy with a dynamic approach (Gilardoni et al., 2016). If the analysis concludes that the system is not sufficiently reliable, the periodicity of the PM, fixed before the initial operating time, shall be reduced (Doyen & Gaudoin, 2011).

It happens that preventive maintenance often seen as periodic and deterministic, can be understood as random, because there are changes in the system not known or not controlled. Thus, it is important to investigate this problem, and for the purposes of this work, the objective is to analyze the main causes that influence the performance of performance indicators of truck maintenance, focusing on measuring the impacts caused by the preventive maintenance strategy adopted in the off-road trucks in the company under study.

In this context, this work formalizes the objective in four research questions **(RQs)**:

RQ_1: How adherent is preventive maintenance in relation to the expected quantities and times predetermined maintenance schedules?

RQ_2: How many failures can occur due to lack of adherence to preventive maintenance?

RQ_3: What is the impact factor of preventive maintenance?

RQ_4: What is the total impact on the physical availability of the system or equipment?

This work is divided as follows: in section 2, the description of the loading and transport process cycle is presented, as well as the key performance indicators used in the context of mining and its supporting elements. In section 3, the moderate factors of maintenance are described, addressing the main concepts and indicators related to maintenance, in addition to presenting a proposal for new analysis indicators. Section 4 presents the materials, fleet information, and data used to analyze the results. The results and discussions, on the other hand, are presented in section 5. Finally, section 6 presents the conclusions of this work.

2 Operational performance measurement in mining

2.1 Cycle of loading and transport processes

The cycle of loading and transportation processes, belonging to the mining stage in the mining, occurs only when the truck is in “ready for operation” status in which the analysis metrics and own indicators are established for process optimization. Figure 1 shows that the cycle begins in the direction of the truck, which runs empty to the loading point (ETT – Empty Travel Time), waits in the load queue (QTL – Queue Time to Load), and performs the maneuver (STL – Spotting Time to Load) for loading by the excavator (LT – Loading Time). With the truck full, transport occurs (FTT – Full Travel Time), waits in line for tipping (QTT – Queue Time for Tipping) and finally tipping (TT – Tipping Time). For a single work shift of the operation, a certain number of cycles (NC) is performed.

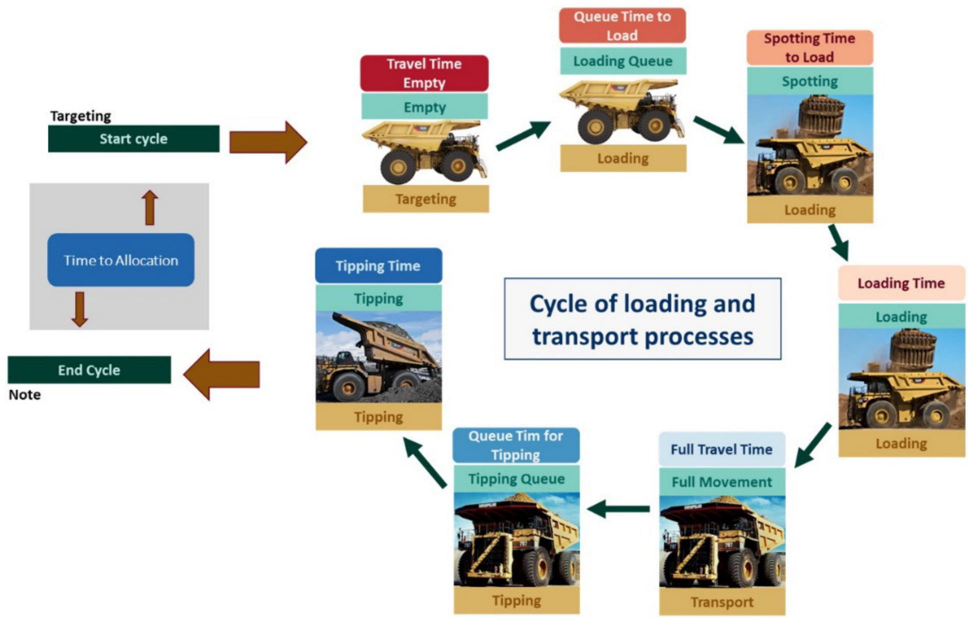


Figure 1. Cycle of loading and transportation processes.

2.2 Equipament status

As the measurement is made based on time durations, the notes are performed whenever the truck changes its operating status, these, which are subdivided into 4 classes: ready for operation, released by maintenance, maintenance, or operational shutdown.

These classes, exercise an important direction of responsibilities for monitoring key performance indicators (KPI) and have different operational problems. For example, when the truck is:

- **Ready for operation:** the operating team is responsible and focused on the cycle of loading and transport processes. Its main challenge lies in the selection and sizing of equipment. According to Mohtasham et al. (2021), this is related to the selection and proper dimensioning of loading and transport equipment to perform the material handling task optimally during the operation of the mine and resulting in improved productivity indicator.
- **Released by maintenance:** this status is at the moment immediately following the execution of the maintenance and consists of the transition of responsibility for the maintenance team to the operating team. A Service Level Agreement (SLA) between teams must be pre-established for an efficient transition.
- **In maintenance:** this is an activity of responsibility of the maintenance team and includes functions and processes of planning, inspection, programming, and reliability.
- **Operational shutdown:** Large shutdowns are planned and managed considering the necessary contingencies. Despite belonging to the operation team, planning is carried out by management and considering the entire production chain.

2.3 Supporting elements

Support elements are data directly monitored and collected during production (Kang et al., 2016). In the cycle of transport processes, the data collected in trucks, off-road are obtained from the hour meters installed in the measurement system and called operating times. From there, these are pointed out in the database in categories of hours, which are: effective hours (EFH), operational delay hours (ODH), diverse worked hours (DWH), infrastructure worked hours (IWH), internal idle hours (IIH), external idle hours (EHH), corrective maintenance hours (CMH), accident hours (ACH), systematic preventive hours (SPH), and non-systematic preventive hours (NSPH). We will name these elements first level time elements.

For the calculation of indicators, it is common to carry out the synthesis of some categories of hours or, in another way, the addition of hours. Thus, the second level time elements are: total corrective maintenance hours $(TCMH = CMH + ACH)$; preventive maintenance hours $(PMH = SPH + NSPH)$; non-productive worked hours $(NPWH = IWH + DWH)$; idle hours $(IH = IIH + EIH)$ and productive worked hours $(PWH = EFH + ODH)$. Finally, for the third level we have: worked hours $(WH = PWH + NPWH)$; maintenance hours $(MH = TCMH + PMH)$ and IH. At all levels the sum of the categories represents the calendar hours (CH), e.g., we have $(CH = WH + MH + IH)$ for the third level.

2.4 Key performance Indicators

Thus, when grouping the categories of hours in day, week, a month or a year, the nominal value will be given by the sum of the duration of all notes, whose ratio is configured to account for this category. As the main product of the transport cycle is the transported mass (TM), this is configured as a quantitative element.

KPI are derived from measurement elements, so as one element can be used in the definitions of multiple KPI, they are unlikely to be independent of each other. According to Kang et al. (2016), there are two basic types of relationship, the first given by the identity relationship of the KPI, based on their definitions and the other is relevance with shared support elements that can be obtained by peer comparison and/or tiered groupings.

Each KPI reveals a performance aspect for a work unit or system, derived from data monitored from support elements. KPI can be grouped by those representing a group of aspects with similar attributes.

Figure 2 presents an example of the equipment status relationships and support elements, taken from the data under study. Contrary to the theoretical analysis of relations, it is possible to observe other connections with the categories of hours, which represent the second basic type of relationship.

The Physical Availability (PA) indicates the ability of a system to be able to perform a certain function, and its unavailability is due to maintenance hours (MH), that is, the indicator points to improvement opportunities related to maintenance, and associated with the status of in maintenance.

Differently, the Physical Utilization rate (PU) takes into account operational aspects, over which the maintenance team has no influence, that is, indicates how much availability hours (AH) is effectively used for operation (WH – worked hours) therefore, the unused time for operation corresponds to the idleness of the equipment (IH – idle hours). In this way, idleness occurs when the equipment is released by maintenance or operational shutdown.

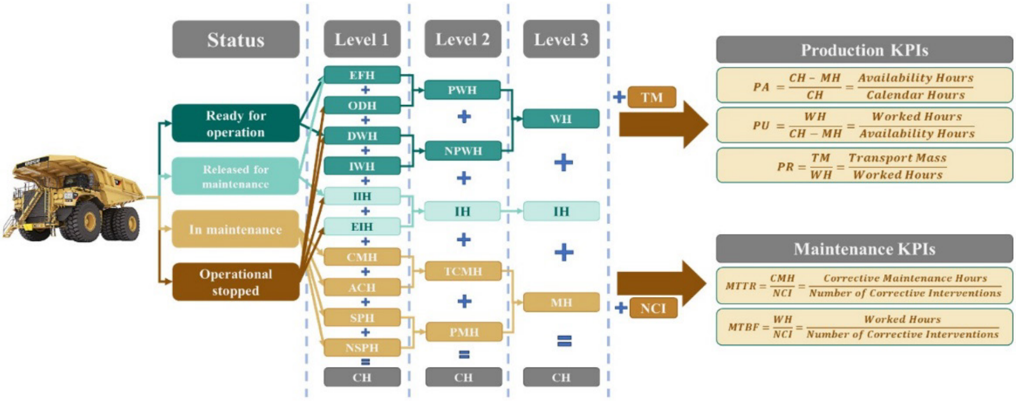


Figure 2. Relationship note's status and category of hours.

The worked hours (WH) are the result of improvement actions in other indicators and used to calculate both PU and the Productivity (PR) indicator, the latter given by the result of the total transported mass (TM) divided by worked hours (WH). Therefore, PR points in the cycle of loading and transport processes and is associated with the ready for operation Finally, for the case where a production system does not meet the production targets, it is still possible to calculate the loss of production by performance indicators, checking the representativeness in tons for each indicator. The production loss calculation equations for each indicator are described (Equations 1 to 3):

$$PP_{PA} = \left(AH_{programmed} - AH_{performance}\right) \times PR_{performance} \tag{1}$$

$$PP_{PU} = \left(IH_{performance} - IH_{programmed}\right) \times PR_{programmed} \tag{2}$$

$$PP_{PR} = \left(PR_{programmed} - PR_{performance}\right) \times WH_{programmed} \tag{3}$$

3. Moderate maintenance factors

3.1 Maintenance management

According to the definition of Kardec & Nascif (2009), maintenance comprises all technical, management and administrative activities aimed at maintaining or restoring an asset to its operational state, so that it can properly serve its functions throughout its life cycle. Specifically, the mission of maintenance is to ensure the availability of assets so that the production plan is fulfilled, safely, preserving the environment and adequate costs, avoiding that failures can interrupt the production process and generate losses (Kardec & Nascif, 2009; Zampolli, 2019).

Maintenance management establishes goals and objectives through standards and work procedures, in order to obtain a better use of available resources, whether these personnel, equipment or materials (Oliveira, 2016). For companies that are willing to seek international standards of maintenance performance (World Class Maintenance), it is essential to identify and manage the risks to its activities through the model of lines of defense, avoiding or mitigating any potential impact throughout the organization (Bokrantz et al., 2020).

Otherwise, the functions maintain and operate must have reliability structure, establish service level agreement with fleet prioritization rules for setting and monitoring goals, define criteria for systemic treatment of repetitive failures through statistical studies, and define systematically for analysis of effectiveness of reliability works. Finding the optimal maintenance strategies to be applied in the production process, and its subprocesses, is the basis of the maintenance policy (Xenos, 2014).

According to Blanchard & Fabrycky (1998), reliability is defined as the probability of a system or product functioning satisfactorily over a given period, provided that it is used within the specific operating conditions. Thus, we have that a system is any part, component, device, subsystem, functional unit, equipment or item that can be considered individually (ABNT, 1994).

Failure is the term used to describe the situation where an item is no longer able to perform the required function, which leads to unavailability of the equipment (ABNT, 1994).

The occurrence of failures over time falls within a more general scope known as recurring events. Recurring event processes are those that generate events repeatedly over time and, for a repairable system, the occurrence of events (in case of failures) contains information about how a system ages over time.

Assumptions regarding how a system ages, and how it is affected by a failure and repair, will guide the choice of model for a repairable system and, consequently, the maintenance policy (Rigdon & Basu, 2000). In general, interventions made in a repairable system in order to correct or avoid the occurrence of failures can be classified into two types: corrective maintenance (CM) and preventive maintenance (PM).

The first aims to return the system to the operating condition after a failure and is adopted in the event that the failures affect the primary or secondary function of the system. It is noteworthy that corrective maintenance is characterized by an occurrence of unexpected failure, to which it is necessary to intervene in the system with a repair action.

The second is a shutdown to improve the condition of the system. Preventive maintenance results from planning, which takes into account the reduction of the system where to reduce the frequency of failures in the system.

3.2 Recurrent event data analysis

Suppose a new industrial equipment is installed in a factory. After its installation and initial testing, the equipment is then put into operation to carry out the activities to which it was proposed. Then, the start time of the operation is characterized by $T_0 = 0$. After a period in operation, the equipment fails of T_1 time and its operation are stopped. The elapsed time of operation is given by $X_1 = T_1 - T_0$.

In order for the equipment to return to operation, a maintenance (or repair) intervention is performed with R_1 duration and thus restarts the operation count after the time T_{1^+}. Another failure occurs at the time T_2 to which a repair is again performed and, similarly, the operating time is $X_2 = T_2 - T_1$, and the repair time is R_2. This occurs successively over a long period τ, where a predetermined maintenance is performed. Figure 3 illustrates the process of operating industrial equipment.

In this way, we can characterize a repairable system as one in which, once the failure has occurred, it can be restored to an operating condition through some repair operation, without the need to replace the system as a whole.

Note that over time a failure history is generated, which leads us to the modeling and analysis of fault data in repairable systems. The theme is of paramount importance in the study of the reliability of specific systems, especially regarding the operation of industrial plants. In this sense, we have that the occurrence of unforeseen stops in the production line, decreases the availability of equipment, translating in many cases in a financial imbalance for the company.

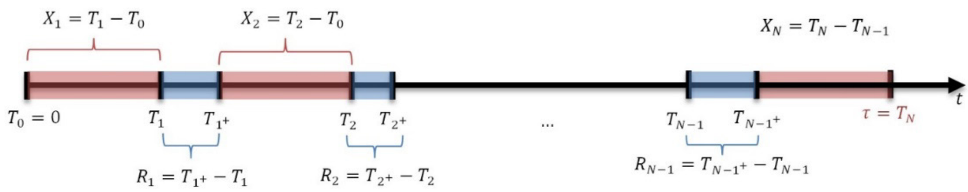


Figure 3. Illustrative graphic to represent the times in the operation and maintenance of a system.

A recurring event, also known as a counting process, is then a stochastic model of a physical phenomenon characterized by events randomly distributed over time. The scale used to characterize event distributions is in units of time, but other scales can be used. For example, the number of defects per fabric length, number of kilometers driven by a car or number of operating cycles performed by a machine.

Figure 4 presents the illustrative process of an operation and maintenance of a repairable system. Note that after the start of operation in $T_0 = 0$, as a result of a period X_1 An unexpected failure occurs and that in turn a corrective maintenance intervention is necessary. At this moment, the process of counting the failures begins, being $N(T_1) = 1$ the occurrence of the first failure at time T_1. Therefore, the time required to repair this fault is R_1 and, immediately after the repair, the equipment returns to operate in T_{1^+} and indicates that at this time there was a corrective intervention, that is, the number of corrective interventions before T_{1^+} is $NCI(t \leq T_{1^+}) = 1$.

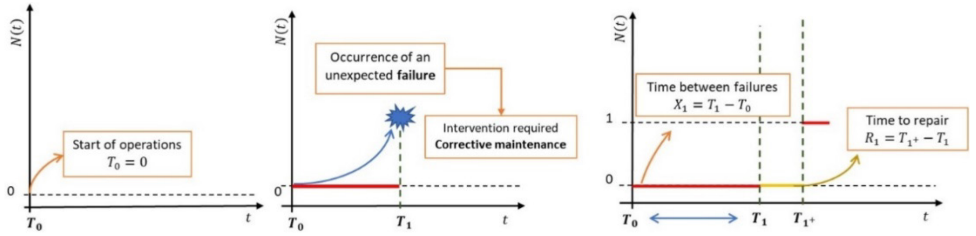


Figure 4. Dynamics illustrating the occurrence of failure and maintenance intervention in a repairable system (Medeiros et al., 2022).

For a single recurring event, process, or failure and repair process, we introduce the following notations:

- $\{T_i\}$, time to failure, or corrective maintenance start times $0 = T_0 < T_1 < T_2 < \cdots < \tau$, were τ corresponds to the truncation time by time. For failure truncation, you have to $\tau = T_N$ is the last time of failure.
- $\{X_i\}$, times between failures $X_i = T_i - T_{i-1}$ e $i = (1, 2, 3 \ldots)$ in which the repair time is disregarded. In other words, X_i is the time of the system in operation.
- $\{R_i\}$, times to repair, or time taken to maintain a piece of equipment after a failure occurs.

• $N = \{N_t\}_{t \geq 0}$, the associated counting process that records the cumulative number of failures.

When considering the times $\{T_i\}$ of failures that occur in an operating system, we have the count of the failures $\{N_t\}$ up to a certain time $\tau = T_N$. We can represent every possible result of this system through the step function as illustrated in Figure 5. In this context, we are interested in the operating time of the equipment in which it is subject to wear over time, being possible that the repair time is neglected.

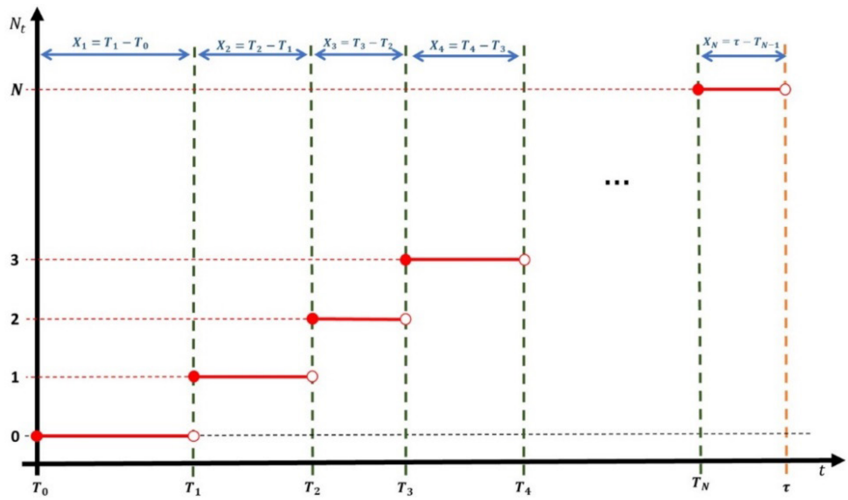


Figure 5. Illustrative process for the counting process.

3.3 Periodic preventive maintenance policy

3.3.1 Availability and maintainability

According to the ABNT (1994, p. 2), availability is:

> The ability of a system to be able to perform a certain function at a given time or during a given time interval, taking into account the combined aspects of its reliability, maintainability, and maintenance support, assuming required external resources are ensured.

From this definition, it is observed that the ability of an equipment to be put back into operation (Maintainability) and the performance of maintenance support, directly impact on physical availability. Thus, when maintenance is done under established conditions and using prescribed procedures and resources, then the execution time is controlled and within the given time interval, with little impact on physical availability.

In addition, the activities are subdivided into sectors and between technicians, in order to generate balance in the workload of the team and optimization of activities. The level of intervention depends on the complexity of the equipment, the accessibility of the sub-stages, the competence of the maintenance personnel, the resources in testing equipment, safety considerations and others.

Therefore, a maintenance policy (or strategy) will determine the guidelines for systematic preventive maintenance (SPM), which are repeated periodically at previously defined intervals, without a prior indication of any failure. The content of the guidelines is associated with the 5W2H quality tool, denomination given according to the initial letters of some questions in English, being them What, Where, Who, Why, When, How, How Much (Ishikawa, 1985).

In particular, the expression "systematic" indicates that, in the construction of the SPM guidelines in a given time, the activities allow to evaluate their costs and determine the resources necessary for the completion of each of their tasks. The measurement of activity performance is relative between elapsed time and degree of completion.

3.3.2 Reliability and optimal periodic

In the literature, the general objective has been to determine the optimal preventive maintenance (PM) policy, that is, the ideal periodicity for preventive interventions to avoid the occurrence of failures. Barlow & Hunter (1960), introduced the notion of establishing a policy of periodic replacement with interventions in the event of failures, Nakagawa (1989) Derived the first optimal preventive maintenance policy that maximizes availability and Barlow & Proschan (1987), They have defined an optimal maintenance policy that minimizes total cost, and maximizes availability based on an objective function of expected cost per unit of time.

Gilardoni & Colosimo (2007), presented a study in which the systems operated under a maintenance strategy, in which preventive maintenance (PM) was performed at predetermined times and corrective maintenance (CM) in the occurrence of failures. Subsequently, Toledo et al. (2016) expanded the model used in Gilardoni & Colosimo (2007), whereas now PM with perfect repair, but CM with imperfect repair.

In this way, any type of maintenance (corrective or preventive) incurs costs, both directly linked to the activity of maintenance or as indirect costs. Thus, increasing the frequency of preventive maintenance, for example, to reduce the expected number of failures, is not necessarily a good strategy.

For a single systematic maintenance process, the following notations are given:

- $\{\tau_k\}$ time to systematics, or periodicities of systematics $0 = \tau_0 < \tau_1 < \tau_2 < \cdots < \tau_k$, were k is the number of systematic maintenances up to a given time $t \geq \tau_k$.
- $\{\chi_j\}$, time between systematics $\chi_j = \tau_j - \tau_{j-1}$ and $j = (1, 2, 3 \ldots)$. The time between systematics is represented by TBS. For a strategy of systematic maintenance at fixed intervals, we have to $\tau_k = k\Delta_\tau$ for $k \geq 1$.
- $\{S_j\}$ time to maintain, or time to maintain a piece of equipment considering the scheduled and unscheduled activities on the agenda.
- $M = \{M_t\}_{t \geq 0}$, the associated counting process that records the cumulative number of maintenances performed.

Thus, when considering a certain equipment subject to an optimal strategy, k SPH guidelines with periodicities $\mathbf{0 = \boldsymbol{\tau}_0 < \boldsymbol{\tau}_1 < \boldsymbol{\tau}_2 < \cdots < \boldsymbol{\tau}_k}$, with their respective maintenance $\{\boldsymbol{S_j}\}$ times are planned up to a certain time t.

3.4 Maintenance performance measurement

After a certain time t, the data is organized into operation (WH) or maintenance (MH) events and, in order to facilitate the representation in a counting process graph, idle hours (IH) are disregarded. Each set of failures and systematic maintenances possible to happen, correspond to a possible result of the system in operation (failures occur in $t_1, t_2, t_3, \ldots$ and maintenances are performed in $\tau_1, \tau_2, \tau_3, \ldots$), and each system result corresponds to a step function.

After recording the event history, where **NCI** is the number of corrective interventions performed and **NSI** is the number of systematic interventions performed, we have to:

- Time Between Failures (TBF) represents the worked hours (WH), given by the expression $WH = \sum_{i=1}^{n} TBF_i$, for $n = NCI$ events. The mean time between failures is expressed by Equation 4:

$$MTBF = \frac{WH}{NCI} \tag{4}$$

- Time To Repair (TTR) is composed of the hours in corrective maintenance (CMH) and hours in accident maintenance (ACH), given by the category of hours $TCMH = \sum_{i=1}^{n} TTR_i,$ for $n = NCI$. The mean time to repair is given by Equation 5:

$$MTTR = \frac{TCMH}{NCI} \tag{5}$$

- Time Between Systematics (TBS) is the worked hours (WH) considering NSI. The mean time between systematics is expressed as Equation 6:

$$MTBS = \frac{WH}{NSI} \tag{6}$$

- Time To Maintain (TTM) is the time spent to maintain a piece of equipment, given by the category $SPH = \sum_{j=1}^{m} TTM_j$, for $m = NSI$ events. The mean time to maintain is given by Equation 7:

$$MTTM = \frac{SPH}{NSI} \tag{7}$$

3.4.1 Measurement of impact on the incidence of correctives

The ratio and number of systematic interventions implemented of the number of scheduled preventive interventions (k) and number of systematic interventions implemented (NSI), after a certain time of operation $WH > t$, it is an incidence of systematic interventions (ISI) given by Equation 8:

$$ISI = \frac{NSI}{k} \tag{8}$$

In addition to the number of agendas carried out, the executions must occur in sequential times, or predetermined periodicities. Therefore, adherence to the systematic maintenance periodicity (ATSP) is the ratio between the amount of scheduled preventive maintenance that was effectively performed within the expected tolerance. Therefore, given that k preventive maintenance is sequential and scheduled in advance, we have to (Equation 9):

$$ATSP = \frac{MTBS}{\chi} \tag{9}$$

were $\chi = \frac{1}{k}\sum_{j=1}^{k}\chi_j$ is the predicted mean time between systematics or mean periodicity.

For example, $ATSP = 1.5$ indicates that, for an expected periodicity of $\chi = 250h$, there is an mean delay of 125 hours for the start of the execution of systematic maintenance and, consequently, for the same time interval there will be fewer executions of systematic maintenance than expected $(ISI < 1)$. Otherwise, a $ATSP = 0.5$ indicates that, for an expected periodicity of $\chi = 250h$, there is an mean anticipation of 125 hours for the start of the execution of systematic maintenance.

In order to relate the impact of systematic adherence on corrective (ISAC), we can relate the delay/anticipation of systematics in relation to the time between failures, that is, we want to know how many failures occur in the delay/anticipation interval of systematics. Therefore, it can be calculated (Equation 10):

$$ISAC = \frac{MTBS - \chi}{MTBF} \times NSI \quad (10)$$

For example, for a single systematic maintenance with a delay of $125h$, with $\chi = 250$ and $MTBF = 25$, it is expected $ISAC = 5$ failures will occur due to delay. On the contrary, in the event that the next maintenance occurs after 200 hours of operation, a reduction of $ISAC = 2$ failures is expected. However, as already mentioned, the optimal preventive maintenance strategy aims to $ISAC \cong 1$. In other words, the $IASC$ represents the mean number of corrective interventions that could have been avoided if all systematic interventions had been carried out at the optimal interval.

It should be noted that, in the event that a certain systematic maintenance schedule is not performed, then the next planned maintenance will occur after twice the optimal periodicity χ and, therefore, also represents a non-adherence. Therefore, both to one $ISI < 1$ as much as a $ATSP > 1$, a worsening of the condition of the equipment is to be expected and, consequently, an increase in the number of corrective interventions (NCI).

3.4.2 Measurement of impact on availability

The extrapolation of the scheduled time to carry out the activities of a given agenda causes a greater unavailability of the equipment in relation to the scheduled. Thus, adherence time to maintain (ATTM) is (Equation 11):

$$ATTM = \frac{SPH}{S} \quad (11)$$

were $S = \sum_{j=1}^{k} \boldsymbol{S_j}$ is the expected time for the execution of all the staves for a given operation time WH.

Given that the choice of an optimal preventive maintenance strategy maximizes availability, it is to be expected control actions that favor preventive maintenance to the detriment of corrective maintenance. However, when there are executions of guidelines that do not adhere to $(ATTM > 1)$, So the impact of preventive maintenance on physical availability can be great. The systematic maintenance factor (SMF) is then given by Equation 12:

$$SMF = \frac{MTTM}{(ATTM - 1) \times MH} \quad (12)$$

And the impact on the physical availability (IPA), considering the increase in the number of repairs, is given by Equation 13:

$$IPA = \frac{IASC \times MTTR + \text{SMF} \times MH}{CH} \tag{13}$$

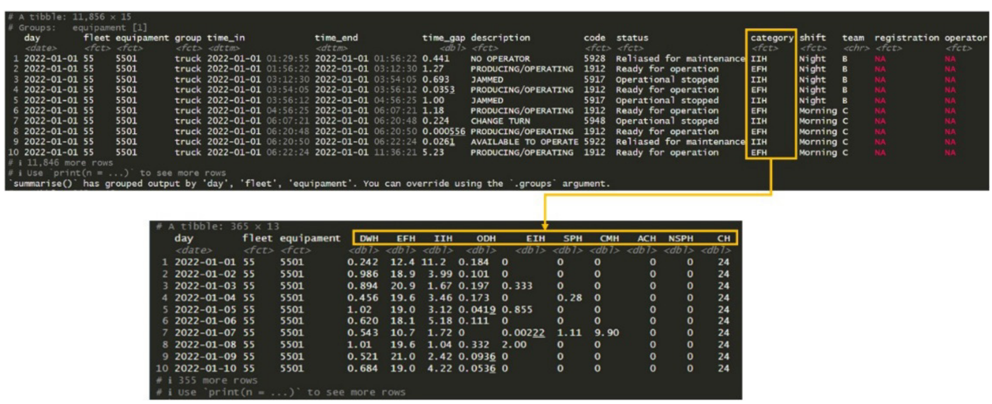
4 Materials

4.1 Collection and processing of data

The data on the historical appointment of hours refer to the year 2022, in which the hours of operations planned for the trucks total 8,760 hours, which is considered calendar hours (CH) for the year, and the database consists of a total of 1,452,136 notes of hours, extracted in the system developed by the company called *"Minecare"*, where it counts in real time the status of the equipment and directs and stores the information for this database.

The data required for this type of analysis, are pointed out in the internal system whenever the truck changes its operation status. Given the classification of hours in categories, it is necessary to group them by day. The values are presented in the categories of hours represent the sum of the duration of all appointed per day, for a certain category. In this way, calendar hours add up to 24 hours.

Therefore, the data is pivoted per day, that is, the transposition of the data that are in rows to the columns is performed and summarized by sum, resulting in a second database. Figure 6 presents the data for the 5501 trucks in which there were 11,856 notes.



```
# A tibble: 11,856 × 15
# Groups:   equipament [1]
   day        fleet equipament group time_in             time_end            time_gap description          code  status                   category shift   team  registration operator
   <date>     <fct> <fct>      <fct> <dttm>              <dttm>                 <dbl> <fct>                <fct> <fct>                    <fct>    <fct>   <chr> <fct>        <fct>
 1 2022-01-01 55    5501       truck 2022-01-01 01:29:55 2022-01-01 01:56:22 0.441    NO OPERATOR          5928  Reliased for maintenance IIH      Night   B     NA           NA
 2 2022-01-01 55    5501       truck 2022-01-01 01:56:22 2022-01-01 03:12:30 1.27     PRODUCING/OPERATING  1912  Ready for operation      EFH      Night   B     NA           NA
 3 2022-01-01 55    5501       truck 2022-01-01 03:12:30 2022-01-01 03:54:05 0.693    JAMMED               5917  Operational stopped      IIH      Night   B     NA           NA
 4 2022-01-01 55    5501       truck 2022-01-01 03:54:05 2022-01-01 03:56:12 0.0353   PRODUCING/OPERATING  1912  Ready for operation      EFH      Night   B     NA           NA
 5 2022-01-01 55    5501       truck 2022-01-01 03:56:12 2022-01-01 04:56:25 1.00     JAMMED               5917  Operational stopped      IIH      Night   B     NA           NA
 6 2022-01-01 55    5501       truck 2022-01-01 04:56:25 2022-01-01 06:07:21 1.18     PRODUCING/OPERATING  1912  Ready for operation      EFH      Morning C     NA           NA
 7 2022-01-01 55    5501       truck 2022-01-01 06:07:21 2022-01-01 06:20:48 0.224    CHANGE TURN          5948  Operational stopped      IIH      Morning C     NA           NA
 8 2022-01-01 55    5501       truck 2022-01-01 06:20:48 2022-01-01 06:20:50 0.000556 PRODUCING/OPERATING  1912  Ready for operation      EFH      Morning C     NA           NA
 9 2022-01-01 55    5501       truck 2022-01-01 06:20:50 2022-01-01 06:22:24 0.0261   AVAILABLE TO OPERATE 5922  Reliased for maintenance IIH      Morning C     NA           NA
10 2022-01-01 55    5501       truck 2022-01-01 06:22:24 2022-01-01 11:36:21 5.23     PRODUCING/OPERATING  1912  Ready for operation      EFH      Morning C     NA           NA
# ℹ 11,846 more rows
# ℹ Use `print(n = ...)` to see more rows
`summarise()` has grouped output by 'day', 'fleet', 'equipament'. You can override using the `.groups` argument.

# A tibble: 365 × 13
   day        fleet equipament   DWH   EFH   IIH    ODH     EIH   SPH   CMH   ACH  NSPH    CH
   <date>     <fct> <fct>      <dbl> <dbl> <dbl>  <dbl>   <dbl> <dbl> <dbl> <dbl> <dbl> <dbl>
 1 2022-01-01 55    5501       0.242  12.4 11.2  0.184  0        0     0        0     0    24
 2 2022-01-02 55    5501       0.986  18.9  3.99 0.101  0        0     0        0     0    24
 3 2022-01-03 55    5501       0.894  20.9  1.67 0.197  0.333    0     0        0     0    24
 4 2022-01-04 55    5501       0.456  19.6  3.46 0.173  0        0.28  0        0     0    24
 5 2022-01-05 55    5501       1.02   19.0  3.12 0.0419 0.855    0     0        0     0    24
 6 2022-01-06 55    5501       0.620  18.1  5.18 0.111  0        0     0        0     0    24
 7 2022-01-07 55    5501       0.543  10.7  1.72 0      0.00222  1.11  9.90     0     0    24
 8 2022-01-08 55    5501       1.01   19.6  1.04 0.332  2.00     0     0        0     0    24
 9 2022-01-09 55    5501       0.521  21.0  2.42 0.0936 0        0     0        0     0    24
10 2022-01-10 55    5501       0.684  19.0  4.22 0.0536 0        0     0        0     0    24
# ℹ 355 more rows
# ℹ Use `print(n = ...)` to see more rows
```

Figure 6. Dataset grouped by hours per day.

The data treatment was performed with the aid of *Software R*. Therefore, the data went through the cleaning and treatment phase, where duplicate observations and values were taken out of the analyzed domain. Column names and their orders were also adjusted to facilitate analysis.

4.2 Definition of priority fleet

The analysis begins by measuring the performance of the fleet for the year 2022, using the data of notes of hours according to the classification of the codes of the company. The number of trucks (NT) for the 6 fleets, the values of production KPIs (PA, PU, and PR) and maintenance KPIs (NCI, MTTR and MTBF) are presented in Table 1.

Table 1. Fleets for monitoring of transport indicators.

Transport	TAG	NT	PR	PA	PU	NCI	MTTR	MTBF
Fleet 40	40XX	29	314.88	81.41%	73.63%	3,502	5.18	42.33
Fleet 43	43XX	3	357.23	82.57%	65.92%	34	4.07	35.73
Fleet 52	52XX	29	405.04	86.18%	76.63%	1,452	4.24	62.51
Fleet 53	53XX	15	329.80	79.87%	76.27%	1,578	4.91	49.85
Fleet 55	**55XX**	**36**	**523.27**	**78.46%**	**81.25%**	**3,870**	**7.24**	**51.95**
Fleet 57	57XX	6	406.03	89.96%	77.24%	399	3.94	91.53
Total		**118**	**413.06**	**81.38%**	**77.34%**	**10,835**	**5.70**	**51.36**

In Table 1, Fleet 55 (5501 to 5536) has 36 trucks, in which physical availability ($PA = 78.46\%$) was the lowest among the other fleets, generating ($NCI = 3{,}870$) interventions, greater unavailability ($CMH = 28{,}023$), high mean time to repair ($MTTR = 7.24$) and the high incidence of failures ($MTBF = 51.95$). Thus, and despite better productivity ($PR = 523.27$), and greater physical use ($PA = 81.25\%$), from the maintenance point of view, fleet 55 can be considered a priority fleet for setting and monitoring goals.

Therefore, the achievement of production goals, from the comparative point of view, is the evaluation of production processes that are the elements that have the capacity to generate quality (Campos, 2004). The most efficient way to verify if the production process meets the objectives of the organization is to verify whether continuous improvements have been characterized and, if the evaluation indicates that this actually occurs, then the general objectives of the organization (quality) are being achieved as a result of the correct functioning of the production process (quality control) (Shiba & Graham, 1997).

4.3 Description of the equipment

The priority fleet in this study is the off-road truck model CAT® 797F (Figure 7) which, according to manufacturer characteristics (Caterpillar, 2022), is driven by a diesel fuel engine, with a rated payload capacity of 400 tons. It is one of the most present trucks in the Brazilian market fleets.

Figure 7. Caterpillar CAT® 797F.

The manufacturer adopts a strategy of systematic preventive maintenance (SPH), following agenda of 500H, 1000H, 2000H, 4000H and 8H000, in addition to making pit-stop stops between the preventive every 250 hours and which are appropriate as SPH.

PH runs follow a flow that begins with level checking, lift and efficiency testing, collecting S•O•SSM for routine verification of oil, coolant, and fuel (Caterpillar, 2022), cleaning procedure and cabin PM checks. Then the maintenance is effectively performed according to a detailed procedure of the respective SPH schedule. Finally, a verification checklist is filled in for maintenance releases, where the truck changes its status from “in maintenance” to “released a maintenance”.

Table 2 describes the execution time SPH schedules, which should occur in CAT® 797F trucks, according to the operating time for a cycle of 8,000 hours, according to the manufacturer’s manual.

Table 2. Periodicity and runtime of PM.

SPH agenda	Time in operation (h)	Runtime (h)
250H	250	2.00
500H	500	11.22
250H	750	2.00
1000H	1,000	14.97
250H	1,250	2.00
500H	1,500	11.22
250H	1,750	2.00
2000H	2,000	16.22
250H	2,250	2.00
500H	2,500	11.22
250H	2,750	2.00
1000H	3,000	14.97
250H	3,250	2.00
500H	3,500	11.22
250H	3,750	2.00
4000H	4,000	16.63
250H	4,250	2.00
500H	4,500	11.22
250H	4,750	18.97
1000H	5,000	14.97
250H	5,250	2.00
500H	5,500	11.22
250H	5,750	18.97
2000H	6,000	16.22
250H	6,250	2.00
500H	6,500	11.22
250H	6,750	2.00
1000H	7,000	14.97
250H	7,250	2.00
500H	7,500	11.22
250H	7,750	2.00
8000H	8,000	19.63
Total		**284.23**

Note that for an operation time of 8,000 hours, a truck must perform 32 preventive interventions, including 16 agendas of 250H SPH (pit-stop), 8 agendas of 500H, 4 agendas of 1000H, 2 agendas of 2000H, 1 agenda of 4000H and 1 agenda of 8000H.

Considering $PA = 90\%$ established by the manufacturer, it is expected that in a given month, for example, 10 trucks operate about $WH = 5{,}651$ hours, 11.3 pit-stop occurs $(SPH_{250H} = 24)$ and 11.3 stops preventive maintenance $(SPH = 192)$ corresponding to a total preventive unavailability of 3.0%. In addition, 50 hours (0.69%) are dedicated to detection routines, 144 hours (2.00%) to tire maintenance and 295.2 hours (4.10%) refer to timely maintenance or unforeseen repairs.

5 Results and discussions

5.1 Identification of the problem Fleet 55

The off-road truck CAT® 797F is responsible for transporting mined ore from the extraction point, in this case the ore pits, where it is loaded by an excavator. This material is taken to the discharge points, which are the semi-mobile crushers, fulfilling the assigned function.

With a demand of up to 23h/day of operation, its availability is the state of capacity in performing its required function. The availability hours (AH) refer to the calendar hours (CH) subtracted from the sum of the maintenance hours (MH). Worked hours (WH) are part of the AH that effectively performs its required function, and idle hours (IH) refer to the unused time.

Figure 8 represents all 10 categories of hours for a total $CH = 315{,}360$, referring to the 36 trucks. In particular, we can analyze the categories related to maintenance, namely: $CMH = 28{,}023;\ SPH = 26{,}966;\ NSPH = 10{,}166;\ ACH = 2{,}771$.

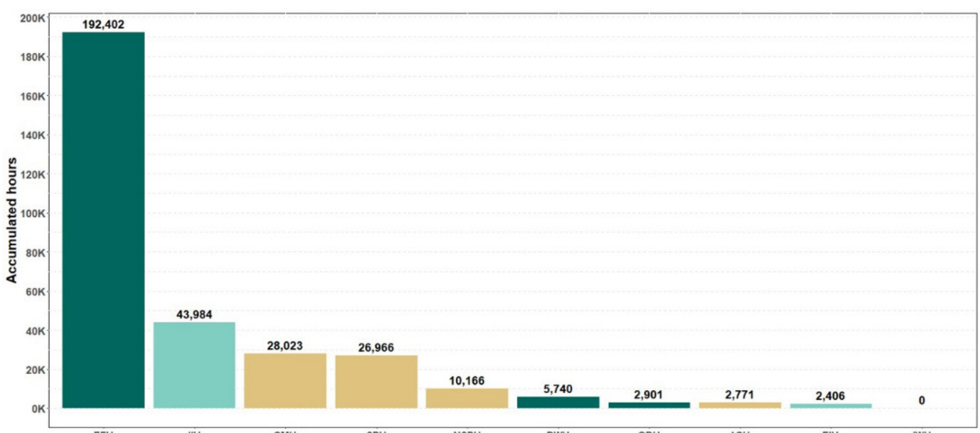


Figure 8. Calendar time chart.

The production plan is made in advance in order to cover the annual period, exploiting the maximum possibilities of the company's resources and providing ideal conditions of efficiency and effectiveness.

For the 36 trucks, the production KPIs are presented in Table 3. Note that for $TM = 100{,}471{,}267\ tons$, a $PR = 465.64\ tons/h$ was estimated, with a $PA = 81.54\%$ and $PU = 83.91\%$.

When we compare the scheduled with the realized, it is noted that the production and productivity closed positive for the year, which is good, but in contrast, it is possible to observe that the indicators that suffered the greatest impact were PA and PU, being for the PA indicator a realized 78.46% and with a loss of 3.08% and for the PU, realized was 81.25% with a loss of 2.66%.

Table 3. Indicators of production of trucks CAT® 797F in 2022.

Production KPIs	Performance	Programmed
Physical availability – PA	**81.54%**	**78.46%** ↓
Physical utility – PU	83.91%	81.25% ↓
Productivity – PR	465.64 $tons/h$	523.27 tons/h ↑
Production – TM	100,471,267 $tons$/y	105,200,782 tons/h ↑

Figure 9 it is possible to calculate the loss of production by performance indicators, checking the representativeness in tons for each indicator.

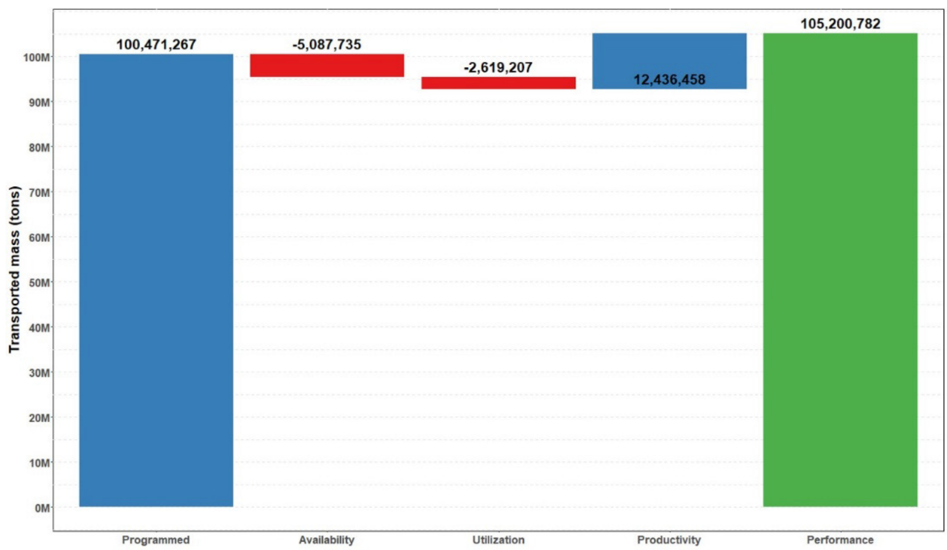


Figure 9. Build-up of production losses by indicator.

It is noted that the PA indicator is the main problem presented in 2022 for the 36 trucks analyzed and that, from the production point of view, resulted in a total loss of $-5{,}086{,}957\ tons/a$ and, from the point of view of maintenance, a total unavailability of $9{,}722.88h$.

5.2 Preliminary descriptive analysis 1

Preliminary descriptive analyses are fundamental to investigate the pattern of failure occurrence over time. Some graphs allow to compare the systems under study and to verify if there are indications that, for example, the time between successive failures tend to increase, decrease or remain constant over time.

Considering that the TAG 5513 truck started its operations in $t_0 = 0$, event data were collected until the occurrence of systematic preventive maintenance in $\tau_1 = 346.72$. In order to understand the dynamics of failure and systematic interventions, Figure 10 presents the step function of the counting process of corrective interventions and, for this analysis, disregarding the repair and systematic times.

It is observed that systematic intervention, predicted for $\chi = 250h$, was performed after $96.72h$ and thus we have a value of $ATSP = 1.39$. In addition, $NCI = 8$ repairs were performed due to failures that occurred on mean for each $MTBF = 43.34h$. In this analysis, the delay of systematic execution is related to the values of $ATSP > 1$ where, the increase in the occurrence of failures is related to the number of failures that occurred in the delay/anticipation time of systematic maintenance and, thus, the calculated impact is $IASC = 2.23$, that is, it is estimated that delay/anticipation of execution of the systematic resulted in an increase of 2 or more failures.

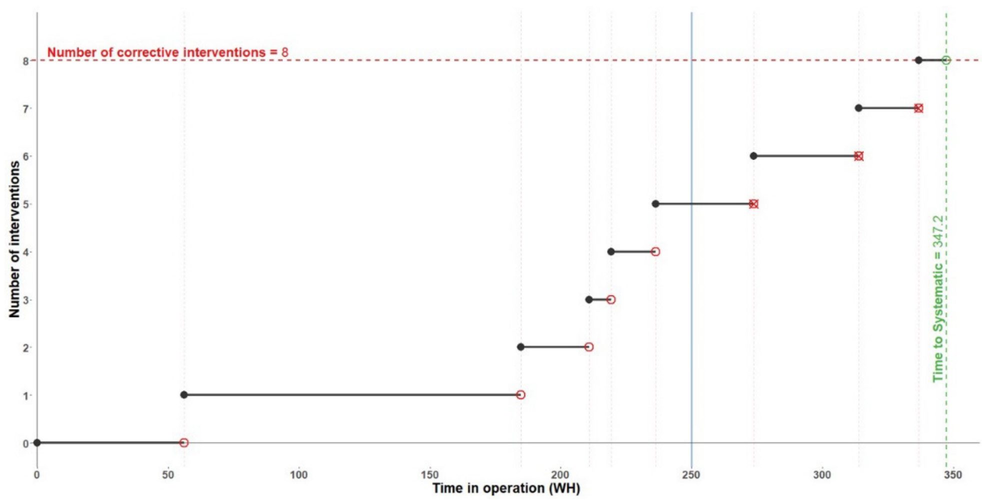


Figure 10. Counting processes applied to TAG 5513 truck for first systematic intervention.

Because it is an $1000H$ agenda, the estimated time to perform the corresponding activities is $S = 14.97h$, however, the time spent for maintenance was $TTM = 39.52$ and $ATTM = 2.64$. Considering all the maintenance performed in the period, in Figure 11, we present the details of the categories of hours and, for $CH = 513.15$, we have $PA = 80.42\%$, $SMF = 23.98\%$ and $IPA = 7.73\%$, that is, the inefficiency of the planning and maintenance control team resulting in a $37.08h$ physical unavailability.

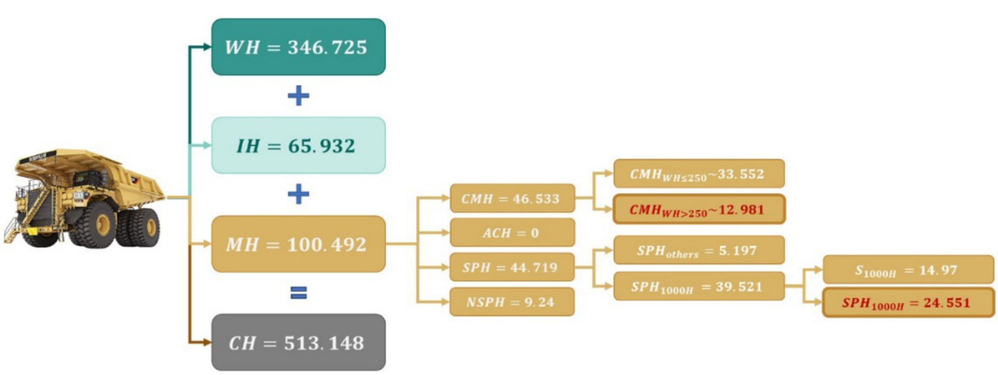


Figure 11. TAG 5513 truck hours categories breakdown.

5.3 Preliminary descriptive analysis 2

Considering that the TAG 5501 truck started its operations in $t\_0=0$, event data were collected until the occurrence of systematic $NSI = 6$, with $\tau_1 = 246.38; \tau_2 = 513.41; \tau_3 = 757.27; \tau_4 = 873.71; \tau_5 = 1{,}345.62; \tau_6 = 1{,}596.24$ the times of systematic maintenance. To understand the dynamics of the occurrence of failures and interventions of systematics, Figure 12 presents the step function of the counting process of correcting and systematic interventions and, for this analysis, disregarding the repair and systematic times.

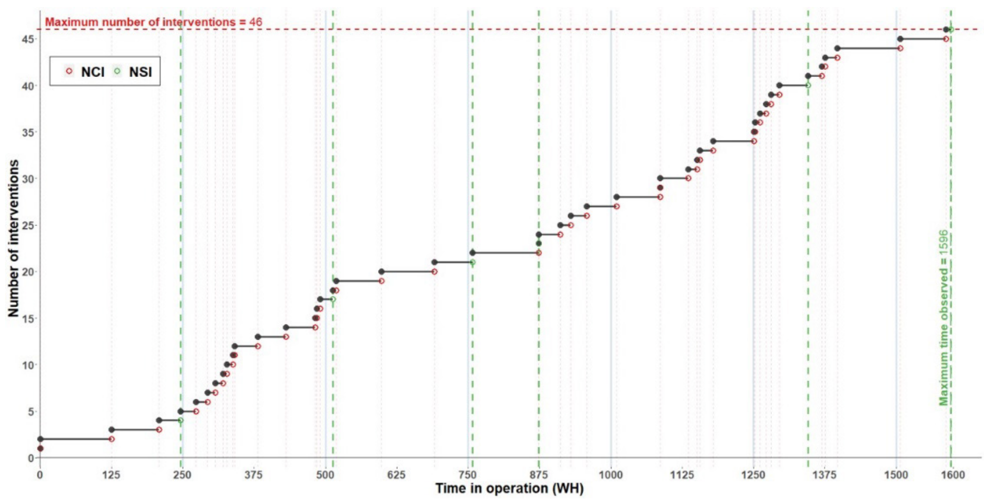


Figure 12. Counting processes applied to TAG 5501 truck.

It is observed that for the operation time ($WH = 1{,}596.24$), the predicted $k = 6$ systematic interventions were performed, and thus we have $ICS = 1$. Then, when extracting the times between systematics (TBS), the $MTBS = 266.04h$ is obtained and, in turn, a value of $ATBS = 1.06$ that indicates an mean delay of $16.04h$ in the executions of the systematics, given that the optimal periodicity of maintenance considered is $\chi = 250h$.

It is possible to observe (Figure 12) a higher incidence in the interval between the systematic $\tau_5 - \tau_4 = \chi_5 = 471.91h$, where there was an anticipation in the execution for τ_4 and delay for τ_5 and, consequently, preventive maintenance is ineffective in its purpose of reducing system wear and minimizing the occurrence of failures.

In the example, $NCI = 39$ repairs were performed at an average time $MTTR = 6.59h$, and failures that occurred on average each $MTBF = 40.93h$. In this analysis, the ineffectiveness of systematic execution related to the values of $ATSP > 1$ resulting in an increase of $IASC = 2.35$ occurrence of failures.

Figure 13 presents the detailing of the categories of hours, with the total estimated time of $S = 34.19$, the total time spent of $SPH = 335.11$ and $ATTM = 9.80$. It is also observed that of the $NCI = 39$ repairs were performed about $IASC = 2.35$ could have been avoided and, $MTTR = 6.59$, it has been that the time that could be avoided in the repairs is $\widetilde{CMH} \sim 15.51$.

Finally, related to the non-adherence of the systematics, there is $SMF = 37.23\%$ and, considering the increase of $\widetilde{CMH} + \widetilde{SPH} = 316.44$, there is $IPA = 11{,}298\%$, for a physical availability of $PA = 71.137\%$.

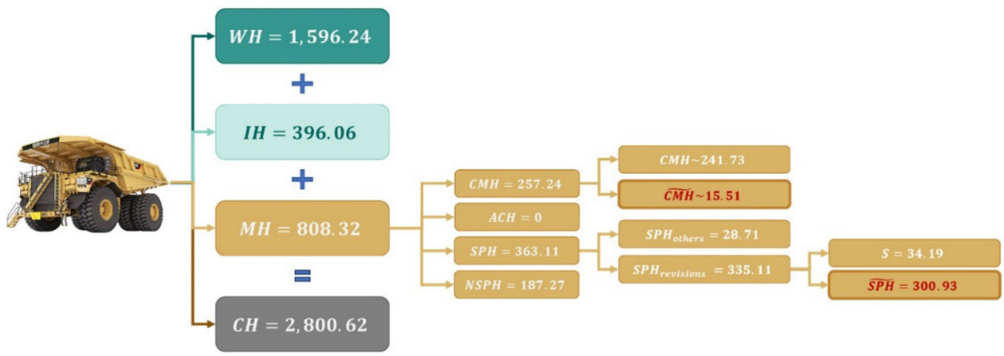


Figure 13. Details of the truck hours categories TAG 5501.

5.4 Adherence to systematic preventive maintenance

Table 4 presents the main information related to SPH notes grouped by trucks. The number of agendas, the number of systematics executed (NSI) and programmed (k), the MTBS, and the MTBF vary because they depend on the number of worked hours (WH).

Table 4. Number of SPH agendas executed, and worked hours by truck.

Truck	WH	250	500	1000	2000	4000	8000	NSI	k	ISI	MTBS	ATSP	MTBF	IASC
5501	4663.85	7	5	1	1	1	0	15	18	0.83	297.11	1.19	29.77	23.74
5502	5125.19	7	3	2	1	1	0	14	20	0.70	334.71	1.34	42.65	27.81
5503	5385.04	7	4	2	1	1	0	15	21	0.71	341.96	1.37	47.23	29.20
5504	5226.65	8	3	1	1	1	1	15	20	0.75	332.90	1.33	37.24	33.39
5505	5704.08	7	5	1	1	1	1	16	22	0.73	340.62	1.36	42.25	34.32
5506	4862.19	5	4	2	1	0	1	13	19	0.68	370.17	1.48	32.24	48.46
5507	5234.57	10	4	2	0	0	0	16	20	0.80	311.43	1.25	38.32	25.65
5508	5103.29	6	4	2	1	1	0	14	20	0.70	359.96	1.44	32.00	48.10
5509	5496.52	8	6	4	1	0	0	19	21	0.90	283.35	1.13	38.47	16.47
5510	5841.01	7	4	3	1	1	0	16	23	0.70	346.74	1.39	46.74	33.12
5511	4226.20	5	3	1	1	1	0	11	16	0.69	347.79	1.39	46.82	22.97
5512	5662.59	6	5	2	1	2	0	16	22	0.73	339.65	1.36	51.57	27.82
5513	6029.97	8	4	4	1	1	0	18	24	0.75	320.79	1.28	58.90	21.63
5514	5928.31	10	3	4	1	0	0	18	23	0.78	298.82	1.20	62.64	14.03
5515	4303.86	6	4	3	1	1	0	15	17	0.88	282.57	1.13	34.45	14.18
5516	5395.04	9	4	3	0	1	1	18	21	0.86	289.26	1.16	63.85	11.07
5517	5557.51	8	5	3	1	1	0	18	22	0.82	302.38	1.21	37.42	25.20
5518	5492.10	8	5	2	2	0	0	17	21	0.81	312.83	1.25	41.82	25.54
5519	5709.67	8	3	3	0	0	0	14	22	0.64	374.34	1.50	48.40	35.97
5520	4760.60	6	4	2	0	0	1	13	19	0.68	347.37	1.39	37.28	33.95
5521	5252.52	7	6	3	0	1	0	17	21	0.81	303.90	1.22	53.93	16.99
5522	5383.93	6	5	4	1	0	1	17	21	0.81	313.15	1.25	36.01	29.81
5523	5203.49	5	4	3	1	1	1	15	20	0.75	339.49	1.36	54.99	24.41
5524	5748.18	9	4	3	2	1	0	19	22	0.86	298.07	1.19	42.35	21.57
5525	5717.43	8	6	3	1	0	1	19	22	0.86	299.55	1.20	42.85	21.97
5526	5677.22	8	5	4	1	0	0	18	22	0.82	311.71	1.25	56.32	19.72
5527	6411.45	9	4	3	1	1	1	19	25	0.76	329.87	1.32	95.34	15.92
5528	6440.65	10	5	2	1	1	1	20	25	0.80	310.41	1.24	112.88	10.70
5529	6428.94	10	6	2	1	1	1	21	25	0.84	302.73	1.21	94.89	11.67
5530	6455.06	9	6	1	1	1	1	19	25	0.76	329.08	1.32	84.77	17.72
5531	5313.83	6	4	3	1	1	0	15	21	0.71	332.16	1.33	70.85	17.40
5532	6013.39	10	5	3	1	0	1	20	24	0.83	295.98	1.18	112.93	8.14
5533	6462.03	7	6	3	1	1	1	19	25	0.76	332.24	1.33	122.00	12.81
5534	6270.73	8	4	3	1	1	0	17	25	0.68	356.55	1.43	124.77	14.52
5535	6227.18	8	6	3	2	1	0	20	24	0.83	308.46	1.23	86.29	13.55
5536	6286.86	11	4	3	2	1	0	21	25	0.84	284.37	1.14	71.32	10.12

For the TAG 5501 truck, analyzed by a total of $WH = 4{,}663.85$, only 15 systematic preventive maintenance schedules were carried out, from an expected 18 to a similar operation time. Clustered, the systematic counting index is $ISI_{5501} = 0.833$ due to the 3 agendas not executed, and adherence of $ATSP_{5501} = 1.19$ corresponds to an mean delay of $45.11h$ which, consequently, caused $IASC_{5501} = 23.74$ or more failures, i.e., of $NCI = 156$, about 18.26% was due to the delay of systematic maintenance.

In summary, analyzing the fleet 55 as a whole, $ISI_{\bar{x}} = 0.77$ indicates a low mean rate of application of systematic preventive maintenance, $ATSP_{\bar{x}} = 1.29$ causes an mean delay of $81.14h$ in executions, and a total of greater than $IASC > 819.63$ failures or more due to delays, accounting for 49.67% of total $NCI = 3{,}827$.

Therefore, it is noticed that the problem of pointing systematic preventive maintenance is generalized by the fleet analyzed, that is, all the tracks presented problems related to the fulfillment of the systematic preventive maintenance guidelines according to the worked hours.

5.5 Analysis of impact on availability

Preventive maintenance is an important strategy to improve the physical availability of a system or equipment, reduce downtime and extend the life of equipment. Can be used in conjunction with the PA indicator to monitor and improve system or equipment performance.

However, although this type of maintenance is an important tactic to increase the physical availability of equipment, there may be cases where preventive maintenance may interfere or impair the physical availability of equipment, as in the example of the fleet of off-road trucks CAT® 797F analyzed, in which the maintenance time is longer than the time planned in the preventive plan, according to the manufacturer's manual. That said, it is important to investigate this problem, since the PA indicator is impacted by maintenance hours.

Table 5 represents the analysis of the execution times of the maintenance schedules, their total (SPH) in the analyzed period, the times predicted by the manufacturer (S), and the total time in which each truck was in maintenance (HM). Given the information, the indicators of adherence to maintenance time (ATTM), the systematic maintenance factor (SMF), mean time to maintenance (MTTM), the impact on the physical availability (IPA) and physical availability (PA) for each truck were calculated.

For, Fleet 55, there are maintenance hours with a total of $MH = 67{,}926.49$, and the value pointing in the $SPH_{note} = 26{,}966.41h$, however, extracting the values that do not represent guidelines for systematic reviews, we have that the value of interest for analysis is $SPH_{revised} = 20{,}883.24$. Therefore, it is estimated that the total executed time of the systematics was $ATTM = 4.14$ times higher than planned, an mean time for execution $MTTM = 34.40h$, a factor of $SMF = 37.87\%$ and impact of $IPA = 8.16\%$.

Therefore, it is understood that one of the main ways in which systematic preventive maintenance can impair the physical availability of equipment, is through downtime beyond the scheduled, which can happen due to lack of manpower, long standby, one-piece manufacturing for exchange or maintenance service support.

Table 5. Systematic preventive maintenance runtime analysis.

Truck	250	500	1000	2000	4000	8000	SPH	S	ATTM	SMF	MTTM	IPA	PA
5501	42.4	348.7	203.1	39.2	78.6	0.0	712.06	117.92	6.04	0.24	47.47	0.10	0.67
5502	78.1	200.7	55.6	35.8	215.6	0.0	585.81	110.45	5.30	0.27	41.84	0.11	0.73
5503	27.9	164.3	142.0	51.4	169.5	0.0	555.20	121.67	4.56	0.31	37.01	0.10	0.76
5504	40.4	231.0	37.3	44.3	142.2	120.3	615.46	117.11	5.26	0.34	41.03	0.10	0.77
5505	84.2	265.9	72.4	59.8	53.6	287.5	823.41	137.55	5.99	0.42	51.46	0.10	0.80
5506	22.7	352.1	125.4	37.8	0.0	172.4	710.39	120.67	5.89	0.24	54.65	0.11	0.72
5507	62.8	443.2	172.0	0.0	0.0	0.0	677.94	94.82	7.15	0.40	42.37	0.10	0.78
5508	24.5	197.8	76.5	54.1	185.4	0.0	538.33	119.67	4.50	0.24	38.45	0.12	0.71
5509	118.7	185.9	224.1	63.5	0.0	0.0	592.06	159.42	3.71	0.40	31.16	0.10	0.78
5510	37.2	217.1	209.4	36.7	90.4	0.0	590.70	136.64	4.32	0.41	36.92	0.10	0.81
5511	15.4	153.2	40.1	40.5	60.0	0.0	309.17	91.48	3.38	0.13	28.11	0.09	0.61
5512	39.5	387.6	171.3	68.8	120.2	0.0	787.48	147.52	5.34	0.38	49.22	0.10	0.78
5513	33.1	117.2	175.2	76.3	62.8	0.0	464.67	153.61	3.02	0.44	25.81	0.09	0.83
5514	78.5	256.1	148.5	113.1	0.0	0.0	596.21	129.76	4.59	0.49	33.12	0.10	0.82
5515	22.3	149.7	268.3	42.8	1.5	0.0	484.56	134.64	3.60	0.18	32.30	0.10	0.61
5516	50.4	175.1	169.9	0.0	94.6	83.9	573.82	144.05	3.98	0.36	31.88	0.10	0.76
5517	34.4	319.6	174.3	57.1	64.9	0.0	650.30	149.86	4.34	0.38	36.13	0.10	0.77
5518	39.4	290.8	149.1	252.2	0.0	0.0	731.57	134.48	5.44	0.38	43.03	0.10	0.77
5519	52.8	229.6	161.0	0.0	0.0	0.0	443.42	94.57	4.69	0.33	31.67	0.10	0.79
5520	94.5	568.5	174.5	0.0	0.0	60.8	898.34	106.45	8.44	0.22	69.10	0.12	0.67
5521	44.1	282.2	88.2	0.0	97.7	0.0	512.19	142.86	3.59	0.29	30.13	0.10	0.73
5522	33.2	135.1	272.6	37.0	0.0	40.8	518.55	163.83	3.17	0.34	30.50	0.10	0.78
5523	23.8	446.2	184.9	73.4	59.5	29.5	817.28	152.27	5.37	0.31	54.49	0.10	0.75
5524	41.8	251.4	147.7	147.8	79.3	0.0	668.02	156.86	4.26	0.46	35.16	0.11	0.80
5525	121.5	293.7	158.5	70.7	0.0	96.9	741.23	164.08	4.52	0.44	39.01	0.11	0.78
5526	64.7	279.6	212.5	43.2	0.0	0.0	599.99	148.20	4.05	0.42	33.33	0.11	0.79
5527	40.8	152.9	89.8	42.1	117.5	65.5	508.67	160.27	3.17	0.72	26.77	0.09	0.88
5528	33.3	191.8	80.5	46.4	70.4	69.9	492.44	158.52	3.11	0.83	24.62	0.09	0.90
5529	39.3	206.6	49.9	39.8	60.3	68.2	464.02	169.74	2.73	0.71	22.10	0.09	0.88
5530	43.1	258.0	37.6	29.2	76.5	58.5	502.85	152.77	3.29	0.69	26.47	0.10	0.88
5531	40.3	119.6	149.7	40.4	102.7	0.0	452.58	134.64	3.36	0.27	30.17	0.11	0.75
5532	67.1	162.8	129.1	41.9	0.0	49.4	450.39	156.86	2.87	0.50	22.52	0.10	0.83
5533	24.8	227.5	134.4	36.9	0.0	62.1	485.66	178.71	2.72	0.71	25.56	0.08	0.89
5534	32.4	176.9	97.6	30.8	71.9	0.0	409.45	138.64	2.95	0.68	24.09	0.08	0.89
5535	48.3	215.6	123.8	42.8	57.4	0.0	487.90	177.30	2.75	0.71	24.40	0.09	0.89
5536	49.1	142.0	100.7	78.8	60.5	0.0	431.14	160.86	2.68	0.71	20.53	0.09	0.88
Total	**1,747**	**8,796**	**5,007**	**1,875**	**2,193**	**1,266**	**20,883**	**5,038.7**	**4.14***	**0.31***	**34.40***	**0.08***	**0.78***

*Calculated value considering the application of the formula in the values of the line of totals.

6 Conclusions

In this study, it was possible to analyze and identify the main causes that led to the low performance of the performance indicators of the maintenance of the CAT® 797F trucks, mainly focusing on the measurement of the impacts caused by the hours of systematic preventive maintenance. Therefore, we first examined the main maintenance hours in 36 trucks in the fleet 55, in order to measure the amount of preventive maintenance that was performed and how the non-compliance of these maintenance could lead to truck failures. It was possible to follow the cycle of transport process and understand how the route that the truck makes works, being empty to the loading point and with the truck full to the unloading point.

It was possible to understand in a structured way the maintenance hours, based on the historical record of hours. We were able to measure the types of hours spent on maintenance and identify which are more recurrent, providing a clear view of the impacts on indicators. When evaluating the impacts on the targets of unavailability of production, we can observe that when we compare the scheduled with the realized, the production and productivity closed positively. The indicators that suffered the greatest impact were PA and PU, being for the PA indicator one performed about 81.25% and with a loss of 2.66% and for the PU, performed was 78.46% with a loss of 3.08%.

Finally, in relation to the divergences in the maintenance programming process, it is possible to measure the adherence between the scheduled x performed, identifying lack of compliance in the planned period for the execution of the activities, idleness of labor, lack of material, shift change, among other problems that may cause delays in preventive maintenance. To minimize this loss of time within maintenance activities, it is essential to systematically review the full preventive reviews and evaluate the productivity time for the activities.

In short, the indicators of maintenance management are a tool to measure quantitatively and qualitatively the production process of the company, it indicates the points of attention to be treated as a priority and demonstrates how to explore the best way to achieve the objectives. Following suggestions for projects and development of future work: use probabilistic reliability models to analyze the occurrence of failures and define criteria and systematics for effective analysis, in this way achieve the expected goal through the realization of an action and use the minimum available resources and time, managing to optimize the processes.

Data availability statement

The datasets may not be publicly available as they are owned by the company that provided the information for the job.

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Rafael da Silva Fernandes and Adriane Freire Souza Silva: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. Rosana Maria do Nascimento Luz and Elizeth Cristina Silva Santos: Formal analysis; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.