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Productivity Improvement of Transmission Electron Microscopes - A Case Study

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Abstract

This paper aims to improve the performance of Transmission Electron Microscopes (TEM) used in asbestos detection processes in a business context. Failure Modes and Effects Analysis (FMEA) were studied, identifying the critical failure modes, proposing risk reduction measures and changing maintenance practices based on the Reliability Centered Maintenance strategy. In the elaboration of the FMEA it was evident the lack of data and poor information quality regarding the reliability and maintenance of TEM. These circumstances led to the implementation of training projects to standardize operations and to the development of a software application for data collection and reports generation with relevant performance indicators (Costs, Mean Down Time, Overall Equipment Effectiveness, …) to support operators tasks and decision-making. The approach followed and the tools developed allowed monitoring TEM productivity and maintenance performance. As a result, more informed decisions can be made that will lead to improved performance of TEM.

Keywords: FMEA; performance indicators; productivity improvement; RCM; software application; transmission electron microscopes.

1. Introduction

The globalization of markets and the increasing competitiveness between organizations mean that they need to become increasingly effective and efficient, taking measures to reduce costs and increase their productivity [1, 2]. In this sense, companies seek an efficient use of all their resources, namely their equipment [1, 3].

For processes heavily dependent on equipment, an increase on its availability will have a direct positive effect on the productivity and performance of the respective processes. These are the circumstances of the process covered in this study - analysis of samples of construction materials to determine if they contain asbestos. Given its properties such as high elasticity and poor thermal conductivity, asbestos had numerous applications, namely in the construction industry [4]. However, over the years, asbestos materials degrade and release small fibers that, when inhaled for a long period of time, can cause serious health problems, such as cancer [5, 6, 7].

The identification of asbestos fibers in a sample is a process that includes the analysis of materials with a Transmission Electron Microscopes (TEM) [8]. This type of equipment is very sensitive and is not designed for continuous use. However, in the studied company, its usage is almost continuous, resulting in frequent failures.

Although no published reliability studies on TEM has been found, in other contexts, and with other types of equipment, there are many published reliability studies [9, 10], showing the relationship of operating stress with its failure rate. While some of the breakdowns do not have an impact on production, others may make it impossible for this equipment to function for long periods (weeks or even months), which can represent high costs for the company.

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Thus, this work aims to improve the productivity of TEM. To achieve this objective was carried out a study of the main failure modes of TEM and were proposed plans to reduce the causes and mitigate the effects. Framed in an Reliability Centred Maintenance (RCM) maintenance strategy, a computer application implemented in Microsoft Excel was developed, facilitating data collection, analysis, and report. In this study, several methodologies and techniques were used, with special emphasis on FMEA, Weibull Analysis, and Overall Equipment Effectiveness (OEE).

The rest of the article is organized as follows. Section 2 presents a literature review on these topics. The main results obtained from the application of the methodologies / techniques are described in section 3 (case study). Finally, section 4 presents the main conclusions of this work.

2. Literature review

The equipment performance directly determines the productivity of the production processes, influences the efficiency of the workforce, and contributes to the product level of quality and customer satisfaction [2, 11].

According to Nakajima [12], the major losses that affect equipment performance are grouped into three categories (downtime, loss of speed, and defects):

- equipment failures/malfunctions, setup, and adjustments (tool change…);
- small interruptions, due, for example, to the abnormal operation of sensors, and reduced speed (compared to the design speed of the equipment);
- process defects (defective products, rework) and reduced performance when starting the equipment.

There are no 100% reliable machines, so the possibility of occurring malfunctions, as a rule, is unpredictable. Component failure can affect equipment ability to fulfill its mission (reliability) and, in many situations, bring it to a halt, with all the resulting consequences.

In general, low equipment reliability can be caused by three factors [13]:

- poor design;
- the way it is used - questions such as whether the equipment is suitable for the purpose for which it is intended and the environment in which it will operate;
- the way it is maintained.

To safeguard the first factor, guarantees must be demanded from suppliers. However, after purchasing the equipment, it may be necessary to improve its weaknesses by implementing tuning and monitoring systems. Aspects associated with maintainability and maintenance management strategies are essential for good equipment performance. In these situations, it is essential to use appropriate methodologies and techniques [13].

2.1. Reliability Centered Maintenance

The focus of traditional maintenance is on repairing/ preventing equipment failures, while the RCM methodology focuses on equipment functions and preventing the consequences of failures. The objective of this methodology is to determine the best maintenance strategy (preventive, predictive, or corrective (Table 1) to be applied in items based on reliability criteria that result from the systematic analysis of failures, to ensure that it complies with reliability and availability specifications at the minimum cost [14].

Table 1. Types of Maintenance.

Strategy	Description
Reactive Maintenance, Corrective Maintenance, or Run-To-Failure	The good only receives maintenance interventions (e.g., repairs, replacement of parts) after failing [15]. Disadvantages: low reliability of the asset that can be reflected in its long-term interruptions and high cost (e.g., extra work, stocks ...) [15].
Preventive Maintenance (PM)	It is performed on the well before it fails, at predetermined intervals or according to prescriptive criteria [16]. Disadvantage: It implies a strong correlation between reliability and asset lifetime [15].
Predictive Maintenance or Condition Monitoring (CM)	Permanently monitors the operation of the asset to identify signs of failure, such as wear, and correct it before the failure occurs. Disadvantage: It cannot always be implemented and implies costs such as the installation of sensors [15].
Proactive Maintenance	Seeks to improve maintenance based on what was learned in previous maintenance (e.g., improving design, improving maintenance procedures) [15].

The RCM methodology, when properly conducted, consists of finding an answer to the following questions applied to each item [14]:

1. What are the item's functions (capacity, quality, service level, environment, costs, and security) and the required performance levels (or standards)?
2. How can these functions fail?
3. What causes each failure mode?
4. What happens when a failure occurs?
5. What are the consequences of the occurrence of each failure?
6. What can be done to prevent or prevent each failure?
7. What to do when a preventive maintenance policy is not possible or justified??

Some important tools support the implementation of the RCM methodology. FMEA allows answering to questions 1 to 5 [17] and the Decision diagram of the RCM methodology, usually outlined in the form of a flowchart, allows answering questions 6 and 7 [15].

To monitor the processes and assess whether the decisions made were (the most) appropriate, organizations need to define key performance indicators (KPI) [18].

2.2. Failure Modes and Effects Analysis

The FMEA is a qualitative technique of continuous improvement that seeks, through the analysis of potential failures, to identify actions that can be implemented to avoid the occurrence of these failures or, at least, mitigate their effects. Although there are several types of FMEA, the principles of the analysis are the same [19]. This should include:

- Functions of each item (component, part, subsystem, or system) in the analyzed system;
- Potential failure modes for each item - events that can cause failure states, such as component deterioration;
- Potential causes of each failure mode - corresponding to the causes that lead to the occurrence of each failure mode, such as corrosion and misuse;
- Potential effects of each failure mode - the impact of the failure mode on system performance;
- Current controls for each failure mode - methods currently implemented by the organization to prevent and/or detect each failure mode;
- Recommended actions to avoid the occurrence of each failure mode - new methods of prevention and/or detection of failure modes, and/or actions to prevent or reduce the impact of effects.

Often, to identify the failure modes for which the implementation of improvement actions would have the greatest impact, it is common during FMEA to study the criticality of failure modes. According to one of the most used methods - the RPN - the criticality of each failure mode can be assessed using three factors:

- severity of effects (S) - the severity of the consequences of the occurrence of the failure mode, considering the impact in areas such as safety, environment, and financial;
- occurrence (O) - frequency or probability of occurrence of the failure mode due to a specific cause;
- detectability (D) - ability or probability of detecting the failure mode before it occurs or, at least before the impact of its effects is felt.

By multiplying these three factors, each of them evaluated on a scale of 1 to 10 according to previously defined criteria, the RPN = S × O × D is obtained for each failure mode.

Once the critical failure modes have been identified (those with the highest RPN), priority should be given to implementing actions to reduce the criticality of these failure modes. After implementing these actions, it is necessary to assess its impact on the RPN by reassessing the criticality of the failure modes.

The FMEA technique must be developed by a multidisciplinary team whose knowledge and creativity are important for its successful application [19].

2.3. Weibull Analysis

One of the steps in analyzing the reliability of an item from a sample of its life data is choosing the theoretical distribution that best fits those data. There are several distributions (e.g., Normal, Negative Exponential, Lognormal, and Weibull) that are normally used in this type of study, with emphasis on the Weibull distribution, due to its adjustment versatility. This distribution is defined by three parameters (although it is usually presented with only two parameters, β and η):

- shape parameter β - controls the shape of the distribution;
- scale parameter η (or characteristic life) - time for which 63.21% of the items under study have already failed;
- position parameter γ (or minimum life) - if $\gamma > 0$, it means that it has a period, γ, free from failures; if $\gamma < 0$, it means that when the test started, at t=0, the item was already “old”, γ [20].

Weibull's analysis consists of estimating the parameters of the Weibull distribution that best fits the set of an item's life data. For this purpose, there are several methods, of which the graphic method (the one used in this study) and the maximum likelihood method [20] stand out.

Based on the Weibull distribution (knowing the values of its parameters), a set of reliability indices for the item in question can be obtained (MTTF, R(t) λ(t), etc.) [20, 21]. For a continuous random variable t distributed according to a Weibull, the functions Reliability (R (t) and Risk (λ (t)) are given by Equations 1 and 2, respectively.

$$R(t) = exp\left(-\frac{t-\gamma}{\eta}\right)^{\beta} \quad (1)$$

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \quad (2)$$

Parameter β can be used as a good (but not conclusive) indicator of the life stage of an item and also as a diagnostic aid for failure mode. It is known that if:

- $\beta<1$: λ (t) is decreasing - corresponds to the infant phase (failures or early failures);
- $\beta=1$: λ (t) is constant - corresponds to the equipment's life phase, with the failure mode being random and independent of time;
- $\beta>1$: λ (t) is increasing - corresponds to the wear, obsolescence or old age of equipment.

2.4. Performance Indicators

To evaluate the effectiveness of maintenance actions, the following KPIs can be used [3, 22]: Mean Time To Repair (MTTR), Mean Time To Failure (MTTF), Mean Time Between Failures (MTBF), Overall Equipment Effectiveness (OEE), Mean Down Time (MDT) and Mean Waiting Time (MWT).

Based on the idea that the ideal operating potential of equipment is not reached due to several losses, the OEE allows evaluating the operating efficiency of equipment compared to that which would be obtained under ideal operating conditions [23, 24]. This is obtained (Eq. 3) by multiplying three factors - availability (A), performance (P), and quality (Q) [24].

$$OEE = A * P * Q \quad (3)$$

There are different approaches to calculating these factors [24], depending on the author and the application context. Table 2 presents De Groote’s [25] approach.

Table 2. Approach to calculating OEE factors (adapted from [23]).

Factor	Calculation method
Quality	$\frac{Actual\ amount\ of\ production - Non\ accepted\ amount}{Actual\ amount\ of\ production}$
Performance	$\frac{Actual\ amount\ of\ production}{Planned\ amount\ of\ production}$
Availability	$\frac{Planned\ production\ time - Unplanned\ downtime}{Planned\ production\ time}$

Due to different OEE calculation approaches and differences between organizations, it is difficult to identify optimal OEE values and compare this metric across organizations. Nevertheless, for [12], under ideal conditions, the values of the availability, performance, and quality indices must be greater than 0.9, 0.95, and 0.99, respectively, therefore the OEE value must be at least 0.85 [24].

The remaining indicators, MTTR, MTTF, MTBF, MDT, and MWT are defined as follows:

$$MTTR = \frac{Total\ repair\ time}{Total\ number\ of\ failures} \quad (4)$$

$$MTTF = \frac{Total\ operating\ time}{Número\ de\ itens} \quad (5)$$

$$MTBF = \frac{Total\ operational\ lifetime}{Total\ number\ of\ failures} \quad (6)$$

$$MDT = \frac{Total\ downtime\ (due\ to\ failures)}{Total\ number\ of\ failures} \quad (7)$$

$$MWT = \frac{Total\ waiting\ time\ for\ repair\ to\ start}{Total\ number\ of\ failures} \quad (8)$$

3. Case study

In this section, there is a brief presentation of the TEM, which are the object of this study, covering its constituent parts and the maintenance policy. Based on the little data available and the knowledge of the operators and maintenance technicians about these pieces of equipment, a diagnosis of the current situation of the TEM concerning reliability and maintainability was carried out, supported by a coherent set of performance indicators. Since its operational failures are a critical factor for productivity and taking into account what is referred to in section 2.1, the RCM methodology was assumed as the maintenance methodology to be followed by the company and it structures the case study.

3.1. Transmission Electron Microscopes

Although there are some differences between TEM of different models or versions, the working principle of this equipment is the same - a beam of electrons passes through a sample suffering different types of scattering depending on the characteristics of the material. The electrons that suffer little deviation cause bright field images, while the electrons diffracted by the crystalline planes of the material cause dark-field images [8].

A TEM (Fig. 1) is a complex piece of equipment that, in general terms, can be broken down into the following parts: (i) Column; (ii) Commands; (iii) Computer; (iv) Other Equipment.

Fig 1. Transmission Electron Microscope JEOL JEM-1400Plus.

3.2. Diagnosis of the current situation

A general analysis of the current situation of the operation and maintenance of the TEM, through the consultation of operational and maintenance data, meetings and workshops with operators, maintenance technicians and managers of the maintenance process, allowed, the identification of the following problems that can be grouped into three categories:

1. Maintenance plan and record of the accomplishment of the planned tasks:
   - The maintenance plan is not structured so that maintenance technicians can easily be aware of the maintenance tasks planned for each day and inform the production planner for potential deviations of the time required for planned maintenance;
   - There are no reliable records about the maintenance tasks carried out.
2. Record of corrective interventions performed at TEM:
   - The record of corrective interventions performed in each TEM is not standardized, i.e., not all records contain the same type of information (description field) and different technicians (sometimes even the same technician!) refer to the same anomaly differently.
3. Assessment and improvement of the current status of TEM maintenance:
   - History of corrective interventions performed at TEM makes it impossible to conclude the causes of the occurrence of anomalies;
   - The preparation of the weekly Breakdown requires time for specialized maintenance technicians to record information that they have already recorded in the intervention history of the equipment's life sheets.
   - Not all maintenance interventions performed are always recorded at the Breakdown, so the Breakdown report may not accurately portray reality;
   - Absence of a system of maintenance performance indicators.

Several of the identified problems are linked to TEM failures. To deepen the diagnosis of these problems, a TEM

FMEA was carried out, which will also be used as a tool for risk analysis and continuous improvement [26].

3.2.1. FMEA of TEM

A multidisciplinary team was formed to prepare the FMEA of the TEM. It was composed by one of the authors of this paper, two maintenance technicians, and two TEM operators. Fig. 2 shows an excerpt from the FMEA and the full version is available in [27].

The identification of the potential failure modes and the respective occurrence was made through the analysis of the records of maintenance interventions, of all TEM existing in the company operating under identical conditions, carried out during the last year.

The criticality of each failure mode was assessed according to the Risk Priority Number (RPN). Table 3 highlights the criteria used to define the scale values (1 to 10) for each of the RPN factors.

Table 3. Criteria for defining the values of the RPN factors.

Factors	Criteria
Severity of Effects	– Operational Impact, Environment, and Security (OIES); – Operational Flexibility (OF); – Repair costs (RC) of failure mode.
Failure mode occurrence	– Frequency of failure mode occurrence in relation to the occurrence of all failure modes during the studied period.
Failure Prevention and Detection Capability	– Existence of methods or devices for preventing/detecting the failure mode and/or mitigating its effects; – Effectiveness of these methods, devices or and procedures.

The value of the severity factor (S) and the respective criteria presented in Table 3 are related by the following equation:

$$S = OIES \times OF \times RC \quad (9)$$

In turn, the criteria used to determine the severity factor of the effects of each failure mode were evaluated according to the sub-criteria presented in Table 4.

It was necessary to normalize the severity factor (convert to values on a scale of 1 to 10) to give generality to this study and to ensure comparison with other studies. Table 5 shows how this normalization was carried out. For example, for a non-normalized value of S = 45, obtained by (9), the corresponding normalized value (scale from 1 to 10) would be 4.

Table 4. Sub-criteria used to assess the criteria of the severity factor of the effects of failure modes.

Criteria	Sub-criteria
OIES	– Impact of failure mode on production; – Time needed to repair the failure mode; – Maintenance team trained to repair the failure mode; – Impact of failure mode in terms of safety and environment..
OF	– The existence of redundant equipment or other alternatives available that allows reducing the impact on production, i.e., the unavailability of TEM during the repair of the failure mode.
RC	– Financial impact of the failure mode occurrence.

Table 5. Normalization of the severity of effects factor.

S	Normalized S	S	Normalized S
$S < 14$	1	$62 \leqslant S < 74$	6
$14 \leq S < 26$	2	$74 \leqslant S < 88$	7
$26 \leq S < 38$	3	$88 \leqslant S < 102$	8
$38 \leq S < 50$	4	$102 \leqslant S < 116$	9
$50 \leq S < 62$	5	$116 \leqslant S$	10

From the FMEA it was found that the majority (about 75%) of the failure modes have RPN lower than 50 and the highest risk failure mode has an RPN of 200. Figure 3 shows the main failure modes of TEM, ordered in decreasing order of RPN.

Based on the potential causes for the occurrence of the failure modes, the associated effects, and the existing control/mitigation mechanisms, some actions were recommended by the FMEA team to reduce the risk associated with the failure modes (RPN value). Of these, we highlight the failure modes whose potential causes are related to the TEM operators' competence. Awareness posters about the importance of the good use of the equipment and its maintenance should be created and displayed in the company. In the case of failure modes whose occurrence is related to the use/wear of the equipment throughout its operating time, it is recommended to implement methods of prevention and/or early detection of these failure modes.

Before deciding to implement any of the proposed risk reduction actions, it should be investigated its expected cost.

Subsystems/ Components	Potential Failure Mode	Potential Effects of Failure	Sev.	Potential Causes/Mechanisms of Failure	Occ.	Current Design Controls		Det.	RPN	Recommended Actions
						Prevention	Detection			
Unknown/ Not defined	Unknown failure mode / No failure mode	TEM must stop (reason: air inlets)	4	Operational error (technician pulls the sample holder out of the goniometer with great force; technician forgot to turn on the vacuum button)	5	None	Through the effects	10	**200**	Training actions for TEM operators
Filament	Broken filament	TEM must stop (nothing can be done: total failure)	7	Intensive use and is damaged with air intakes	2	None	Through the effects	10	**140**	Poka-yoke development
Other/ General	Faulty processing board	TEM must stop (PC does not communicate with TEM: total failure)	9	Operational error (Air intake when moving the sample holder)	1	None	Through the effects	10	**90**	Training actions for TEM operators

Fig. 2. An excerpt from the TEM FMEA.

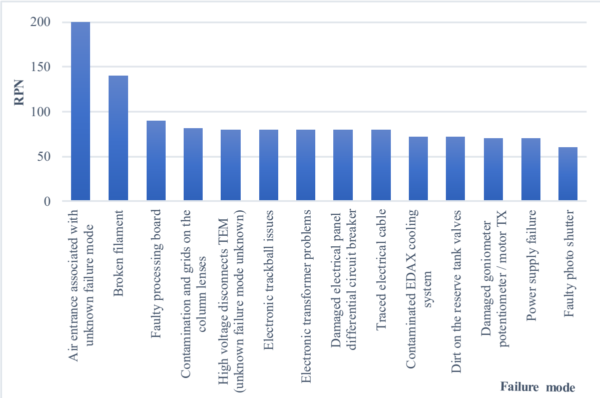

Fig 3. TEM failure modes and respective RPN.

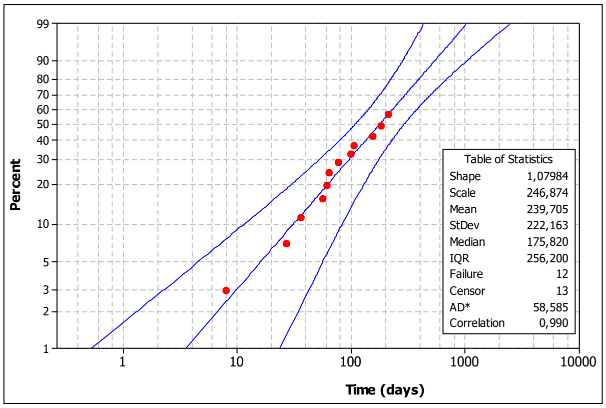

Fig. 4. Results obtained in Minitab for adjusting filament life times to Weibull Distribution.

3.2.2. RCM logic tree decision

The RCM logic tree [13] guides decision making on the best maintenance strategies (preventive, predictive, and/or corrective), which should be applied to each part of the TEM considering the risk associated with failure modes. To understand the feasibility of implementing preventive maintenance, a study was carried out on the lifetime of the TEM filament - a component associated with the failure mode with the highest risk. This filament may fail due to the use/wear of the equipment components throughout its operating time.

3.2.3. Analysis of filament lifetime

The lifetime (in calendar days) was obtained from the time a filament is placed in a TEM until it fails or it is replaced (the TEM is permanently turned on). The data presented in Table 6 were collected from the set of records of TEMs' maintenance interventions. This data was also analyzed to support FMEA development. Data quality is crucial to carry out this type of study. Although this is a practice in the studied company, the records are not made consistently, presenting some errors and making difficult to extract useful information.

Using the Minitab 16® software, some tests of adjustment of statistical distributions were made to the sample of data under study, having chosen the Weibull distribution, given the quality of adjustment obtained and the failure mode under consideration (wear of the filament due to use). Figure 4 shows the Weibull graph obtained for the data under analysis.

Table 6. Filament lifetime data (in days).

Lifetime	Type	TEM	Lifetime	Type	TEM
106	F	1	148	C	6
4	C	1	268	C	7
183	C	1	375	C	8
182	F	2	56	F	10
217	C	2	99	F	10
27	F	3	134	C	10
279	C	3	213	F	11
155	F	4	41	C	11
77	F	4	8	F	12
167	C	4	36	F	12
64	F	5	180	C	12
279	C	5	138	C	13
61	F	6			

F- Fault; C- Censored

The correlation coefficient r^2=0.99, suggests that the Weibull Distribution, with β =1.07984, η = 246.9 days and γ=0 days, makes a good adjustment to the filament's lifetime. As β>1, the failure rate of the filaments increases with time (Fig. 5), indicating systematic preventive maintenance as the best policy to adopt for the maintenance of the filaments. However, given that the value of β is very close to 1 (value for which the failure rate is constant over time, running the failures at random), the adoption of this maintenance policy for the filaments needs further technical/economic analysis.

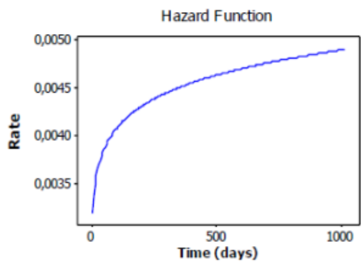

Fig. 5. Graphical representation of the filament failure rate function.

Finally, one of the causes pointed out for the filament break was the deterioration caused by the air intakes - critical failure mode, resulting from operational errors. It is expected a greater awareness of TEM operators to reduce the occurrence of this failure mode and, consequently, increase the life of the filaments.

3.2.4. Maintenance performance indicators

In addition to the referred problems, there is a lack of structuring of the maintenance plan and the absence of a set of maintenance performance indicators. Thus, it was not possible at this stage (diagnosis of the current situation) to evaluate the maintenance performance indicators presented in section 2.

To address these problems was developed an application in Microsoft Excel for maintenance management, using VBA (Visual Basic for Applications). The decision to develop the application instead of purchasing a commercial application was related to the following aspects:

- Inexistence of a specific commercial application for similar companies;
- Predictable difficulties in adapting commercial applications to this context;
- The high cost of acquisition/maintenance of commercial applications;
- Dependency on the company that markets and/or develops and updates the commercial application.

3.3. Implementation of improvement proposals

3.3.1. Computer application for maintenance management

Given the problems identified in the diagnosis made at TEM and the main objective of this project, the application developed had as main requirements:

- Allow to register the corrective maintenance interventions carried out in the TEM in a uniform manner;
- Allow to register the tasks that are planned to be carried out, not only at the TEM but also at other company equipment and access this planning more intuitively;
- Allow to generate reports automatically with information on maintenance performance;
- Allow the calculation of OEE.
- Be easy and quick to use;
- Be flexible;
- Have mechanisms to avoid errors, omissions, and the unintentional removal of information.

To meet these requirements the application is constituted by three parts: corrective interventions, planned interventions, and maintenance reports. The Maintenance Report has three sections: corrective maintenance, planned maintenance, and failure modes. These parts can be accessed by the user on the application home page and through the navigation panel of each page. To facilitate the application usage, the navigation panel allows access to a page with instructions for use. Application details are presented in [26].

For the application to be faster to use, some fields of the user forms are self-fulfilled. However, they can be changed. To avoid errors and omissions, whenever any operation is validated, it is verified that all mandatory fields are filled in, and a message is displayed otherwise.

Each Maintenance Report, produced periodically and automatically, contains the performance indicators shown in Table 7.

Table 7. Performance indicators included in the maintenance report.

Corrective maintenance	**Planned maintenance**	**Failure modes**
– Costs	– Costs	– Costs
– Nº of Failure Communications	– Total time spent	– Number of occurrences
– MDT	– Number of tasks completed on the scheduled date	– MDT
– MTTR	– Number of tasks completed late	– MTTF/ MTBF
– MWT	– Number of tasks completed before the scheduled date	
	– Average number of days late	
	– Average number of days in advance	
	– Number of canceled tasks	

These can be consulted by month/week and by TEM. At the end of the report is presented the evolution of these indicators over the months/weeks of the year.

In the maintenance report, Planned Maintenance, are presented the reasons for rescheduling and canceling tasks. To calculate OEE by TEM and by week/month, a new separator was created (Fig. 6) using the expressions shown in Table 2.

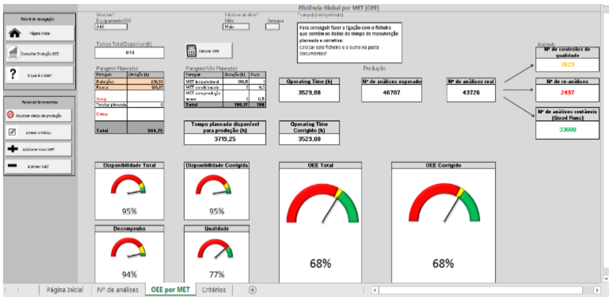

Fig. 6. OEE Board of Laboratory 1.

3.3.2. Analysis of results of improvement proposals

A careful analysis and discussion of the results obtained for the performance indicators allow to evaluate/monitor the TEM and the maintenance management, and propose new measures to improve the performance of the entire process, thus initiating a new cycle of improvement.

The first version of the application is implemented and gradually being used in the company. In general, the feedback is very positive - the application complies with the requirements initially defined. It is expected that when fully implemented in the company, the application will be of great use.

Through the OEE will be possible to have a better knowledge of the productivity improvement of TEM and, together with the other performance indicators that appear in the periodic reports produced automatically, will allow making more informed decisions to minimize costs and improve performance.

4. Conclusions

The adoption of the RCM methodology supported by a set of tools (FMEA, Weibull analysis, Pareto charts) proved to be adequate for the case study.

The FMEA tool was useful in this study of risk analysis and assessment of TEM failure, as it was in many other studies. Some difficulties were perceived in the evaluation of RPN, resulting from the subjectivity in the definition of the factors' scale levels. The lack of published works with this type of equipment in similar contexts constituted a challenge and impeding the use of Benchmarking.

Operators' responsibility and coherence during data acquisition regarding equipment maintenance are indispensable to have good quality data, which allows obtaining reliable performance indicators, such as OEE, MTTF, or maintenance costs.

There is much commercial software for maintenance management on the market that helps in this task. However, the specificity of many companies, such as the one of this case study, presents, among other disadvantages, increased adaptation and implementation efforts. Particularly in these cases, the possibility of companies developing applications adapted to their reality should be considered, considering the advantages and disadvantages of such a decision.

In this project, the computer application for maintenance management was developed in Microsoft Excel using VBA. Despite being a time-consuming task, the option for Microsoft Excel proved to be a good route, although limitations in terms of data that it can store are recognized, which do not make it suitable for all situations. Alternatively, Databases and Data warehouse tools could have been developed, such as MySQL, among others.

For specific equipment such as TEM, OEE proved to be a good performance indicator of the equipment's efficiency, allowing it to identify productivity losses, thus constituting a good decision support tool.

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