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Chapter

Maintenance and Asset Life Cycle for Reliability Systems

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Abstract

This chapter presents tools, methods, and indicators, in order to develop a successful and modern maintenance program. These are based on reliability engineering that improves the reliability of a system or complex equipment. Frequently, the industry implements maintenance schemes, which are based on equipment's manufacturer's recommendations and may not apply changes throughout the asset life cycle. In this sense, several philosophies, methodologies, and standards seek to assist this process, but most of them do not take into consideration their operation characteristics, production necessity, and other factors that are regarded as being important to one's company. This method is based on the analysis of preventive component replacements and the subsequent critical consequences. These analyses may be used as a decision-making tool for defining component replacement decisions. In this chapter, the first section introduces and justifies the importance of this topic being approached from the perspective of asset management. Next, it discusses key maintenance concepts and techniques, with the aim of establishing the foundation of a maintenance management. The purpose of the final section is to present a maintenance strategy model, and it presents the findings of the case study about model implementation at home cleaning service company.

Keywords: maintenance asset management, reliability management, maintenance optimization procedure

1. Introduction

Industry implements maintenance schemes based on equipment manufacturers' recommendations that might not be able to generate positive changes throughout the asset's life cycle. For instance, some diesel engines are designed to operate in Europe. Maintenance tasks need to be adjusted to operate in the South American tropics. This also happens with automatic transmissions. These tasks, sometimes, are neither adjusted nor improved. In this sense, several philosophies, methodologies, and standards seek to assist this process; however, most of them do not take into consideration their operation characteristics, production necessity, and other factors that are important to a company.

This chapter presents a modern maintenance strategy proposal aimed to comply with the ISO 55000 series of standards. These strategies are needed to develop a successful and modern maintenance program. In doing so, an appropriate maintenance strategy ought to be defined that will form the foundation for ensuring a high reliability degree of operating production systems. The challenge is to restructure maintenance strategies and, hence, to guarantee a high reliability level of the production system operations. The strategy presented herein was validated in a transport truck public company's policy regarding operational excellence and asset management, achieving satisfactory results.

The concept of "maintenance" in the industry has evolved in the last two decades. It is no longer seen as an expense or a team simply responsible for replacing production system components. Now, maintenance is considered an indispensable activity which guarantees not only the availability and functionality of a system or a component but also the high quality of the goods and services produced [1]. Likewise, in the early years, maintenance has solely been the responsibility of mechanical and electrical engineers. However, managing maintenance activities has become a multidisciplinary and far-reaching task within the organization. Maintenance directly impacts levels of production, budgets, timelines, and forecasted profits. Maintenance also increases the lifetime of equipment and ensures acceptable levels of reliability during usage. This occurs in every step from preventive maintenance through redesign. Moreover, operation teams must adapt to the specifications of each piece of equipment and each industrial need. Critical equipment may not have been manufactured uniquely for the organization's specific facilities, operators, or supplies. Additionally, proper management of equipment lowers operational costs. It reduces energy consumption, maintenance resources themselves (such as spare parts and labor), and risks to system operators, facilities, and production. Overall, managing maintenance activities results in savings for the organization.

However, production and engineering leaders focus on generating, modifying, and restructuring maintenance plans. Organizations consider the following questions: "Where to begin?" "Do we need to restructure the department of maintenance?" "Is it necessary to create management for this field?" "What kind of structure should we use?" and the like.

The objective of this chapter is focused on identifying three fundamental pillars for highly reliable systems: managing information, creating indicators, and restructuring preventative maintenance plans. These concepts aim to support production and maintenance managers in decision-making processes. They equally intend to support individuals and organizations seeking excellence in maintenance management practices in terms of facilitating decisions based on information with principles of excellence.

This chapter is organized as follows:

Section 2 provides a brief history of maintenance management and the definitions, related terms, and fundamental concepts.

Section 3 presents the proposed maintenance strategy model and the main results and analysis stemming from a study case. Lastly, conclusions are drawn in Section 4.

2. Literature review

Several scholars postulate the necessity of creating an integrated maintenance management system. This management system should aid the decision-making process and include some level of forecasting acknowledging the inevitability of occasional failure [2]. In other words, effective management requires systems and tools to predict the reliability of production systems. Predicting failures or defects with a high degree of certainty allows the operator to manage logistics and resources necessary to make interventions with the least impact on production [3, 4]. Moreover, it is necessary to clearly identify the goals of maintenance management within the organization, which must fully align with those of corporate management. Thus, maintenance decisions ought to be strategically framed within the corporate mission [5, 6].

The major changes to maintenance strategy are due to a need for more efficient production lines. The latter was sparsely automated, of low complexity, and only corrective in nature before the Second World War. Performed literature review reveals that this era of maintenance strategy came to a close in the 1950s [7]. From this point until the 1970s, the so-called second maintenance generation was developed. This era was characterized by the implementation of process planning, the advancement of technology, and more complex equipment. It also marked the beginning of industrial automation. In short, maintenance was based on well-defined cycles of spares, replacement, and reconstruction of equipment. In the pursuit of high reliability levels, these cycles became very short and ultimately drove an increase in maintenance costs [8].

The third generation of maintenance was marked by the influence of the aeronautical industry and their particular maintenance needs as required by the Federal Aviation Administration, in particular with the start-up of the Boeing 747 aircraft [9].

This change to maintenance brought financial hardships, which is why United Airlines formed a team to evaluate potential means of developing a new preventive maintenance strategy so as to find the balance between safety and costs in the operation of commercial aircrafts [10]. These changes have been considered and implemented in maintenance planning and activities for large aircrafts up to now. The circular advisory, maintenance steering group (MSG-3), presented a methodology for developing scheduled maintenance tasks and intervals acceptable to the regulatory authorities, operators, and manufacturers [11]. Years later, the MSG-3 gave rise to the current methodology of reliability-centered maintenance (RCM) [12]. The same was characterized by increasing demands in terms of quality for products and services alike. This in turn gave rise to standards and regulations that called for implementing changes in the traditional way of operating production systems. In the never-ending quest to establish optimal conditions for preventive maintenance, the probability and reliability studies of the aeronautical industry were applied in the production industry, as well. These early reliability studies were initially applied to providers of electrical energy in thermonuclear power plants, soon to be followed by the gas and petroleum industry, and was finally adopted and implemented by the general industry [13, 14].

The application of maintenance-specific reliability concepts characterized the fourth generation of maintenance standards, which in turn exemplified high-quality production and described the need for addressing operators' safety, as well as the proper operation of the equipment and the protection of the environment [15]. The fourth generation wanted to keep sight of resource optimization or the production of high-value goods. Value is defined as performance over cost and is presented in Eq. (1):

$$Value = \frac{Performance}{Cost} \tag{1}$$

Currently, the concepts of risk assessment and operational excellence were incorporated as a target of maintenance activities to minimize system failures and to guarantee reliability and availability. This maintenance stage was characterized by the implementation of risk-based maintenance techniques, such as risk-based maintenance (RBM) and risk-based inspection (RBI), which take the risk of an issue into account for the entire maintenance processes. At the same time, it was influenced by the new management standards, namely, asset management and facility management [16, 17].

The Federation of European Risk Management Associations (FERMA) states that it would be practically impossible to encompass every technique for risk analysis in a single standard and, likewise, impossible to resolve all problems with only one method. For this reason, each industry must adapt or develop its own method instead of trying to find a single general method. In other words, the methods implemented must consider the actual operation and asset failure, as well as the operating environments thus far, since all these aspects affect its performance.

2.1 Concepts and definitions

The British Standard Glossary defined maintenance as "the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function" [18]. In addition, maintenance is a set of organized activities that are carried out in order to keep an item in its best operational condition with minimum cost required. Likewise, maintenance tasks are defined as "Sequence of elementary maintenance activities carried out for a given purpose. Examples include diagnosis, localization, function check-out, or combinations" [19].

Preventive maintenance is the performance of inspection and/or servicing tasks that have been pre-planned or scheduled for specific points in time in order to retain the functional capabilities of operating equipment or systems [20, 21]. Other standards such as ISO 13372:2012 [22] define preventive maintenance as "maintenance performed according to a fixed schedule, or according to a prescribed criterion, that detects or prevents degradation of a functional structure, system or component, in order to sustain or extend its useful life."

Corrective or reactive maintenance is carried out after fault recognition and intended to put an item into a state in which it can perform a required function [23]. This maintenance policy is also called failure-based maintenance because the asset is operated until it fails.

Predictive maintenance refers to the routine inspection of equipment, machines, or materials to prevent a failure. It is a type of proactive maintenance that focuses on determining the potential root causes of machine or material failure and dealing with those issues before problems occur. It is achieved by the measurement of some physical or performance variable [24].

Robert Davis defined asset management as "a mindset which sees physical assets not as inanimate and unchanging lumps of metal/plastic/concrete, but as objects and systems which respond to their environment, change and normally deteriorate with use, and progressively grow old, then fail, stop working, and eventually die" [25].

Table 1 shows additional important concepts of maintenance management for reliability systems, in which the following four factors are recognized:

a. Equipment has a life cycle

b. Maintenance management is as important for those working in finance as it is for engineers

c. It is an approach that looks to get the best out of the equipment for the benefit of the organization and/or its stakeholders

d. It is about understanding and managing the risk associated with owning assets such as equipment

2.2 Fundamental aspects in the maintenance strategies

Maintenance decisions are of diverse natures and, depending on the level of impact, require proper identification and ranking. This is the starting point to develop suitable management policies and bring assertive strategies of reliability. Decisions associated with production maintenance are of four levels:

a. Instrumental (dispatch)

b. Operative

c. Tactical

d. Strategic

The strategic level incorporates the top direction of the organization and the maintenance implementation with tangible results in a time frame upward of 2 years. These decisions require important investments of resources and market studies, opportunities, and returns on investment.

In operations and production, tactical decisions generate results within several months to 1 or 2 years. Tactical decisions are made by management and mid-level management, involve project modifications, and often are associated with important investments. Operation-specific decisions have immediate impact (from several days to a few months) and are made by technical personnel that do not require changes and investments in the operational budgets. Instrumental or dispatch decisions are also made by technical personnel. The costs related to these decisions are considered in the plans pertaining to preventive maintenance, and their impact is reflected in hours. The maintenance activities related to these decisions are called adjustments.

Often, the governing bodies of the industries only stop to consider the need to restructure their departments or maintenance processes when faced with frequent expensive failures or costly downtimes that cause significant production losses. In addition to the above, performed research indicates that implied processes of documentation and registration processes are precarious, even though, in many cases, significant sums of money have been invested in information systems. When

Term	Definitions
Availability	Ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided
CBM	Condition-based maintenance: preventive maintenance which includes a combination of condition monitoring and/or inspection and/or testing, analysis, and the ensuing maintenance actions
CMMS	Computerized maintenance management system: a system that can provide important information that will assist the maintenance management in planning, organizing, and controlling maintenance actions
CMMS	Computerized maintenance management system: a system that can provide important information that will assist the maintenance management in planning, organizing, and controlling maintenance actions

Table 1.
Concepts for maintenance management for reliability systems [26].

confronted with these loss-potential scenario initiatives to strengthen and structure, the corresponding maintenance departments are taken.

The following are the first steps to properly establish the maintenance requirements inside the organization to guarantee high reliability, equipment availability, and compliance with operational and environmental risk regulations.

It has to be noted however that discussing the performance evaluation of a production system without having prior implemented a maintenance information system may lead to inherent failures. Indeed, an MIS is a tool in which failures, time interventions, spare parts, etc. are saved, treated, and processed in order to inform maintenance managers and facilitate decisions. Although there could be other tools to evaluate the performance of the production equipment, the maintenance information system is where the key indices are considered and integrated with the general maintenance strategies.

Overall, a maintenance information system has four main functions:

a. Collect data

b. Support engineering decisions

c. Record interventions

d. Plan for spare parts and equipment expenses [27, 28].

The MIS can be integrated with a general computerized maintenance management system (CMMS).

The following sections introduce on the one hand its basic aspects and on the other hand highlight the means of using one for performance evaluations and, subsequently, decision-making processes.

In order to have organized and conscientious data collection, it is imperative to define the following:

a. The critical assets

b. The failure

c. The desired capabilities and limits according to the functions for which the assets were designed

The reason therein may be associated but not limited to the fact that the plant could have hundreds of assets which could result in useless, inefficient work. Data collection should begin with an organized set of information which must include static information, such as:

- Hierarchy classification
- Nameplate information
- Processes and instrumentation diagrams (PIDs)
- Assembly and spare part drawings
- Functional analysis charts

- Catalogs, technical bulletins, etc.

Once static data is collected, it is important to record information related to failures and interventions. It is at this point where the record of work orders and failure report may be used as it may be regarded as the foundation of the availability and maintenance indicators incorporating essential information concerning financial planning and evaluation. The correct filing of work orders should include at least the nametag of the asset, time records, workforce, downtimes, spare parts, and detailed descriptions of activities and operative windows.

Similarly, a fault report should accurately describe the type, nature, and time the fault was observed and, if it is already cataloged, put the fail mode number or tag. There are international standards such as the ISO 14224 describing general guidelines to report faults and tag them. One of the biggest benefits of recording the failures according to the international standard is the ability to share and use information to estimate failure rates. An example of the failure rate prediction and database is in the OREDA Handbook for the offshore oil and gas industry [29, 30].

A work order is the main tool that allows recording fault information. It begins with a planning process in which the workforce, deadlines, procedures, and route sheets are established. The work order continues with a programming stage where the precise dates and the maintainer's ID are selected, and, after this, the work order is executed and closed in the information system. This last step may be regarded as the triggering point and the interface to the real world as it gives rise to all these processes, since it documents and depicts in the equivalent data record, the KPI's computing, evaluation, and the provision for making decision [31–33].

Even so, work orders and failure reports are not enough. If only work order data is tracked, it is difficult to establish tendencies, averages, and alerts. As such, it may not be possible to establish equipment-specific degradation levels as well [34]. This is when quantitative variables become necessary because they indicate the performance state of the equipment. These quantitative variables come from sensory devices such as gauges, thermometers, pressure and temperature transducers, flow meters, gas detectors, vibration sensors, etc. It is important to highlight the fact that a quantitative variable could be useful only if the correct functions of the equipment and their parameters are well established. This may be demonstrated by using the PF curve [35]. In some plants, SCADA and DCS are commonly found where the variables can be analyzed remotely and stored, and, in many cases, they are only used for operational purposes. In brief, quantitative and qualitative maintenance and cost data are necessary to evaluate the performance of any asset or piece of equipment.

3. Result and analysis

3.1 Proposed maintenance strategy model

The model proposed strategically incorporates the "better practices of maintenance management" in order to achieve operational excellence in the framework of the international standard ISO 55000:2014. Better practices in maintenance management have the following attributes: they are realistic, specific, achievable, and tested in the industry; they contribute in making maintenance more efficient and profitable, while optimizing operation costs and improving equipment's reliability. Authors have equally postulated an overall improved level of satisfaction and motivation among personnel [36].

In order to identify the most relevant indicators facing a company's maintenance strategy, it is necessary to distinguish between effectiveness and efficiency. For maintenance purposes, effectiveness measures the health of equipment, while efficiency measures the state of the equipment in comparison with the effort and resources needed to maintain that state (**Figure 1**).

Once relevant assets, work order flows, and related indices for efficiency and effectiveness are identified, it is possible to discuss maintenance optimization and economic evaluation by considering how to predict failure rates with quantitative and qualitative data. Although a common maintenance information system does not include tools such as FMEA, RCM, and data analytic packages, it is important because it allows users to analyze information and the subsequent decision-making. In conjunction with the data collected, different maintenance strategies (preventive, periodic, and predictive) can be analyzed and compared.

The model incorporates the building blocks of the ISO 55000, PAS 55, and ISO 39001 series of standards and promotes the development in three stages, namely:

a. Planning

b. Process design

c. Maintenance management

It is worth noting at this point that all stages mentioned above integrate personnel, processes, and the equipment in an improvement cycle, as described later.

The proposed model is based on the requirements of an asset management system set out in the international ISO 55000 and ISO 55001 series of standards while considering aspects of the ISO 39001 standard. The latter addresses the fundamentals for developing a road safety management system, such as shown in **Figure 2**.

3.1.1 Phases of the maintenance strategy model proposed

The development of a maintenance strategy model could be a long process, and it could depend on each productive system or company guidelines or even real context. Due to the latter, it could be difficult to run into a particular methodology which comes over all necessities. It has the intention to bring up some guidance for the achievement of a maintenance strategy. Although this guidance has a general focus, it was applied in a truck fleet and consequently may be more specific in some areas/ideas.

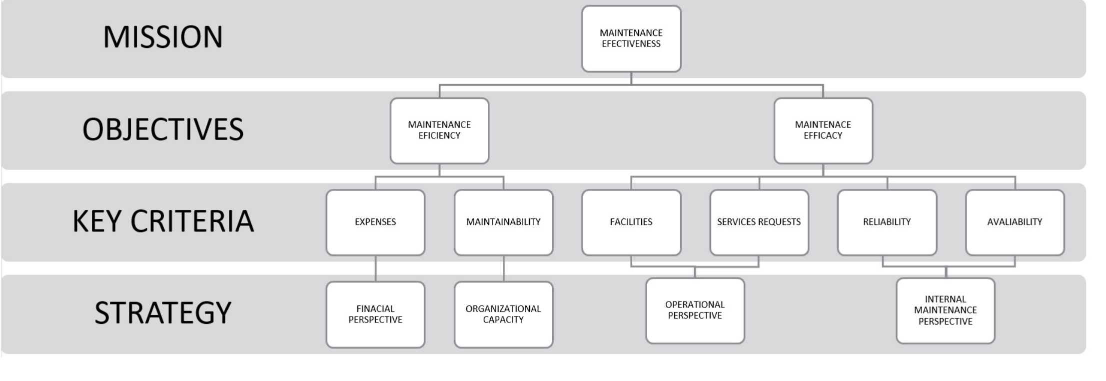

Figure 1.
Maintenance effectiveness indicators.

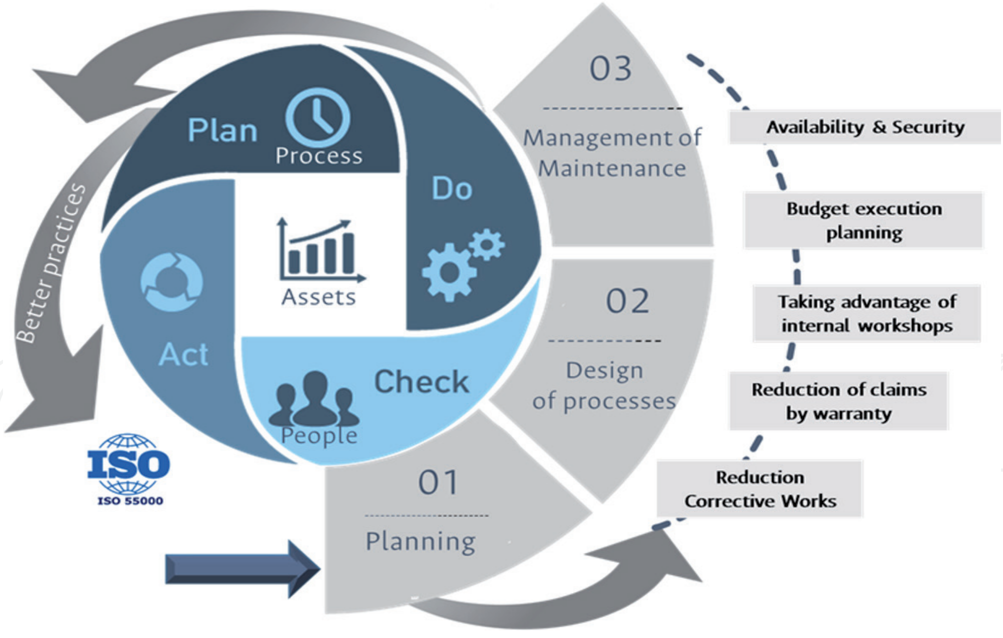

Figure 2.
Excellence model.

For the reason that the proposed model is based on the guidelines of international standards, it is suggested that the aforementioned fundamentals be considered during the execution of each stage of the model. These stages are developed through frequent interaction of the staff (tactical and operational level) with the maintenance processes and finally the interaction with top-level management in charge with setting up the company's strategy.

In order to develop the model, the following stages are considered:

a. Planning

b. Process management

c. Data collection

d. Process evaluation

e. Baseline development

f. Feedback

The development of these phases results in a maintenance management process that is lately generating value for the organization:

- Planning maintenance management: In this stage, the current state of corporate maintenance management is analyzed, considering the mission of the organization, the identification of the vision and mission, and the core focus of the business. The strategic indicators have to be considered and raised and defined in the "performance evaluation" with the aim to establish the starting point and address the processes to higher levels of excellence. In this stage, activities this stage, activities such as budget planning and execution, maintenance plan checking, resource planning and spare part planning, predictive task managing, and inspections, among others, ought to be considered [37].

- Process management: This stage introduces the current activities developed in maintenance management teams. Contextualization is necessary when the organization is in the process of restructuring. This applies in cases such as a new maintenance management team or if an asset management process is being structured. Maintenance management must be studied and reconsidered in the context of pursuing operational excellence. This full process is developed with the goal of not interrupting daily operations by structuring of the new maintenance strategy. Developing this stage often initiates documentation that becomes the basis of the maintenance strategy and endures over time.

- Data collection: The objective of this activity is to collect all information available from the maintenance department regarding assets such as technical sheets, roadmaps, plans and current maintenance frequencies, manuals of parts and components, spare part catalogs, checklists and inspection formats, inventory of components and assets, management procedures and technical processes, considerations, results of current indicators, and requirements.

This stage can be complex depending on the organization. It is the authors' view that even if one does not manage to complete the whole survey, one should continue onto the other stages. It is deemed that this point should not become a "dead end" or a bottleneck of the process. In the future, one may update it using on the one hand the information system and on the other hand, information from providers, among other sources. In order to accomplish this stage, it is necessary to devote workforce and work plans so as to do all data collection tasks.

- Information assembling and analysis: This stage, as its name implies, consists of the organization of information. A large part of its success relies on focusing on the amount of information collected in the previous stage. At this point the information is organized in order to eliminate irrelevant matters that are of no value to a company's strategic objectives. As such, the needs of storage, capture, and updating are defined. Additionally, it is the authors' view that corporates information systems such as ERP, EAM, CMMS, or simply databases ought to be further developed and incorporated for measuring purposes.

Once all the relevant and necessary data have been compiled, the evaluation of the characteristics of the data that incorporates, among others, the identification of the information needs, the update or the creation of formats and the feedback of the new processes, if necessary. It is the authors' view that this stage should mark the participation of the information technology (IT) teams, which will define the most appropriate computational tools to load the information systems. The vast majority of robust information systems communicate in a friendly way with database files, since they are well structured by the IT team. With regard to maintenance activities, this point should equally identify any shortages such as maintenance plans, frequency adjustments, elimination of assets not in use or already written off, equipment not incorporated, etc.

- Process evaluation: At this stage, the existing processes in the maintenance management system are surveyed. It is worth noting that from a study [38] of about 14 companies in the mineral extraction sector, only 4 companies had documented processes associated with maintenance activities, the vast majority of which were related to purchase processes. Once processes have been documented, the effectiveness of these ought to be analyzed, by identifying the inputs and outputs of each and their means of interrelation. Emphasis ought to be placed on the structure needed to capture the data that can generate management indicators and establish controls. At this stage, the team must work more closely with the quality team in order to verify the documentation processes of the international standard [39].

This phase will bring to light any potential needs pertaining to the modification and the generation of new processes that are accompanied by all the documentation and methodology. This is detailed in previous sections:

- Baseline development: It is to generate a minimum state in the equipment that thoroughly satisfied its primary functions. This state must have an acceptable level of reliability for them to operate safely. This point is possibly the most complex because it consolidates the previous stages in order to generate a baseline of work. This is where the mission and objectives of maintenance management are well-defined. The KPI classes are defined to follow up on new and consolidated ones. Only with the fulfillment of this stage do operation structures change for improved productivity. Also, savings begin as a result of the elimination of redundant or unnecessary processes. The generation of the baseline gives a solid start to the knowledge of maintenance needs in the organization [40]. To complement this stage and its results, it is necessary to communicate with the personnel involved and responsible for production, by identifying improvement opportunities, defining the actions to be implemented, and clearly establishing the requirements necessary for an adequate implementation of the strategies.

- Feedback: As a fundamental part of the operational excellence model, the team will be confronted with the strategic objectives of this project. These activities are monitored, and improvement plans are established (preventive or corrective) in accordance with the traditional process of continuous improvement presented by the Deming Prize Committee in 1950 [41].

3.1.2 Maintenance process design

This section presents the necessary processes pertaining to maintenance management which are presented under the guidelines of the international standards [42], such as:

- EN 16646 Maintenance—Maintenance within physical asset management

- ISO 55001 Asset management—Management systems—Requirements

- ISO 9001 Quality management systems—Requirements

According to the ISO 9001 standard, a process is the set of mutually related activities that interact, transforming input elements into ISO 9001 output elements. In maintenance management, the input elements are usually associated with operational demands, requests for intervention over assets, results of internal and/or external audits, needs for the maintenance of assets, and customer requirements, among others. In order for these to be transformed into maintenance plans, preventive, corrective, or improvement actions are aimed at achieving strategic goals. The objective of designing a process for maintenance management is to achieve compliance with the specifications required by all interested parties (customers, shareholders, related entities) such as costs, quality, flexibility, availability, reliability, maintainability, operation times, environmental regulations, safety, and health, among others.

Consequently, it involves making strategic decisions regarding human resources, machinery, tools, materials, infrastructure, methods, and technologies to be used. In general, it is the authors' view that it is necessary to design or redesign a process in the following cases that involve:

- Important modifications in the requirements
- Quality problems
- Priorities of the organization have changed
- Altered demand
- Performance indicators not reaching the expected results
- New processes or technologies used by competitors
- Important changes in the inputs or in cases where their availability has changed significantly

The issues mentioned above are derived from a full analysis of the internal and external context of the organization, a necessary requirement to implement standards ISO 55001 and ISO 9001 [43].

Designing a process involves the definition and systematic management of all processes and their interactions, for which analysts can use visualization tools such as process maps, information flowcharts, and task lists by activity. These tools help under a process management approach to establish the following:

- The existing processes
- The relationship between processes
- Strengths and weaknesses
- Easier operations
- Activity and operation integration
- Activities and tasks which might be eliminated or do not add value
- Delivery delays or issues
- Communication flow issues

Bravo C. in his work [44] expresses that "… Process management is a discipline that helps the management of the company to identify, represent, design, formalize, control, improve and make more productive the processes of the organization to win customer confidence. The organization's strategy provides the necessary definitions in a context of wide participation, where process specialists are the facilitators…"

At the same time, the cited work presents a four-cycle framework for the integral change management. These cycle stages are listed in order as follows:

1. Strategy design

2. Visual modeling

3. Process intervention

4. Useful life management

The four cycles mentioned above incorporate new practices and require a high commitment from all bodies. Based on the strategy and on a preliminary analysis of maintenance processes, it is possible to build a process map, which must be circulated to all organization personnel. A process map provides a global–local perspective, grouping each process into strategic, key, or support. The design of a process map depends on the context in which each organization is developed under the following criteria:

- Strategic processes: They are identified at the top of a process map, and their objective is to plan the strategies of the organization, make the relevant plans, and provide feedback to the other processes. In maintenance management these processes are related to the planning of the activities to be carried out, in accordance with the work orders that are generated, the monitoring of performance indicators, and the generation of policies to improve the results. The BS EN 16646 standard recommends considering the following processes: planning of maintenance activities, management and development of resources, creation of maintenance plans, monitoring and continuous improvement, evaluation and control of risk, and decisions regarding the portfolio of assets.

- Key or business processes: They are pinpointed at the center of a process map; they are derived directly from the organization's mission. In a maintenance department, the processes involved here correspond to the execution of preventive, corrective, or predictive plans from the implementation of asset management to the generation and scheduling of work orders and the supervision of actions in the operation plant. According to the maturity of the organization, this layer may also include the processes of acquisition of physical assets (if they exist in the market) or manufacturing physical assets (if they do not exist in the market in acceptable economic conditions). This may also include updating or improving assets for higher value throughout the global life cycle of the assets, taking out of service, and/or withdrawal of assets when their utility is worn out.

- Support processes: They are identified at the bottom of a process map and support the entire organization in aspects that are not directly related to the business, but it is necessary to convert the strategies into concrete activities. In maintenance management, this includes the communication protocols, inspection and diagnosis of the assets, and the monitoring of processes designed to achieve the organizational objectives. One may consider processes for resource management (human, information, materials, and tools) and information management (CMMS).

The relationship of the processes depends on the context of the organization, as well as the specifications of the associated procedures and the detail that the instructions and records must possess (see **Figure 3**). Once the processes and the way they are related are identified, the specific procedures of the key activities must be characterized and defined. This equally includes the instructions for technical operations (inspection routines, road maps, among others) and the formats of the records necessary for the analysis of data (asset resumes, fleet profile, failures, failure modes, frequent causes), as will be explained later.

The characterization involves documenting each of the processes designed for management, identifying the inputs, outputs, and activities in each of the stages of the improvement cycle proposed by Deming in 1950 (PDCA). For their part, the procedures detail the sequential steps to properly develop the processes, which in some cases are stored as part of a process manual. Roadmaps detail the procedures considered for maintenance management and are used at technical levels. These tools must show records of their execution necessary for the monitoring of activities and the collection of performance indicators (KPI).

3.1.3 Maintenance operative process management

The management of operational processes from the tactical perspective refers to the need for a system that allows the administration of work, materials, and resources, in order to gain control over the maintenance processes while requiring planning and programming that include an established order of work, equipment stops, and the creation and development of preventive and predictive maintenance plans. Within the framework of this management, the performance of the work team must be measured at each level, and the performance of aspects such as the implementation of lubrication routines, inspection, condition monitoring, and activities for the prevention of failures must be evaluated. The scope of process management incorporates five areas with defined global scope.

Work management guarantees well-established planning and programming that all tasks are planned at least 24 hours in advance and programmed with a week minimum margin, except emergency work. The adequate administration implies the existence of criteria for the creation and programming of work orders, which are used and respected, wherein the work flow is continuous and is not hindered by material or resource problems and in case of delays there are no major disturbances of the schedule. The latter implies that these are contained in 2 to 4 weeks of work. The indicator of worker efficiency is high, which leads to high staff performance.

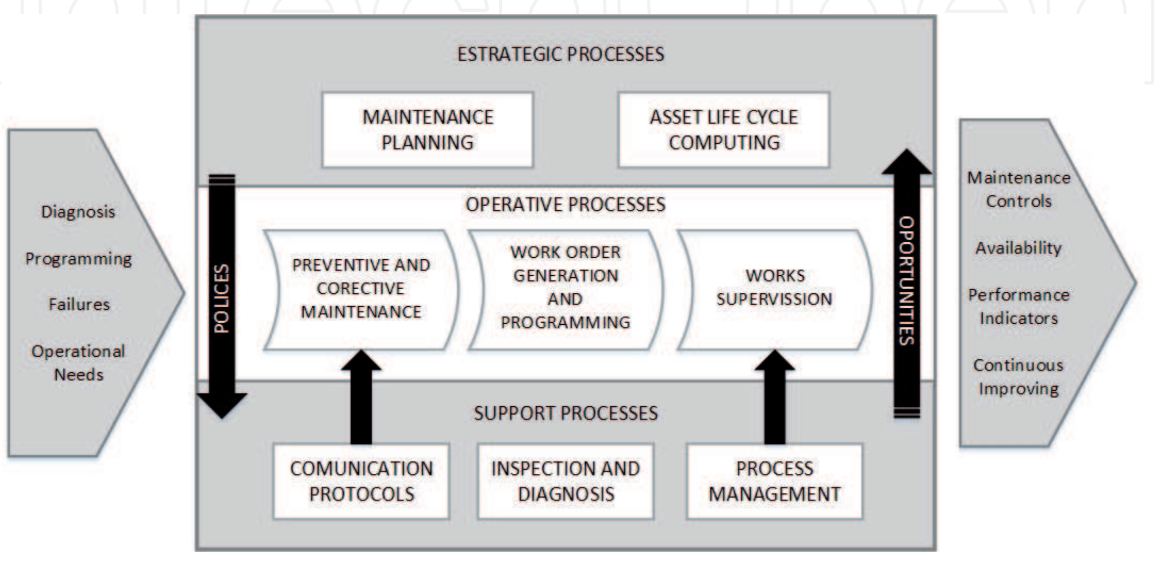

Figure 3.
Process map of maintenance asset proposed.

For the adequate workflow, the design of the work order is necessary, which must act as a transversal mechanism to guarantee compliance with the Deming Cycle (PDCA) in the flow of maintenance activities. The work order must be standardized as a document that calls on the completion of a task or set of tasks and serves, among others. It should be considered as the nucleus for the compilation of data, for the attention as a whole or for the attention of individual components and their processes. The work order becomes a starting point for the control mechanism since it transmits information about the work carried out, the start dates, estimated completion, and actual completion.

The work order flow must involve all the maintenance and operation personnel. It shall reflect the prioritization of the needs where the most critical and urgent must be dealt with first. Another suggested point is to establish a hierarchical limit in the execution of the work order. Therefore, in this stage it is necessary to define among four options: a) include actions at the system level, b) include actions at the subsystem level, c) include specific part tasks, or d) include inspection routines. This hierarchical limit will allow the tracking of work orders within the operational model of excellence. In addition, a work order must be allocated to the personnel in charge, detailing, among others, the materials, resources, previous analysis of the situation, and static data such as manuals, inspection routines, catalogs, etc. Furthermore, it must give space for the order of opening, planning, programming, and finalization. In general, the cycle time of a maintenance work order can be reduced by incorporating the following activities:

- Management of main stops: The maintenance management involves scheduled stops up to 6 months in advance and a precise definition of the scope of the work to be executed, giving enough time for realistic fulfillment of the objectives. This implies managing the process, formalizing scheduled stops, high involvement by production, engineering, maintenance, and processes. In the period of fulfillment of the scheduled major stop, attention is only given to emergencies.

- Management of materials and resources: The availability of material and resources is solved with automated inventory controls that are part of the maintenance management information system and by stock levels supported by the economic analysis of internal maintenance. Resource management is based on the history of materials and resources, generation lists, vendor databases, inventory monitoring, and inputs.

- Management indicators: Evaluating performance is part of the day-to-day process. Key indicators characterize costs in terms of quantity, type, area of origin, materials and resources, and work order. The management indicators should contemplate, measure, and obtain information on the company, plant, departments, improvement team, and work teams. The process indicators are directed to be effective, and external and internal benchmarking is used to lead the process.

- Reliability management: For operational processes to achieve a high reliability degree, it is essential to use CMMS/EAM as a tool for making optimized decisions, along with the experience of the staff. The use of the systems includes a diverse area of disciplines such as engineers, planners, and different work teams. The analysis of the condition is linked to the monitoring and preventive maintenance activities completed in all areas. The frequencies and activities of the maintenance routines are refined through the feedback of the work order and a root cause analysis of the failures.

- Planning and programming: It is the authors' view that adequate planning and programming should include short-term activities in the planning and scheduling of preventive maintenance. Activities of greater complexity can be addressed through root cause analysis. Likewise if, say, 80% of the total activities is scheduled in adequate time, then this may be regarded as demonstrating a stable maintenance operation. Another important point is to try planning in the long term and scheduling in the short term as much as possible.

Requirements for proper planning and programming include understanding the need to respond, properly preparing a work order with appropriate prioritization, and integrating operations to reduce programming delays due to nonavailability of the asset for maintenance [45]. Planning and programming involve:

- Assigning a programmer and planner to review the pending work and coordinating modifications in the allotted time

- Establishing roles, responsibilities, rules, and lines of authority between planners and programmers and maintenance and operations

- To assign engineering as a support to planners

- Conducting daily meetings between programmers and operations to align the needs of both parties

- Measuring delay times and operating hours

- Holding meetings to level the needs of programmers and planners alike

- Establishing a defined level of service for materials and resources

- Notifying maintenance or purchasing leaders of material and resource needs

- Considering routes for maintenance personnel and analyzing the tasks and frequencies of the assigned activities

The improvement cycle of planning and programming begins with an analysis of the existing maintenance plans and ends with a new plan, whose effectiveness is measured from the mean time between failures classified as critical systems. The implementation is progressive from the identification of the most critical systems, considering relevant indicators such as mean time between failures (MTBF) as input variable. The improvement process at its starting point cannot ignore the recommendations of the manufacturers.

3.1.4 Critical maintenance task (CMT) list and regular maintenance task list

The process to generate critical roadmaps and regular route sheets for maintenance tasks begins in accordance with asset ranking, that is, the severity of the impact of their failures within the production process. The hierarchical level of assets is defined in the generation stage of the baseline.

Roadmaps, by definition, are documents designed to direct maintenance activities by minimizing the level of human error on the part of operators. They were developed by the aeronautical industry in the 1970s within the framework of technical recommendations pertaining to reliability in maintenance [46]. Roadmaps direct maintenance activities from preventive to predictive and even corrective, with the aim of reducing human error during their development and, thus, guaranteeing high reliability in complex and high-risk systems.

Implementation of roadmaps allows the development of technical benefits in integral maintenance management. They detail the activities, procedures, tools, and spare parts necessary for the execution of each of the activities scheduled in stated preventive maintenance plans and are based on the technical specifications recommended by the manufacturer [47]. Based on the work of the aeronautical industry, the reduction of error can be concentrated as shown in the **Table 2**.

The maintenance tasks can be classified in the main groups: corrective, preventive, and predictive (condition-based and condition monitoring) [48]. Souza and Guevara present two tables that can help determine the main causes of mechanical failures based on RCM studies [49].

3.2 Case study

The proposed model was implemented at an organization with 54 years of experience in providing home cleaning services and complementary activities in the city of Medellin and five nearby municipalities. The company has 767,668 users, among the residential, commercial, and industrial sectors. Service delivery in the residential sector is carried out twice per week (Monday–Thursday, Tuesday–Friday, Wednesday–Saturday), for a total of 104 services per year. Frequencies in the commercial and industrial sector may vary between 1 to 7 times per week, depending on the waste generation of each subscriber, which leads to a total of 104 to 365 collections per year. The main activities of the organization are collection and transport of solid wastes, sweeping and cleaning of roads and public areas, grass cutting and pruning of trees in public areas, and washing off roads and public areas. The range of services extends to the collection of special wastes, among which are waste generated at events and mass shows, points of sale in public areas, dead animals, construction and demolition wastes (C&D), hospital wastes, mattresses, vegetables, furniture, carpentry wastes, and collection (dismantling and installation) of public baskets.

As part of the solid waste collection strategy, the organization has a diversity of vehicles with different dimensions in order to access areas with adverse geographic conditions. To allow great maneuverability in limited-access roads, the company has model 2009 Kenworth vehicles with only two axes (simple) and smaller vehicles such as NPR model 1998 and 2012. In general, to meet the demand, the organization

Error location in flowchart	Definition
Scheduling (E1)	Wrong execution of either of the two tasks: identify next inspection or move to a location
Inspection (E2)	Not seeing a defect when one exists
Inspection (E3)	If human induced, due to either forgetting to cover area, covering area inadequately, or a scheduling error
Engineering judgment (E4)	An error in deciding whether the area in which a defect is found is significant or not
Maintenance card system (E5)	Arises because the work cards themselves may not be used to note defects on the hangar door immediately as they are found
Noting defect (E6)	The error is noted incorrectly or not noted at all

Table 2.
Potential errors in the inspection process.

has its own fleet broken down as follows for each type of service. Collecting wastes from hospitals are carried out by using three vehicles equipped with containers and UV light, to ensure crew condition and reduce biological risk. The vehicle fleet has two skid-steer loaders transported by dump trucks for the collection of C&D waste. The organization operates light vehicles (NPR) for transportation of baskets in poor condition for waste disposal. Besides, the vehicle fleet has two series of equipment that allow the provision of collection services for special containers. Both use a lifting system equipped in the back part of the truck which is called lifter. One of the series of vehicles is employed for collection of big containers, whereas another series is used for the collection of buried containers. An availability indicator is generated, based on the data of the information system reports and the work orders of the equipment maintenance activities. All of this for a 30-day operation period during 2018 is shown in **Figure 4**.

In **Figure 4a**, it is possible to observe the increase in availability of the fleet of light vehicles per quarters during 2018, from 78% in the first quarter to 89% in the fourth quarter showing signs of stabilization. This improvement may be attributed to the reduction of the occurrence of failures, which in turn is the result of the implementation of a preventive maintenance program, and critical maintenance tasks. These availability standards are appropriate for a program of operational excellence. During 2018 one may see that the month having the best behavior in terms of availability was November showcasing a growing trend due to the implementation of the excellence model.

Despite the improvement in terms of availability that was evidenced in this study, it is the authors' view to analyze the specific behavior of the fleet vehicles. This is because being an average, the availability of the light vehicles could be

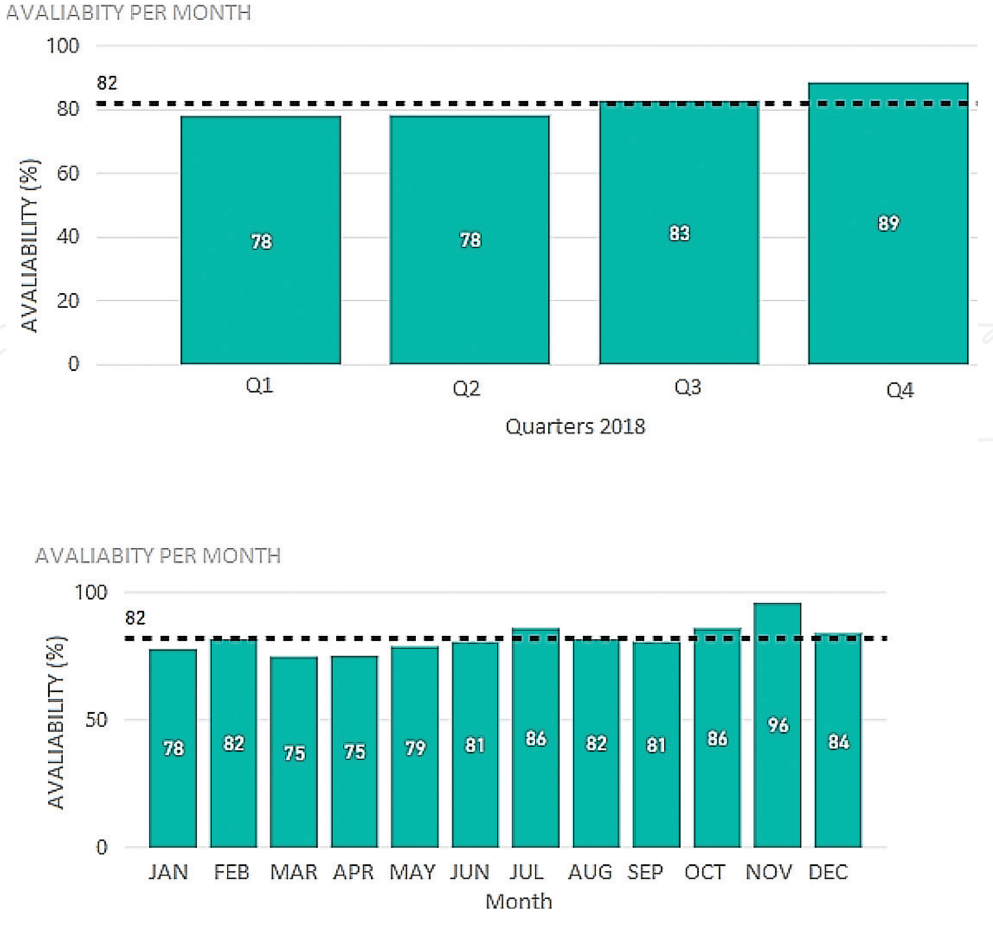

Figure 4.
Availability indicator for light vehicles per 2018 quarters.

affected by extreme values. **Figure 5** shows the behavior of each of the vehicles that make up the fleet. The vehicles that have worse average availability are #313 and #416. However, if the growth of the availability of these vehicles is observed, the positive impact of the implementation of the model of excellence can be verified.

To evaluate the impact of the excellence model implementation, availability indicators besides indicators like efficiency must be considered. Next, the data related to the maintenance cost is compared, through the execution of work orders. The amount of orders generated, their typology, and the effective cost paid for these works are taken into consideration.

It is pertinent to mention that each work order carried out carries with it the corresponding audit report, which gives information of the tasks executed in detail, the report of time units, and the quality of spare parts used. These data are essential for the administrative review phases, in case of any type of claim, and verify the agreement with the terms of the contract.

Additionally, the maintenance work of the first 10 months of the year 2018 is analyzed and compared with the same period for the year 2017. A reduction of 5.06% in the sum of the maintenance costs is evidenced. In addition to this, the average cost per work order generated was reduced by 12.94% thanks to the recommendations of good management practices in the processing and management of information (**Table 3**).

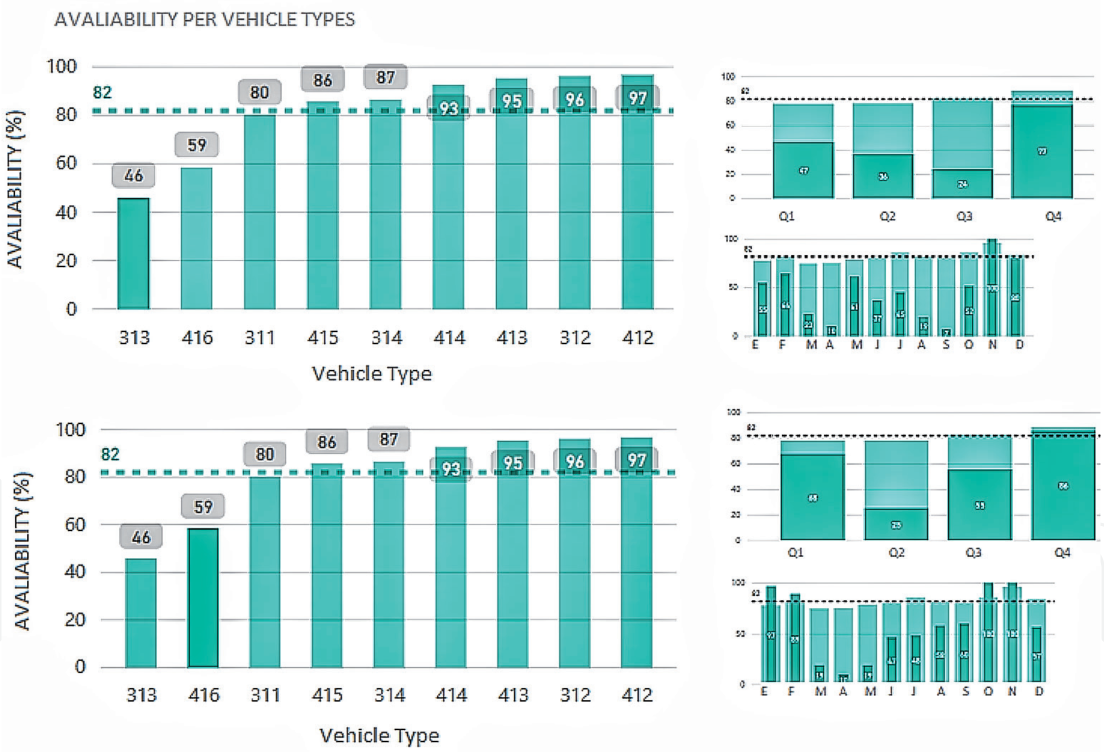

Figure 5.
Availability indicator for critical light vehicles.

	# OTS	% OTS prev	OTS value
2017	5755	6.23	−12.96%
2018	6277	10.12	
Difference (%)	−5.06%	3.89	

Table 3.
Budget execution in maintenance cost 2017 vs. budget execution in maintenance cost 2018.

In this analysis, an increase of 3.26% is observed. A fundamental part of this increase is due to the optimization of downtime, because with the operational excellence model, preventive critical tasks are programmed and executed in the same time periods of the corrective activities.

4. Conclusions

During the life cycle of an asset or a production system, different costs are incurred, which span the purchase (initial investment) to the operation and maintenance costs that guarantee productive and financially worthy outputs for investors. The life cycle cost corresponds to the costs of both investment and operations inherent to the useful life of the asset.

Development and implementation of management models, applied to the maintenance of equipment, often present results in periods that exceed 1 year. This model, based on the ISO 55000 standard, presented immediate results mainly by, firstly, defining maintenance as a strategic activity for the collective benefit of the organization and, secondly, collecting all necessary information pertaining to defining the critical maintenance needs, in such a way so as to guarantee the high availability of the assets.

In this chapter a maintenance strategy model of the asset life cycle is proposed. It has a direct influence on maintenance management regarding decision-making, as well as the planning of preventive tasks and analysis of the equipment's useful life. Positive results are obtained in the overall development of this maintenance model. It is possible to notice a reduction of costs in the global execution, and so the average cost per work order has been reduced too. At the same time, an increase in the execution proportion of preventive tasks has been achieved. These findings may help other to implement the model successfully, even though the tasks performed and the model itself remain in continuous analysis and improvement.

The common maintenance budget models only present a general sum of costs; it does not provide enough information for decision-making. These results confirm the association between cost control, technical decisions and physical interventions, which have been and exemplified, and therefore, in this document, a new way of disaggregating the cost has been suggested.

Frequently the summation is separated monthly to fit in with the scale of the time series. These estimators of central tendency allow the visualization of how data variability alters this tendency according to the behavior of the series. It is also evident that the median is less susceptible than the average.

The result of the implementation has shown an increase of the availability indicator and a reduction of the general maintenance costs.

These preliminary results that cover a 12-month period suggest that in the long term/medium term, the availability may reach the level demanded by the company and may guarantee stable operation with lower maintenance costs. Finally, it is important to highlight that, without the support of the general management of the organizations, the initiatives to achieve operational excellence, or an adequate management of assets, may fail, causing loss and discouragement.

Abbreviations

CMMS	computerized maintenance management system
CMT	critical maintenance tasks
DCS	distributed control system

EAM	enterprise asset management
ERP	enterprise resource planning
FAA	Federal Aviation Administration
FERMA	Federation of European Risk Management Associations
FMEA	failure modes and effect analysis
IT	information technology
KPI	key performance indicator
MIS	maintenance information system
MSG	maintenance steering group
MTBF	mean time between failures
OREDA	Offshore and Onshore Reliability Data
PID	processes and instrumentation diagrams
PDCA	plan, do, check, act
RCM	reliability-centered maintenance
RBI	risk-based inspection
RBM	risk-based maintenance
SCADA	Supervisory Control and Data Acquisition

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