Contemporary maintenance management: process, framework and supporting pillars

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Abstract

This paper presents a holistic framework for managing the maintenance function heretofore inundated by myriad tools, trappings, practices, and prescriptions. It begins by reviewing the concepts, state-of-art processes and standards available to help maintain today’s complex systems. It then proposes a framework in which to couch the various maintenance functions in an organization. In doing so, this paper characterizes factors that breed complexity in maintaining today’s operations. Next, it closely analyzes the strategic, tactical and operational aspects of maintenance and sets up a structure to help complete the tasks at each of these levels. The term “process” in this paper implies actions directly associated with maintenance, while “framework” embodies the supporting infrastructure. The results are clear statements of (1) the functionality required of enablers such as IT to abet maintenance; (2) the distinctive capabilities extended by modern maintenance engineering; and (3) the critical requirement of relationship competencies in maintenance. This work sums up decades spent in maintenance shops, engineering, standardization, and research in maintenance management.

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1. Introduction

In the recently released European Standards regarding maintenance \[1\], maintenance is defined as the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.\textsuperscript{1} In the same standards, maintenance management (MM) is defined as all the activities of the management that determine the maintenance objectives or priorities\textsuperscript{2}, strategies\textsuperscript{3}, and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving the methods including economical aspects in the organization.

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\textsuperscript{1} Function or a combination of functions of an item which are considered necessary to provide a given service.

\textsuperscript{2} Targets assigned and accepted by the management and maintenance department. These objectives may include availability, cost reduction, etc.

\textsuperscript{3} Management method in order to achieve maintenance objectives.
This definition of MM is very aligned to other such notions found in modern maintenance literature such as Campbell and Jardine [2], Campbell [3], or Shenoy and Bhadury [4]. Still other definitions consider MM as the management of all assets owned by a company, based on maximizing the return on investment in the asset [5]. Wireman [5] says that MM would include, but would not be limited to, the following: preventive maintenance (PM), inventory and procurement, work order system, computerized maintenance management systems (CMMS), technical and interpersonal training, operational involvement, proactive maintenance, reliability centered maintenance (RCM), total productive maintenance (TPM), statistical financial optimization, and continuous improvement. Each of these initiatives is a building block of the MM process. Another approach to MM definition is offered by Duffuaa et al. [6]. They indicate how a maintenance system can be seen as a simple input—output system. The inputs are the manpower, management, tools, equipment, etc., and the output is the equipment working reliably and well configured to reach the planned plant operation. They show that the required activities for this system to be functional are maintenance planning (philosophy, maintenance workload forecast, capacity, and scheduling), maintenance organization (work design, standards, work measurement, and project administration) and maintenance control (of works, materials, inventories, costs, and quality oriented management).

The purpose of this paper is to present a holistic framework for managing the maintenance function heretofore inundated by myriad tools, trappings, practices, and prescriptions. It proposes a framework in which to couch the various maintenance functions in an organization and provides clear statements of: (1) the functionality required from information technologies—the first mainstay or “pillar” of the framework—applied to maintenance. Section 5 defines the functions of modern ME, the second pillar of our framework, while Section 6 describes the requirements in terms of relationship competencies in maintenance, the third pillar of the proposed framework. Finally, the paper presents the concluding remarks and provides directions for further research.

2. Complexity of MM

MM is frequently associated with a wide range of difficulties. Why is this function, at least apparently, so difficult to manage?

Jonsson [7] finds a lack of MM models that could improve the understanding of the underlying dimensions of maintenance. In subsequent research [8–10] Jonsson shows that maintenance is somewhat “under-developed” with lack of effective prevention methodologies and the integration of these methods in manufacturing companies on most continents. According to Vagliasindi [11], this is because maintenance is composed of a set of activities for which it is very difficult to find procedures and information support systems in one place to ease the improvement process. Normally, there is a very high diversification in the problems that maintenance encounters, even in business of the same productive sector; therefore, it has been difficult to design an operative methodology of general applicability.

Hipkin and De Cock [12] present a ranking of barriers in implementing maintenance systems. Managers, supervisors and operators typically find that lack of plant and process knowledge is the main constraint, followed by lack of historical data, lack of time to complete the analysis required, lack of top management support, and fear of disruptions in production/operations.

Besides, during the last two decades, as a consequence of the implementation of advanced manufacturing technologies and just-in-time production systems, the nature of the production environment has changed. This has allowed many companies to manufacture products massively in a customized and highly efficient way. However, the increase in automation and the reduction in buffers of inventory in the plants have clearly put more pressure on the maintenance system, because the disruption to production flows can quickly become costly by rapidly disrupting a large portion of the operation. In highly automated plants, the limitations of computer controls, the integrated nature of the equipment, and the increased knowledge requirements make it more difficult to diagnose and solve equipment problems [13]. This makes maintenance centrally relevant to operations management to stay productive and profitable. It has been found that when human intervention in these highly automated environments is required, the problems are normally complex and difficult to solve [14]. The level of variety in the technology used to manufacture the product causes another complexity in maintenance problems [15]. When this happens, novel or unfamiliar problems often arise. In addition to these process and technology related issues, new and more exigent safety and environmental factors such as emerging regulations put pressure on a maintenance manager and create complexity to this function (for a complete discussion of these aspects in relation to maintenance see Chapter 8 in [60]).

Crespo Marquez and Gupta [16] characterize the complexity found in managing the maintenance function in a production environment (see Table 1). As may be observed,
Table 1
Assessment of MM complexity [16]

<table>
<thead>
<tr>
<th>Domain</th>
<th>Factors impacting maintenance management complexity</th>
<th>Degree of fulfillment (DF)</th>
<th>Relevance factor (RF) Total: DF (_i) \times RF (_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information system</td>
<td>Lack of CMMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lack of historical data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process technology and integration</td>
<td>Complexity of the production process technology</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Variety of technologies used in the production process</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Level of automation and process integration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production management system</td>
<td>JIT—non-stock production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance management system</td>
<td>Lack of maintenance procedures in place</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personnel technical expertise</td>
<td>Low level of operator knowledge and involvement in maintenance</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low technical expertise of the maintenance staff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>...etc.</td>
<td>...etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>(\sum DF (_i) \times RF (_i))</td>
</tr>
</tbody>
</table>

This is patterned after FMEA. The higher the degree of fulfillment of each factor in an industrial plant, the more is the complexity associated with the MM process. The eighth column of Table 1 deals with the relevance (estimated by "RF") of each factor according to the production environment. The assessment of each factor can be on a 0–5 scale. Experience indicates that a higher RF rating of an issue is associated with a higher complexity of the MM process. Such assertions reflect experiences in the related domains in factories, transportation fleets, service providing infrastructures, etc. For instance, using CMMS is a highly relevant issue in a production environment where the number of critical equipment is very high or where the need for maintenance resources management is very significant. Similarly, if a production process engages only a small number of critical equipment, "Absence of CMMS" could lead to a DF score of 5, but relevance of this factor would score only 1 for its relative unimportance. Multiplication of DF and RF here would be 5 \(\times 1 = 5\), the maximum possible complexity for any factor being 25. Another example is the importance of the technical expertise of the maintenance staff. This factor may not be important for production facilities where the production process is either simple or where maintenance is outsourced for cost savings or even outsourced for capability, as discussed in Hui and Tsang [61]. If we populate Table 1 in a factory and complete all the table calculations, we would arrive at a total complexity index that one may compare across different production environments to help decide the relative effort and resources required to maintain them.

3. Maintenance management: a process and a framework

What is the framework—the essential supporting structure and the basic system—needed to manage maintenance effectively? At the same time, what would be the process—the course of action and the series of stages or steps—to follow? This section addresses these two questions. To begin, we review some of the most interesting and useful contributions found in literature about these issues. Then, by a synthesis of the observed ideas and schemes offered by experts, we propose a framework for modern MM.

Pintelon and Gelders [17] discuss a MM framework in which the primary aspects of MM are included. The framework has three building blocks: (1) the operations management/MM system design activity. This formally places MM
within the broader business context where marketing, finance and operations interact for their key decisions, to avoid each function to pursue its own limited objectives. Here MM is considered as one of the sub-functions of the operations function; (2) a second building block in MM decision making is planning and control which includes decisions that the maintenance manager should make in three major business functions (marketing, finance, and operations), management of resources, and performance reporting. The more technical maintenance theories and methods (like maintenance technology—studying technical issues that can help improve maintenance such as new repair or monitoring technique or techniques related to better maintenance design) are not directly included here; (3) the last building block is called the MM toolkit. It consists of statistical tools to model the occurrence of failures in the system, plus various OR/OM techniques and computer support to help optimize the actions and policies.

Vanneste and Van Wassenhove [18] propose an approach that assesses the MM process—in two parts—(a) effectiveness analysis and (b) efficiency analysis. The first part helps detect the most important problems and locate their potential solutions. The second part identifies the suitable procedures. The investigators define eight phases to accomplish this comprehensive assessment as: (1) determination of current factory performance; (2) quality and downtime problem analysis; (3) effectiveness analysis of alternative solutions; (4) efficiency analysis of maintenance procedures; (5) plan actions; (6) implementing actions and gathering of data; (7) monitoring actions and processing of data, and (8) adaptation of plans or effective information handling procedures in case of undesired deviations. When these phases are completed, one may have to return to phase 1 to seek further efficiencies in the spirit of Deming’s PDCA cycle, as it would work in practice.

Wireman [5] proposes a sequential implementation of steps to ensure that all functions for MM are in place. He believes that a PM program should be in place before we advance to the next level, the CMMS implementation. He asserts that a suitable “work order release system” (to schedule and trigger appropriately prioritized tasks) and a maintenance resources management system are required before one considers the implementation of RCM and predictive maintenance programs. Besides, the operators must be aware of the importance of their own role in the maintenance function. Thus, operator as well as general employee involvement would be the next level addressed in the implementation process. It is noted that “TPM” programs, an innovation of the 1980s, consist of management initiatives and interventions (as is TQM) that heavily emphasize operator involvement in routine maintenance. Therefore, if in place, TPM would considerably help in achieving operator involvement and routinize the use of optimization techniques, TPM would also help configure also the necessary maintenance organization structure—to facilitate continuous improvement in maintenance practices.

Campbell [3] also suggests a formal structure for effective MM. The process starts with the development of a strategy for each asset. It is fully integrated with the business plan. At the same time, the HR related aspects required to produce the needed cultural change are highlighted. Next, the organization gains control to ensure functionality of each asset throughout its life cycle. This is done through the implementation of a CMMS, a maintenance function measurement system, and planning and scheduling the maintenance activities. This is accomplished according to various tactics employed depending on the value that these assets represent and the risks they entail for the organization. Among these tactics Campbell includes: (a) run to failure, (b) redundancy, (c) scheduled replacement, (d) scheduled overhauls, (e) ad hoc maintenance, (f) PM, (g) age or use based, (h) condition based maintenance, and (i) redesign.

Finally, Campbell proposes the implementation of two highly successful methods for the continuous improvement—RCM and TPM. He also recommends use of process reengineering techniques (activity based process mapping techniques, process value analysis techniques, and innovative process visioning techniques, among some others) for stepped leap improvements in maintenance.

Pintelon and Van Wassenhove [19] provide a MM tool to evaluate maintenance performance. The tool consists of a control board and a set of reports to analyze certain ratios. This tool is applied in five different domains falling under the control of the maintenance manager: cost/budget, equipment performance, personnel performance, materials management and work order control. For each of these domains the control board displays ratios with actual, expected, target, notes and attention data.

A generic framework for integrating the MM is presented by Hassanain et al. [20] for built and in-use assets. Their framework consists of five sequential management steps: (1) identify the asset, (2) identify its performance requirements, (3) assess the asset’s current performance, (4) plan for its maintenance, and (5) manage the maintenance operations. To facilitate clear exchange and sharing of maintenance information between applications, this model defines the required objects and their relationships.

Some other works in this area are also interesting and useful [21]. However, in order to facilitate maximum (organizational) agility for the purpose of maintenance, it is
desirable to pursue a holistic approach in order to systemize the relevant maintenance knowledge as a whole, and then to make the right information available at the right place and at the right time [22].

3.1. A proposed approach to maintenance management

A myriad considerations, data, policies, techniques and tools affect the effective execution of maintenance, particularly in a modern technologically endowed factory. In such instances, an integrated, rather than the conventional “silo” style approach to MM would play a pivotal role. However, much difficulty in the practice of MM arises from the mix-up between the actions and the tools designed to enable them. This issue often remains unresolved by practitioners and unaddressed by researchers. To help resolve this, we describe the essentials of an effective maintenance process and a corresponding framework to enable this process to yield the desired results.

As mentioned before, “process” in our discussion includes only the course of action while “framework” as used here is the supporting structure. Although we could also say that a given process has a structure, we consider the proposed framework as the distinct technological support to the process as envisaged here and the process to consist of the set of various tasks that one must accomplish each day to manage maintenance [16]. We also suggest that MM must be aligned with actions at three levels of business activities—strategic, tactical, and operational (see Fig. 1). Actions at the strategic level will transform business priorities into maintenance priorities. To meet these priorities, this process will help craft mid-to-long-term strategies to address current and/or potential gaps in equipment maintenance performance. As a result, a generic maintenance plan will be obtained at this level.

Transformation of business priorities into maintenance priorities is done by establishing critical targets in current operations. Detailed analysis creates measures of such items as the incidence of the plant equipment breakdowns as these would impact the plant’s operational targets (by criticality analysis, as done in FMCA). MM would then develop a course of strategic actions to address specific issues for the critical items. Other actions would focus on the acquisition of the requisite skills and technologies (for instance, condition monitoring technologies) for the micro-level improvement of maintenance effectiveness and efficiency.

Actions at the tactical level would determine the correct assignment of maintenance resources (skills, materials, test equipment, etc.) to fulfill the maintenance plan. As a result, a detailed program would materialize with all tasks specified and resources assigned. Moreover, during the process of detailed maintenance requirements planning and scheduling, this level of activity must develop a competency to discriminate among a variety of resource options (of different values) that may be assigned to execute a maintenance task at a certain asset (say a particular machine), location and time. Such action would spell out the tactical maintenance policies.

Actions at the operational level would ensure that the maintenance tasks are carried out by skilled technicians, in
the time scheduled, following the correct procedures, and using the proper tools. As a result, work would be done and data would be recorded in the information system. Procedures at the operational level would be needed for preventive works, equipment repairs, and troubleshooting with a high degree of attention. Note that the diagnosis of the reasons for a system’s failures has become a critical function. This task often engages specialists and uses complex technological systems. Therefore, it is reasonable to expect that the troubleshooting process would heavily rely on the maintenance information systems that provide information about all the work done on each equipment.

As shown in Fig. 1, these three courses of action and the related processes going on in the organization are clearly interrelated. To simplify the MM process in an organization (at the three mentioned levels), one would have to build a basic supporting structure. This structure would comprise, as explained by Crespo Márquez and Gupta [16], three primary pillars as follows:

3.1.1. The IT pillar

This would allow managers, planners, and production and maintenance personnel to have access to all equipment data. It would also transform this data into information that would be used to prioritize actions and to take superior decisions at each of the three levels of business activities. As envisaged, this would be built as the company’s computerized maintenance management system (CMMS). CMMS would allow proper monitoring and control of assets. It is expected that the installation or the availability of CMMS would be considerably much more significant when the number of items to maintain is high and the complexity of the plant is high, as in modern production plants. When appropriately configured and interfaced with the company’s ERP system, CMMS can become a critical tool and be useful to each of the three levels of maintenance activities in the organization. A state-of-art information processing capability, decision support and communication tools, and the collaboration between maintenance processes and expert systems are jointly forming a distributed artificial intelligence environment commonly referred to as e-maintenance. E-maintenance may allow remote maintenance decision-making. However, this would require not only information exchange between customers and suppliers, but also cooperation and negotiation, based on the sharing of different complementary and/or contradictory knowledge [23]. The IT pillar also includes condition monitoring technologies. By focusing continuously on potential tactical and operational decisions and actions, they greatly improve MM efficiency.

3.1.2. The maintenance engineering methods pillar:

A set of key techniques together constitute this pillar:

- **RCM** plays an important role at strategic and tactical levels and helps design and define maintenance plans that ensure desired equipment reliability.  
- **Quantitative tools** that can be used to optimize the MM policies will also fall under this section.
- **Tactical activity oriented** stochastic tools to model the failures, allowing a further use of quantitative techniques.
- **Other operations research/management science (OR/MS)** techniques that focus on optimizing maintenance resources management.

The last three set of techniques are generally most useful at the tactical maintenance planning level.

3.1.3. The organizational (or behavioral) pillar

This pillar is perhaps the most important one as long as humans are involved in the various decisions related to maintenance and execution of tasks. The techniques here can impact all three levels of maintenance activities. Here we include all techniques that can help foster relationships competency. The object of these techniques would be to ensure the attainment of the best interface between different activity levels, between different functions within the organization, respect and care for all internal and external customers, and smoothness in inter-organizational relationships.

Table 2 summarizes these structured elements in the proposed system to better manage maintenance. In this table we include the processes (actions) and the framework to couch management actions. We call reader’s attention to the fact that MM processes are continuous closed loop processes in which feedback is used to lead to continuous improvement. In the following sections we further elaborate the functions of the three pillars of the proposed management framework.

4. Functions of the IT pillar

We expand here on what we consider to be the essential functionality of the IT pillar. The software programs in the typical CMMS provide functionality that is normally grouped into subsystems or modules for specific activity sets. Cato and Mobley [27] list some of these activities which include but are not limited to: (a) equipment/asset records creation and maintenance; (b) equipment/asset bill of materials creation and maintenance; (c) equipment/asset and work order history; (d) inventory control; (e) work order creation, scheduling, execution and completion; (f) PM plan development and scheduling; (g) human resources; (h) purchasing and receiving; (i) invoices matching and accounts payable; and (j) tables and reports.

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6 An interesting case study about RCM can be found in [24].
7 A case study about TPM can be found in [25].
8 Some case studies may be found in [26].
We must point out that mere cataloging of such tasks and tools or even the possession of expensive CMMS software would not make the organization proactive in MM. Rather, these are sought-after enablers of certain key MM functions. We envisage a much more productive approach. We should view these modules that are generally designed to support “silo” style decision making as interacting decision support entities. The functionalities achievable from such holistic apparition of IT in CMMS are as follows:

- **Capturing and processing information:** Clearly, only codified information can be accessed and processed electronically. Descriptive information, information not classified and codified according to some criteria, cannot be considered to establish measurements and comparisons. To achieve that, the organization will have to learn to codify failure causes, types of maintenance work, the physical assets, the technical structure of the plant, the maintenance resources, etc. Capturing information here also means collecting “on line” data from automatic devices and condition monitoring systems. This would help to move away from conventional maintenance strategies to more proactive ones. In order to do so, an organization will also have to learn about components interoperability, timescale for maintenance data and information, communication constraints, information integration between maintenance systems, and shop-floor components (like CMMS, ERP, and PLCs).
- **Providing maintenance related support at the operational level:** This is made possible through the processing of the equipment historical records from the perspective of the maintenance operations and through the processing of the real time equipment information. The idea goes beyond summarizing history. It envisages the configuration of a real expert system based on the codification of the symptom, cause, and solution of each equipment maintenance problem. This system is a critical tool for technical decision making tasks at the operational (which requires rapid response and routine actions) and tactic levels. This results in easier diagnosis and prognosis, facilitating the proverbial “an ounce of prevention in time.”
- **Deriving and tracking maintenance performance indicators:** Maintenance priorities must be set according to criticality functions linked to the company’s business goals. Priority of maintenance activities should be in accordance with an equipment’s failure and criticality goals. Criteria to assess criticality can be very diverse such as maintenance direct and indirect cost, availability, and reliability.9
- **Supporting maintenance activities planning,** avoiding any kind of servitude to the planning system, primarily by fostering management by exception and the production of alerts.
- **Providing procedures for auditing maintenance activities,** intra and inter-enterprise benchmarking.10 This will allow the implementation of a continuous maintenance improvement cycle at the three levels of activities.
- **Integrating the maintenance information system within the global enterprise information system:** This means database sharing for purchasing, personnel, cost accounting, production, etc., with the corresponding coding unification. It also means connection to the rest of the systems for plant data capturing.

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9 Establishing the variables influencing the criticality function, and their relative weight in it, will be a main concern of the business Management. This function will surely change depending on the type of activity and on the current circumstances of the company.

10 Readers interested in this topic are referred to Komonen [29] for an industrial maintenance cost model for benchmarking.
Emerging functional and technical trends in CMMS in evolution are as follows:

- Integration of functional attributes with ERP systems; packaged solutions where applicable; enterprise-wide, easily customized and configured; embedding condition-based maintenance, embedded predictive maintenance, and embedded e-maintenance automatically producing exception parts and flags.
- Technical attributes TCP/IP/Internet enabled, use of open standards, client/server, relational data based, and context-sensitive/on-line help.

Condition monitoring is the second element of the IT pillar of modern MM. Predictive maintenance is a key consequence of condition-based maintenance. However, condition monitoring is becoming a plant optimization and reliability improvement tool rather than a MM tool [28]. During the last 5 years, we have seen the percentage of plants using these tools for MM increasing enormously, from 15% to 85% as indicated by a survey of 1500 American plants [28]. However, much higher benefits can be obtained when one simultaneously uses these tools for all these three purposes. Configured in this manner, a system for MM would be expected to substantially raise the likelihood of materializing the following benefits:

- Preventing catastrophic failures while increasing plant throughput through higher equipment availability and the elimination of big repair losses and unsafe incidents in the plant.
- Ensuring planned repairs while improving the quality of the repairs and lowering the number of repair labor hours and the stock of spare parts.
- Identifying the machine problems before equipment dis-assembly to provide faster repairs. This also increases the possibility of eliminating repetitive failures.
- Reducing operating cost including reduced excessive energy consumption, reduced need for stand-by equipments to cover critical, stops and reduction in insurances cost.

According to Moubray [30] and many other experts, vibration monitoring and lubricant analysis are the most effective, proven and validated techniques for condition monitoring in countless industries. In addition, one would find important utilization of other techniques and tools including ultrasonics, ferrographic analysis, spectroscopy analysis (atomic emission and infrared), chromatography, electrical testing (resistance testing, impedance testing, Megger testing, etc.) and other non-destructive methods (like acoustic emissions, magnetic particle, residual stress11).

5. The ME pillar functions

Earlier, in Section 3, we mentioned a set of techniques that many authors consider to be integral within the implementation of the MM process. Often, their classifications are given according to the sequence in which they are implemented (see, for instance, comments of Wireman and Campbell’s work in Section 3). These techniques can also be grouped according to the different levels of maintenance development.

In Baldin et al. [31], a plant maintenance handbook, maintenance techniques are classified according to the functions of the modern maintenance engineer. Since we want to pay special attention to the functions of the ME methods pillar, we shall follow this classification. They group techniques into three categories: (1) techniques used to design the maintenance system; (2) techniques used to improve the execution of maintenance activities and operations; and (3) techniques used to control and assess maintenance performance. This classification scheme is similar to the one given by Duffuaa et al. [6] who divide the functions of a maintenance system into planning, organization and feedback control.

The functions of the ME methods pillar are summarized in the following subsections.

5.1. Design of the maintenance plan and its process of continuous improvement

ME is actually an analytical function with a very methodical development carried out during the preparatory and the operational phases of an equipment. Therefore, methods for the maintenance plan design, for instance RCM, are also understood as methods that assist in the continuous improvement of the equipment’s maintenance during its lifecycle. Within this function we find the following sub-functions:

- Failure analysis, reliability analysis and risk analysis of the system’s operation: Techniques such as failure modes and effects analysis (FMEA), failure modes effects and their criticality analysis (FMECA), hazards and operability analysis (HAZOPS), failure trees, etc., belong to this area. Study and analysis of system reliability, failure, and a system’s behavior under extreme situations beyond its design conditions generally provide in-depth system knowledge to those who execute this function. Praxis indicates that these studies are normally iterative because advances in the steps of the study provide a new and better understanding of the system, which simplifies the ulterior system assessment. The selection of the failure analysis method depends on a system’s technical and qualitative data that is available. It also depends on the scope, degree of detail and time horizon of the study. Failure analysis methods may be classified according to different criteria. Hauptmanns [32] catalogs them according to

11 See complete set of handbooks published by the American Society of Nondestructive Testing (ANST).
the following concepts:

- **Type of reasoning**: Inductive and deductive methods. Inductive methods start the study departing from specific events with the idea to reach overall system implications. Such individual or specific events are failures that occur in system components, and the implications that such failures have on the global system. The common methods used in industry include:

  - FMEA;
  - FMECA;
  - HAZOP;
  - (Markov analysis) MA;
  - Event sequence analysis.

  By contrast, deductive reasoning methods start with the definition of the event of interest at the system level, proceeding subsequently to study the causes of that event (and their causes), until the degree of detail predefined for the study is reached. Examples of deductive methods are failure tree analysis and event tree analysis.

- **Scope**: Qualitative and quantitative methods.

- **Goal of failure analysis**: Methods to identify possible risk potentials and methods to assess risk potentials.

It is also common to find methods that involve multiple aspects of these categories.

- **Design of the maintenance plan**: Techniques such as RCM help accomplish this sub-function. According to Rausand [33], RCM identifies the functions of a system, the way these functions may fail and then establish, a priori, a set of applicable and effective PM tasks, based on considerations of system safety and economy. According to Campbell and Jardine [34], RCM specifically allows:

  - detection of failures early enough to ensure minimum interruptions to system’s operation;
  - elimination of causes of some failures before they show up;
  - elimination of the causes of some failures through changes in design; and
  - identification of those failures that may happen without any decrease in system’s safety.

- **Ensuring employee involvement in maintenance**: This helps pursuing the continuous improvement. TPM is an example of this sub-function. TPM was formally defined in 1971 by the Japan Institute of Plant Engineers (JIP), predecessor of the Japan Institute of Plant Maintenance) as a methodology. TPM helps the plant to systematically accomplish productive maintenance activities (PM activities, reliability centered activities, etc., maintainability improvement activities, from the perspective of the economic efficiency). TPM fosters the concept of failure prediction and the idea of reaching active involvement of production workers (rather than the separate maintenance personnel) in plant and machine maintenance tasks (first line of maintenance) and in plant improvement. TPM’s stated goal is not only zero breakdowns but also zero defects in the operability of the equipment. In reality TPM has transformed many conventional preventive activities into condition-based ones and has strongly applied techniques for better communication, participation and the generation of personnel motivation to reduce downtime and interruption of production in the plant [35].

- **Maintenance resources management**: Specific techniques to engage the correct resources, to plan their best utilization, and to manage their use would fall within this function. In order to calculate a good estimate of the required number of maintenance personnel by skills, Shenoy and Bhadury [4] found that queuing theory models offer very good results, especially those that help minimize equipment unavailability and labor cost. Monte Carlo simulation is also used for this purpose (see for instance [36] or [37]). Regarding popular techniques to deal with the problem of managing maintenance materials, Shenoy and Bhadury list the following:

  - **Probabilistic inventory models**: The complexity of the problem here lies in the fact that neither the demand nor the spare parts procurement time is constant (see [38]).

  - **Selective control policies along with some heuristics**: The principle here is to use a set of procedures to classify items into homogeneous groups based on their characteristics. Among selective control procedures are: ABC analysis (Pareto rule), fast slow and non-moving (FSN) analysis and scarce, difficult, and easy to procure (SDE). These in turn lead to appropriate heuristics.

  - **Material requirements planning/manufacturing requirements planning (MRP/MPRII) applied to maintenance**: This technique has been applied mostly for spare parts procurement in scheduled maintenance.

Besides the need to effectively manage maintenance personnel and material resources, the maintenance function has recently evolved towards aiming at establishing very high levels of contractual relationships. This may be explained as a consequence of the high level of skills and technologies required for certain maintenance tasks, client’s focus on core business competencies, and business pressure on labor cost. Managing maintenance contracts requires both a process and a framework. Good guidelines to ensure proper maintenance contracts management may be found in new European pre-standards [39]. In these standards the practitioner would find processes to be followed by both parties before and after the contract is signed and a suitable structure for drafting a generic maintenance contract.
5.2. Optimization of the maintenance policy

In the last five decades we have seen fast growth in the use of statistical and operational research techniques that help managers, engineers, and others pursue optimization in maintenance policy making [40]. We feel therefore that this work deserves a separate functional identity within the broad area of ME. The overall activities here may be divided as follows:

5.2.1. Analysis and preparation of reliability and availability data of the system

In MM two categories of micro-level data are needed: failure rates (which is possibly time dependent); and repair/restoration and PM times. Several different sources may provide failure rate information [41]: (1) public data books and databanks; (2) performance data from the actual plant; (3) expert judgments; or (4) laboratory testing. A review of reliability data collection and its management is given in EuReDatA [42].

5.2.2. Data quality

Regarding source type (1), reliability databanks, much remains yet to do in terms of quality of the data available in these banks. In addition to the materials used, design and surface treatment, detailed studies [43] have shown that reliability is often significantly dependent on a wide range of environmental and operational factors. While these factors are normally not specified in the data books, OREDA [44] supplies data for the repair times and different failure modes. The data supplied are at best the average values with certain confidence levels. Moreover, most data sources present only constant failure rates.

5.2.3. Laboratory testing

Laboratory testing [41] is commonly carried out by engineers to estimate the life time distribution $F(t)$ for a particular component of a system. For these $n$ units, component are activated and their lifetimes recorded to obtain a so-called “complete” data set. Sometimes, due to economical reasons, or the timeframe of the analysis, incomplete data sets, so-called “censored” data sets have to be used. But in many laboratories tests are neither affordable nor available to maintenance decision makers. The data from the plant has to be screened properly to ensure that the data represents the same failure mode in technically homogeneous equipment collected under the same operating conditions, and therefore such data must be closely reviewed. In cases where preventive actions have not yet been accomplished and there is enough data available for a given failure mode under analysis, it is frequently useful to use a “natural estimate” of the failure rate by splitting the time interval in discrete time units as explained by Hoyland and Rausand [41, pp. 22–23].

In cases where the possibility of changing a current PM strategy in a system is to be analyzed, information regarding failure distribution functions for the failure modes under analysis is normally difficult to find—with the available historic plant data. This is because the preventive actions may impact the failure rate distribution (This effect is explained by Tsuchiya (1992); also see the explanations in Resnikoff Conundrum [30]).

5.2.4. Analysis and preparation of maintenance financial data of the system

In addition to the failure history or reliability data of the system, financial information is needed to determine the payoff of different maintenance strategies being considered. For this purpose, in addition to the maintenance direct cost, engineering cost plus the possible cost of lost production every time a maintenance related cost variable need to be evaluated (as defined, for instance in British Standard BS6143 [45]). For example, a particular PM strategy might require a certain cost in labor, spare parts, tools, information systems, and human resources to support the program. At the same time, PM would require a certain downtime of an equipment/line/plant with a possible lost production cost. Safety implications and/or environmental implications on maintenance cost of equipment could also be considered at this point.

5.2.5. Modeling systems for maintenance policy optimization

The integral process for the utilization of optimization models in maintenance has been discussed by some authors [46] who described the necessary aspects to take into account in order to consider the modeling of a maintenance problem scientific and exhaustive. These points may be summarized as follows: (1) recognition of the problem and aim of the study; (2) agreement, and enumeration, on the required data for the study; (3) design of the system for the future withdrawal of data (if required); (4) preparation of the data and information to fit the models; (5) benchmark of the data with other sources/alternatives; (6) formulation of the suitable maintenance policies using the models; (7) explanation of the process followed to the maintenance manager; and (8) discussion of model results and model utilization payoff analysis. We can find a variety of models generally devoted to several key areas/problems within the MM. According to Campbell and Jardine [34, p. 276], these problems are several, namely, (a) determining time intervals or equipment age for optimal maintenance, (b) determining frequency of inspections and condition-based optimal maintenance, (c) determining optimal resources to meet maintenance requirements, or finally (d) finding the economic life cycle of an equipment studying the repair vs. replace problem. Traditional methods to deal with these problems have been linear and dynamic programming, simulation models, stochastic models, and analysis through net present value functions. Although there are many contributions showing interesting results using models following these categories, much of the
work done is of mathematical interest only, exploring the consequences of a model format [47]. Baker and Christer [48] suggest that little attention has been paid to the required data collection process and its appropriateness in developing or using mathematical models. Therefore, little evidence exists that many classic replacement and age-based models [49], or block replacement with/without minimal repair type models [50] are enthusiastically used in practice [47]. At the same time, difficulty in developing good maintenance optimization models has been growing as modern industrial systems grow in complexity. The significant bibliographical reviews of maintenance quantitative models include Pier-skalla and Voelker [51], Osaki and Nakagawa [52], Sherif and Smith [53], Valdez-Flores and Feldman [54], and Cho and Parlar [55]. Each of these reviews classifies the optimization models according to some particular criteria.

5.3. Measurement and control of ME activities

A complete set of indicators for the control and improvement of MM may be found in Coetzee [56], Campbell and Jardine [34] and Wireman [5]. A more specific set of indicators dedicated to the assessment of the different ME tools may be found in Wireman [5].

Table 3 summarizes the different functions that constitute the ME pillar.

6. Organizational techniques pillar

In many organizations, the MM function is centralized through the maintenance manager who is responsible for all aspects of plant and facility maintenance and support. Almost all services are dispatched here centrally and all spares and materials are regulated from the central stores. This system is assumed to ensure control over policy, procedures, system, quality, and training. The expectation is that of efficient allocation of maintenance workload across different operations would thus be guaranteed. The major disadvantage, however, is a lack of flexibility which is manifested in many ways: time to market, rigidity, ignorance of specific equipment, customer dissatisfaction, focus on efficiency not effectiveness, etc. [3]. Global competition has transformed such centralized management in the past decade. Product managers have become responsible for different production areas, promoting decentralized decision making and job enrichment, particularly for front line workers. This has fostered decentralization and moved maintenance out of the central maintenance shop into the mainstream of operations. Decentralization of maintenance has been found to be an effective means of improving communication and coordination particularly in a technically complex environment [15]. But decentralization is not the panacea. With complete decentralization it is easy to lose sight of the business plan and the (corporate or business) environment in which maintenance function must perform. Campbell [3] maintains that there are no correct maintenance organization structures but only strategies that can be effectively applied in specific business situations.

In any case, in accord with the new decentralized positioning of maintenance, the maintenance organization itself needs to be very flexible. It must easily adjust to possible hybrid and even changing centralized-decentralized configurations and, at the same time, must have the necessary capabilities to interact with other internal functions of the business as well as with other external partners (see Table 4).

Some techniques fostering flexibility within the maintenance organization are given by the Japan Institute of Plant Maintenance [57] and by Nakajima [35]. They present, for instance, techniques to have multi-skilled technicians, by grouping tasks performed by maintenance into skill modules and then linking clusters of these modules, logically pursuing the proper technician skills progression. Another technique is the use of small groups with the purpose to reach the best work environment, moral, etc. This speeds up the improvement of technical capabilities of the group members.

Team work also supports more direct communication between different functional groups. For instance, two maintenance activities that have shown good results when performed as team-based activities are maintainability improvement and PM.

Another technique proposed to support communication while improving coordination between different functions in the organization is the use of advanced information processing technologies such as CMMS [58] and their integration with ERP systems.

But relationships competencies are not constrained to remain within the boundaries of an organization, customer–supplier relationships have evolved to what has been defined as co-destiny [59]. Everyone from raw material suppliers to local distributors and dealers in the supply chain share a common destiny, and they commit efforts, time, and mainly trust that the other players will do their part and make the entire project an enduring success. In the case of mass customization, the customer is in a unique position, but that also means that he remains responsible to divulge critical information and spend time in training the supplier in order to get the best value in the product or service sold. It is not surprising then that MM and personnel in a modern manufacturing firm will have to develop

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12 For instance, Wireman [5] defines a set of indicators divided by groups: (a) corporate, (b) financial, (c) efficiency end effectiveness, (d) tactical and (e) functional performance. He says that the people have to use those indicators connecting properly to corporate indicators. Objective of the performance indicators are: make strategic objective clear, tie core business processes to the objectives, focus on critical success factors and track performance trends, and identify possible solutions to the problems.
Table 3
Classification of functions within the ME pillar

<table>
<thead>
<tr>
<th>Functions of the ME methods pillar</th>
<th>Design of the maintenance plan and its process of continuous improvement</th>
<th>• Failure analysis, reliability analysis and risk analysis of the system’s operation - Design of the maintenance plan - Ensure the total employees involvement in maintenance, to pursue the continuous improvement - Management of maintenance resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization of the maintenance policy</td>
<td>• Analysis and preparation of reliability and availability data of the system</td>
<td>• Analysis and preparation of maintenance financial data of the system - Modeling systems for their maintenance policy optimization</td>
</tr>
</tbody>
</table>

Table 4
Functions of the organizational techniques pillar

<table>
<thead>
<tr>
<th>Functions of the organizational techniques pillar</th>
<th>Providing flexibility to the maintenance organization</th>
<th>• Develop multi-skilling - Small group development - Foster team work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supporting communication and coordination with other functional areas (inter.)</td>
<td>• Extensive use of CMMS - Integration of CMMS into ERPs</td>
<td></td>
</tr>
<tr>
<td>Improve external (intra) relationships</td>
<td>• Improve relationships with OEMs - Improve understanding and response to customer needs</td>
<td></td>
</tr>
</tbody>
</table>

techniques and processes that help accomplish the following objectives:

- Maintain a proper relationship with the original equipment manufacturers (OEMs) providing equipment to the plant. Work in cross functional teams and share common and suitable information to ensure, or even improve, equipment reliability and maintainability over time, as well as create a reliable support for equipment maintenance (here, of course, enter all the e-maintenance activities). These organizational aspects together would make the designed equipment effectiveness attainable.
- Understand and respond to customer needs. Maintenance departments of the manufacturing firms will have to be aware about any possible external non-conformity of the product rejected or returned by any customer, which could be a consequence of improperly maintained equipment. Shifting tolerances in machine shops is a typical example. The maintenance department will have to be part of products quality audits and be responsible to execute the necessary corrective actions to avoid any related problems.
- Have a strategic perspective to maintenance outsourcing, developing a framework for the selection of appropriate sourcing strategy in particular situations. In many cases, it has been shown that ensuring the proper input from the client organization is a key factor for success. Nevertheless, developing a framework to study other possible alternative to outsourcing like selective outsourcing or out-tasking [61] will be a must in modern organizations.

7. Conclusions

Maintenance management (MM) has rapidly grown into a very complex undertaking as technologies, competition, and product characteristics evolve. But with newer enablers in business such as IT, opportunities have also emerged. In this paper the concepts of maintenance and MM are briefly reviewed and then used to develop a framework to set the various functions within MM. A clear perspective of the three levels of business activities—operational, tactical and strategic—is maintained in positioning these functions within the organization. We separate actions from the
framework (the tools and methods constituting the supporting structure for help in the execution of all maintenance-related actions), to reduce the burgeoning complexity in the MM process. This structure itself is analyzed in depth, and characterized according to three main pillars that support maintenance, namely, Information Technology (IT), Maintenance Engineering (ME), and Relationship management. Each of these pillars contains a set of sub-functions that are in turn classified and studied here in correspondence with the strategic, tactical and operational activities. This paper also provides the reader with an up-to-date review and citations of the significant methods, techniques and technologies—to enable an organization to develop various maintenance-related functions, allowing them to face the complexities typical in today’s manufacturing and service environments.

The paper also locates the opportunities to contribute to improving MM through original research. We propose the following as a possible research agenda:

- Within the IT pillar, research efforts could be directed to define potential e-maintenance frameworks, and to integrate different approaches of condition and failure monitoring, to help obtain a comprehensive model for failures management.
- Within the ME pillar, it would be productive to explore the integration of on-line equipment and process condition data with failure prediction and maintenance optimization models.
- Within the pillar of organizational techniques, we feel that it would be interesting to deal with the problem of “customizing” maintenance organization structures according to evolving business strategies as product mix, supply chain scenarios, technologies, or product development opportunities change.

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