2

Maintenance Management Characterization: Process, Framework and Supporting Pillars

2.1 A Reason for MM Characterization

Maintenance management is frequently associated with a wide range of difficulties. Why is this function, at least in appearance, so difficult to manage? We have carried out a review of literature to find out some of the reasons:

- *Lack of maintenance management models* [1]. There is a lack of models that could improve the understanding of the underlying dimensions of maintenance. Maintenance is somewhat "under-developed" ([2-4]) with a lack of effective prevention methodologies and the integration of said methods in manufacturing companies in most continents;
- *Wide diversification in the maintenance problems* [5]. 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 wide diversification in the problems that maintenance encounters, sometimes a very high level of variety in the technology used to manufacture the product [6], even in businesses within the same productive sector; therefore, it has been difficult to design an operative methodology of general applicability;
- *Lack of plant/process knowledge and data* [7]. Managers, supervisors and operators typically find that the lack of plant and process knowledge is the main constraint, followed by the lack of historical data, to implement suitable maintenance policies;
- *Lack of time to complete the analysis required* [1]. Many managers indicate how they do not have the required time to carry out suitable maintenance problems analysis. Day to day actions and decision making activities distract them from these fundamental activities to improve maintenance (see Figure 2.1);
- *Lack of top management support* [1]. Lack of leadership to foster maintenance improvement programs, fear of an increase in production

disruptions, *etc*., are other common causes of maintenance underdevelopment in organizations;

- *The implementation of advanced manufacturing technologies* [8]. 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 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 [8]. This makes maintenance crucially relevant to operations management in order 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 [9]. When this occurs, new or unfamiliar problems often arise;
- *Exigent safety and environmental factors* [10]. In addition to process and technology related issues mentioned above, new and more exigent safety and environmental factors such as emerging regulations put pressure on a maintenance manager and add complexity to this function (for a complete discussion of these aspects in relation to maintenance, see Chapter 8 in [10]).

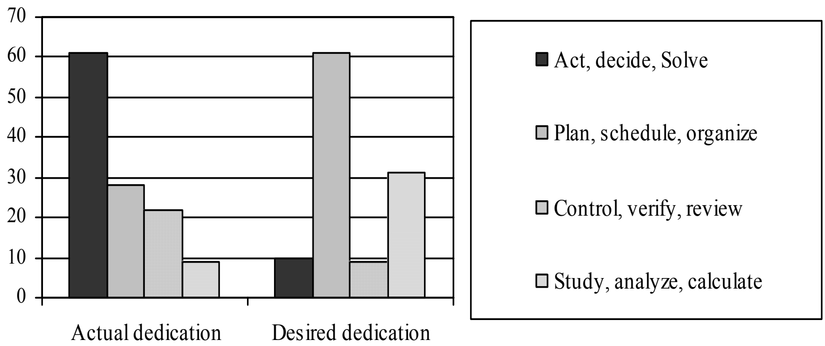

Figure 2.1. What maintenance managers do *vs* what they think they should do

Some authors [11] have worked on the characterization of the complexity found in managing the maintenance function in a production environment, creating tools where we are able to value each one of previously reviewed factors for a certain organization (with a degree of fulfilment – DFi), and evaluate them according to environmental aspects (with a relevance factor – RFi). The relative importance of the factors, the use of evaluation (weights), is obvious. For instance, the use of computerized maintenance management systems (CMMS) is a highly relevant issue in a production environment where the amount of critical equipment is very high or where the need for maintenance resources management is very significant. 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 [12]. The maintenance management complexity index [11] can be helpful as one way of comparing across different production environments to help decide the relative effort and resources required to maintain them.

Table 2.1. Characterization and assessment of MM complexity index of a production system

Factors impacting maintenance complexity		Degree of fulfilment (DF_i)					Relev. Factor (RF_i)	Total: $DF_i \times RF_i$
		1	2	3	4	5		
Information system	Lack of CMMS							
	Lack of historical data							
Process technology and integration	Complexity of the production process technology							
	Variety of technologies used in the production process							
	Level of automation and process integration							
Production management system	JIT – Non stock production							
Maintenance management system	Lack of maintenance procedures in place							
Personnel technical expertise	Low level of operators knowledge and involvement in maintenance							
	Low technical expertise of the maintenance staff							
…etc.	*…etc.*							
							Total	$\sum DF_i \times RF_i$

2.2 The Maintenance Management Process

2.2.1 The Course of Action

What is the process — the course of action and the series of stages or steps — to follow in order to manage maintenance properly?

Let us assume that the maintenance strategic planning is done, and that a series of target maintenance performance measures exist and a generic budget assigned to maintenance. Let us also assume that high level management and organizational responsibilities for specific maintenance activities are established. What are the next steps that we need to follow to manage maintenance properly?

A generic process for maintenance management, integrating ideas found in the literature [13,14] for built and in-use assets, could consist of the following sequential management steps:

- Asset maintenance planning:
    - Identify the asset;
    - Prioritize the asset according to maintenance strategy;
    - Identify its performance requirements according to strategy;
    - Evaluate the asset's current performance;
    - Plan for its maintenance;
- Schedule maintenance operations;
- Manage maintenance actions execution (including data gathering and processing);
- Assess maintenance;
- Ensure continuous improvement;
- Consider the possibility of equipment re-design.

In the following paragraph we review these main categories of maintenance management actions.

2.2.2 Maintenance Planning

Maintenance planning is the maintenance management activity that is carried out to prepare the maintenance plan. According to EN 13306:2001 [15], the maintenance plan consists of a "structured set of tasks that include activities, procedures, resources and the time scale required to carry out maintenance". Once we make the plan, *i.e.* we identify the maintenance task required, we have to establish the maintenance support needs, *i.e.* resources, services and management, necessary to carry out the plan [15]. Of course this support may vary according to changes in strategy, so it will have to be re-evaluated when plans are updated to meet new organizational needs.

However, let us first study how to obtain our plan, our structured set of maintenance tasks for our equipment. In order to do so, we have to prioritize our equipment according to our maintenance strategy; then we may follow a combination of approaches of which the following could be of interest (Figure 2.2):

- Adopting manufacturers' recommendations, such as those contained in the maintenance and operation manual or similar documents, *etc.*;
- Relying on actual experience with the item or similar items;
- Studying and analysing technical documentation of each item, such as drawings diagrams, technical procedures, *etc.*, in order to improve and adapt the recommendations coming from the manufacturer to the real working conditions or maintenance special needs;
- Using maintenance engineering techniques, such as Reliability Centred Maintenance (RCM) based on a FMECA or other methods with this purpose;
- Considering regulatory and/or mandatory requirements, such as safety conditions of item operation, environmental regulations for the item, *etc.*;
- Other approaches.

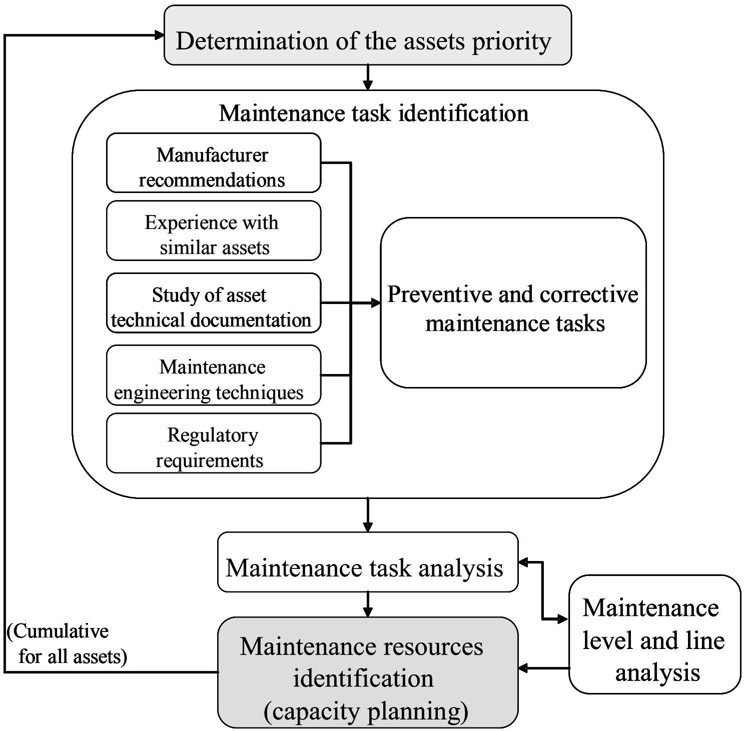

Figure 2.2. Maintenance task and capacity planning model

It is possible to depend solely on manufacturer recommendations for maintenance tasks but users need to confirm that they are appropriate for their own operational use. The manufacturer is usually unable to anticipate factors such as business-related consequences of failure, safety considerations, regulatory requirements, the use of condition monitoring techniques, availability of resources and unique environmental conditions. For items that have sufficient operational experience and maintenance historical records, it may be possible to rely on actual maintenance practices and experience. For situations where manufacturer-based maintenance tasks are not specified or suitable and where equipment is deemed to be critical, a structured analysis such as RCM should be carried out. When different types of maintenance tasks are possible (for example, condition monitoring or regular replacement), trade-offs between such factors as item availability, times available for maintenance and cost may need to be considered and evaluated.

Maintenance task analysis determines the specific information and resources for each item that requires maintenance including:

- Description of the maintenance task (with the level of detail required for a skilled maintenance person);
- Frequency of the task (based on a relevant measure such as elapsed time, operating hours, number of operational cycles or distance);
- Number of personnel, skill level and time required to perform the task;
- Maintenance procedures for disassembly and reassembly;
- Safety procedures to be followed;
- Procedures for handling, transportation and disposal of hazardous materials;
- Special tools, test equipment and support equipment required;
- Spare parts, materials and consumables to be used or replaced;
- Observations and measurements to be made;
- Checkout procedures to verify proper operation and successful completion of the maintenance task.

The tasks are then reviewed and adjustments made to their frequency as a result of constraints such as available outage windows, the need to maximize availability or the optimization of resources. Wherever possible, existing sources of maintenance task analysis data should be utilized (*e.g.* existing manuals, maintenance instructions or ILS reports); however the applicability of these to different applications or environments needs to be considered.

In defining the detailed maintenance operations, it is necessary to determine at which line of maintenance (*i.e.* the position in an organization where specified levels of maintenance are to be carried out on an item) equipment should be repaired or replaced. Examples of line of maintenance are: field, on site, at a local repair shop or by an external repair facility. The objective is to define appropriate lines of maintenance to minimize the costs according to availability constraints. The following information provides input to this level of maintenance analysis:

- Equipment operational data, quantity and location;
- Feasible repair alternatives;
- Cost factors;
- Repair personnel and resources;
- Item reliability and maintainability data;
- Turnaround and transportation time to and from repair facilities;
- User policy and constraints.

The output from this detailed analysis facilitates the assignment of a line of maintenance for each piece of equipment and provides input into the maintenance task analysis and the identification of maintenance support resources. Notice that the determination of the maintenance line will require to take decisions on:

- Whether maintenance personnel are provided by the organization or whether they are obtained from external sources;
- Who provides spare parts, materials and consumables, *e.g.* inventory, local sourcing or external supply;
- Where special tools, transportation, lifting, testing and support equipment is sourced;
- Condition monitoring equipment and software to be used;
- Infrastructure that needs to be provided to implement maintenance policies.

When this process is carried out for all the assets, the complete maintenance task definition and the maintenance capacity planning will be finalized.

2.2.3 Maintenance Scheduling

Scheduling for specific maintenance tasks needs to be done with enough time to schedule and supply the necessary resources. This includes:

- Identifying and assigning personnel;
- Acquiring materials and spare parts from external sources or inventory;
- Ensuring that tools, transportation, lifting and support equipment are available;
- Preparing required operating, maintenance, safety and environmental procedures and work plans;
- Identifying and reserving external resources;
- Identifying communication resources;
- Providing necessary training.

Planned activities are scheduled based on a priority system to ensure that the most urgent and important activities are carried out first and resources are utilized efficiently. The dispatch of maintenance resources may be activated through call centres, specialized callout procedures, remote automatic diagnosis, equipment operators or users, or by other means.

2.2.4 Managing Maintenance Actions Execution

Maintenance tasks should be performed with due care and attention to the technical aspects of isolation, disassembling, cleaning, repairing, refurbishing, replacing, re-assembling and testing equipment and components. Special safety and environmental procedures such as disposal of hazardous materials and consumables need to be followed as specified. Information should be recorded with respect to observations made, readings and measurements required, tasks carried out and resources used.

Preventive maintenance may consist of:

- Gathering technical data and task description;
- Obtaining spare parts and tools and support equipment;
- Travel to the worksite;
- Preparation of the worksite such as equipment shutdown, isolation and lockout procedures;
- Active maintenance time;
- Observations and measurement;
- Testing and checkout;
- Clearing of worksite;
- Recording necessary information.

Corrective maintenance entails the same steps as those for preventive maintenance, but also requires the additional task of fault identification, in order to identify the location and nature of the failure and the necessary refurbishment or replacement of components. In the event of a major failure, the cause needs to be investigated and evidence gathered prior to the repair. In any case, the identification of the cause of the failure should be carried out and registered, as well as the solution given to the problem. This information would be used in later analysis for making improvements and to help maintenance personnel in solving future problems of a similar nature.

Certification of maintenance tasks may need to be carried out if specified by regulatory, contract or company requirements.

In any case, a signature of conformity about the work done should be obtained from the operator, the person in charge of the repaired or intervened equipment, or the person who demanded the maintenance operation.

2.2.5 Maintenance Assessment

In order to assess maintenance we have to use suitable measures. Maintenance performance measures should be defined during the maintenance strategy setting process. Different types of measures can be selected, those that can be related to equipment user results or those associated with direct maintenance effectiveness. Both types of measurement are important to gauge the effectiveness and efficiency of maintenance and maintenance support activities. Measures can be made in absolute or relative terms to enable comparison and must somehow be associated with the collection of dependability data.

The effectiveness of maintenance and maintenance support, as seen by the equipment user, is measured by availability performance, which also includes reliability and maintainability aspects. User-related performance factors can be expressed in terms of:

- Production capacity;
- Availability of equipment or production;
- Downtime or outages;
- Safety and environmental performance;
- Regulatory compliance;
- Operating cost;
- Maintenance cost;
- Corporate profit;
- Product quality;
- And so on… .

The specific contribution made by maintenance and maintenance support may be difficult to establish precisely because of the influence of other factors such as operational error or conscious decisions to operate beyond design conditions. The optimization of these factors often requires tradeoffs to be made. Measurements can be compared for similar equipment, to industry best practices or to other users and for use when benchmarking services.

The purpose of maintenance-related measurement is to measure the effectiveness of maintenance and maintenance support. Measurements related to specific equipment or groups of similar equipment may include:

- Availability, reliability and maintainability;
- Downtime or outage time;
- Mean time between failure;
- Mean repair time;
- Time to failure, statistical representation such as Weibull analysis [16];
- Planned and unplanned maintenance cost;
- And so on… .

Measurement related to general maintenance management may consist of:

- Proportion of planned *vs* unplanned tasks;
- Planned work not completed on time;
- Variation of resources between planned and actual;
- Spare parts availability;
- Workforce utilization and skill level;
- And so on….

Assessment of preventive and corrective maintenance tasks can be performed either each time maintenance is done (such as after a major failure) or on a periodic basis to review overall performance, *e.g*. by type of equipment for a certain time period.

The organization should establish and use a standard and repeatable method for collecting and analysing data and interpreting results, which may be based on corporate or industry factors. The results should be used to support and justify improvements. A computerized maintenance information system may be needed to enable this process by managing data and analysing results.

For preventive maintenance, the review should cover the effectiveness of maintenance, technical aspects of the maintenance task, adequacy of resources and operating, safety and environmental procedures.

For corrective maintenance, major failures should be fully investigated to identify preventive and corrective actions and, for major or costly failures, this involves performing a root cause failure analysis. A detailed root cause failure analysis may consist of:

- Forming a team of experts;
- Gathering evidence;
- Analysing the results and determining failure causes, possibly by performing an FMEA, fault tree analysis or other method;
- Determine a root cause of failure;
- Proposing, testing and validating hypotheses;
- Recommending preventive actions;
- Implementing improvements.

Overall review of corrective maintenance will reveal repetitive failures and trends related to operating conditions, vendor problems and quality issues.

2.2.6 Ensuring Continuous Improvement

Improvement in maintenance and maintenance support activities is achieved by management support, effective processes and communication. Improvement to maintenance and maintenance support can be achieved by changes in:

- Maintenance definition (type, line of maintenance, *etc.*, for the equipment);
- Level of maintenance;
- Maintenance procedures;
- Skills and training of maintenance and operations personnel;
- Spare parts and materials;
- Tools and support equipment;
- Use of external resources;
- Operating procedures and conditions;
- Safety and environmental procedures;
- Equipment and system design;
- Maintainability of the equipment.

A validation process may be needed to ensure that the appropriate corrective or preventive action has been taken and improvement has been achieved.

2.2.7 Considering Equipment Re-design

Modifications to the existing items, in general, means new operational conditions for these items. In other cases the modifications may be addressed to new items that could be prepared in future.

The following recommendations affect the provider of the changes carried out on the items, either when it concerns an external provider or the own user. However, only in the second case, that of the own user, should the maintenance manager issue the relevant documentation (outlined below) and perform the related actions. Concerning the first case, that of an external provider, the user or the entity responsible for maintenance should be aware of, and prepared to receive from said external provider, the technical information (also outlined below). Neither the user nor those responsible for maintenance are bound to issue said technical information, unless the own provider was maintenance responsible.

Modifications to equipment, whether to improve functionality or maintainability, should result in re-assessment of maintenance and maintenance support. This may result in changes in maintenance definition, resources, training and associated documentation.

Documentation issued by manufacturers, such as vendor service bulletins, should be carefully reviewed for changes to maintenance and maintenance support.

Modifications to a system may result in some spare parts becoming redundant. For this reason care should be taken not to buy too large a quantity of spares. A modification may also apply to spare parts in store. A modification may require the provision of new materials and spare parts.

The modification process should be supported by the configuration management system or some other change management system to ensure that changes to maintenance and maintenance support resulting from modifications are implemented and recorded through the proper configuration control procedures.

Modifications should be evaluated to ensure there is no negative impact on maintenance and maintenance support.

2.3 Maintenance Management Framework

What is the framework — the essential supporting structure and the basic system — needed to manage maintenance effectively? To begin, we will review some of the most interesting and useful contributions found in the literature about this issue. Then, by a synthesis of the observed ideas and schemes offered by experts, we will propose a framework for modern maintenance management.

2.3.1 A Review on Maintenance Framework

Wireman [17] proposes a sequential implementation of steps to ensure that all functions for maintenance management are in place. He believes that a basic preventive maintenance (PM) program should be in place before we advance to the next level, the CMMS implementation[1]. 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 Reliability Centred Maintenance (RCM)[2] and predictive maintenance programs. The operators must also 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 “Total Productive Maintenance” (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 the necessary maintenance organization structure — to facilitate continuous improvement in maintenance practices. For an overall picture of Wireman’s model see Figure 2.3.

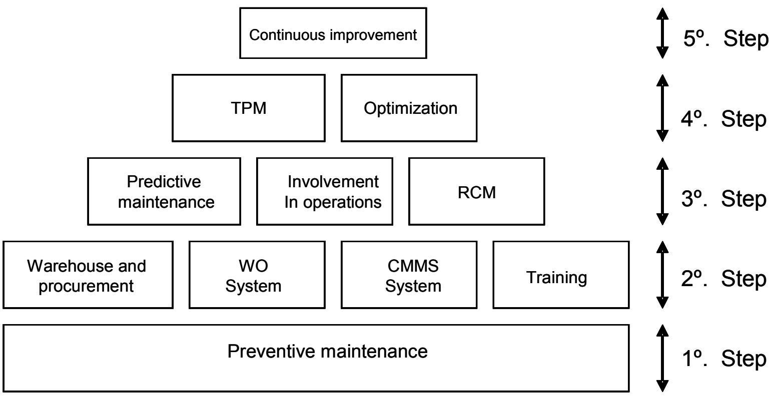

Figure 2.3. Maintenance framework according to Wireman [17]

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[1] With time, and in most of the cases, a PM program reduces the reactive/corrective maintenance to a level low enough so that the other initiatives in the maintenance management process can be effective. Note that the reliability and maintainability of an item are abilities of an item [15], which assumes proper operation, and the maintenance of said item. Without ensuring a certain level of PM, reliability and maintainability are not guaranteed.

[2] To function, RCM tools require data [17]. Therefore, the RCM process should be utilized after the organization has attained a level of maturity that insures compilation of accurate and complete assets data.

Campbell [18] also suggests a formal structure for effective maintenance management (see Figure 2.4). 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 carried out by the implementation of a CMMS, a maintenance function measurement system, and planning and scheduling the maintenance activities. It 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) Preventive maintenance, g) Age or use based, h) Condition based maintenance, and i) Redesign. Finally, Campbell proposes the implementation of two highly successful methods for continuous improvement — RCM and TPM. He also recommends the use of process reengineering techniques (Activity Based Process Mapping techniques, Process Value Analysis techniques, and Innovative Process Visioning techniques, among others) for stepped leap improvements in maintenance.

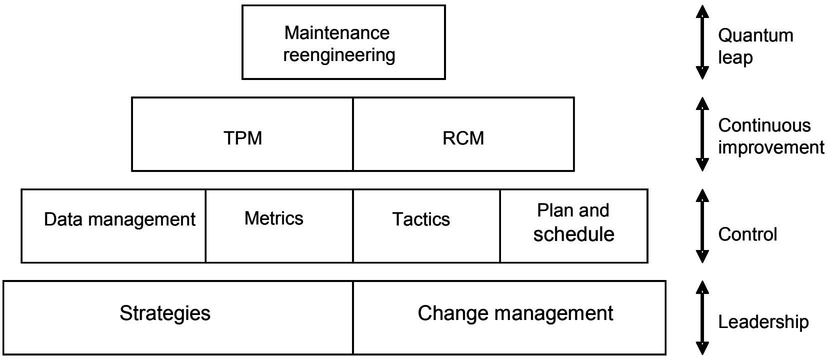

Figure 2.4. Maintenance Framework according to Campbell [18]

Pintelon and Van Wassenhove [19] provide a maintenance management tool to evaluate maintenance performance. The tool consists of a control board and a set of reports to analyse 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.

Pintelon and Gelders [20] discuss a maintenance management framework in which the primary aspects of maintenance management (MM) are included. The framework has three building blocks:

The operations management/maintenance management 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;

A second building block in maintenance management 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 (such as 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;

The last building block is called the maintenance management 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.

2.3.2 Defining the Structure to Support Maintenance Management

A myriad of 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 conventional, "silo" style approach to maintenance management would play a pivotal role. However, in the practice of maintenance management a lot of difficulty 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 problem, we will describe the essentials of an effective maintenance process and put forward a corresponding framework to enable said 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 [11]. As mentioned in Chapter 1, there are three courses of actions at the different levels of the business activity — strategic, tactical, and operational (see Figure 2.5) —, maintenance management must be aligned with action at the three levels of business activities. As shown in Figure 2.5, these three courses of action and the related on-going processes in the organization are clearly interconnected.

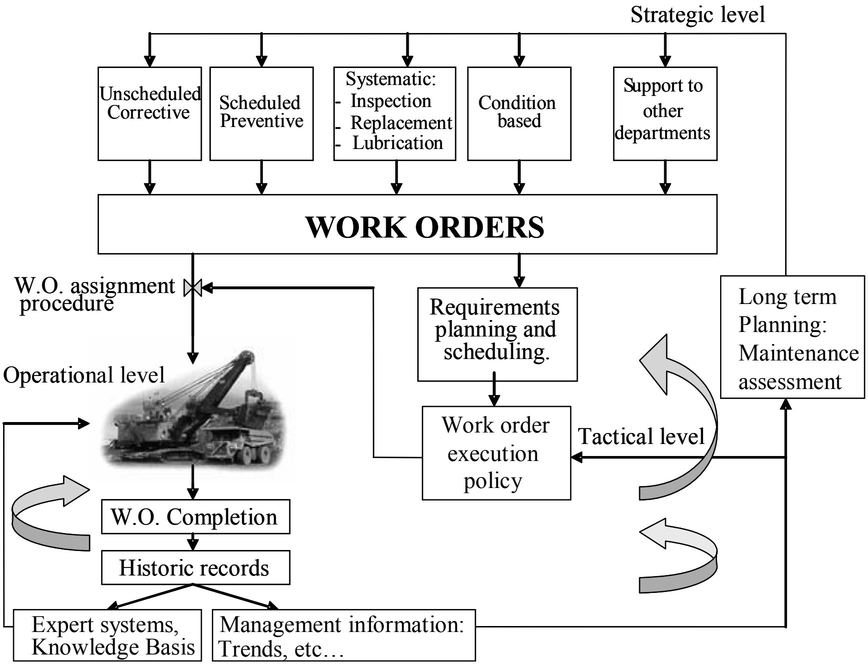

Figure 2.5. Maintenance process, course of action and feedback operating at the three levels of business activities (from Crespo Márquez *et al*. [60])

Table 2.2. The maintenance management process and framework

Maintenance management process	Strategic	From business plan to maintenance plan, definition of maintenance priorities. A closed loop process
	Tactic	From the maintenance plan to the resources assignment and task scheduling. A closed loop process
	Operational	Proper task completion and data recording. A closed loop process

Maintenance management framework	IT	CMMS, condition monitoring technologies
	Maintenance engineering techniques	RCM, TPM, reliability data analysis, maintenance policy optimization models, OR/MM models
	Organizational techniques	Relationships management techniques, motivation, operators involvement, *etc.*

- *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 and the complexity of the plant are 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-the-art information processing capability, decision support, 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 [21]. The IT pillar also includes condition monitoring technologies. By focusing continuously on potential tactical and operational decisions and actions, they greatly improve maintenance management efficiency;
- *The Maintenance Engineering (ME) Methods Pillar.* A set of key techniques together constitute this pillar:
  - *Reliability Centred Maintenance* (RCM). RCM plays an important role at strategic and tactical levels and helps design and define maintenance plans that ensure desired equipment reliability[3];
  - *Total Productive Maintenance* (TPM), on the other hand, focuses on organizational efforts at the operational level to improve overall equipment effectiveness[4];
  - *Quantitative tools* that can be used to optimize the maintenance management policies will also fall under this section[5];
  - *Tactical activity oriented stochastic tools* to model the failures, allowing a further use of quantitative techniques;
  - *Other OR/MS* (Operations Research/Management Science) *techniques* that focus on optimizing maintenance resources management.

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[3] An interesting case study about RCM can be found in [22].
[4] A case study about TPM can be found in [23].
[5] Some case studies may be found in [24].

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

- *The Organizational (or Behavioural) Pillar.* This pillar is perhaps the most important 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. At this point we have included all the 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.

2.4 Functions of the MM Supporting Pillars

2.4.1 Functions of the IT Pillar

We will now expand 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 [25] 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) Preventive maintenance plan development and scheduling;
g) Human resources;
h) Purchasing and receiving;
i) Invoices matching and accounts payable, and;
j) Tables and reports.

We must point out that mere cataloguing of such tasks and tools or even the possession of expensive CMMS software would not make the organization proactive in maintenance management (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. The organization will have to learn to codify failure causes, types of maintenance work, the physical assets, *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 component 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 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 equipment's failure and criticality goals. Criteria to assess criticality can be very diverse such as maintenance direct and indirect cost, availability, and reliability[6];
- *Supporting maintenance activities planning,* avoiding any kind of servitude to the planning system, primarily by fostering management through exception and the production of alerts;
- *Providing procedures for auditing maintenance activities*, intra and inter-enterprise benchmarking[7]. 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

[6] 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.

[7] Readers interested in this topic are referred to Komonen [27] for an industrial maintenance cost model for benchmarking.

corresponding coding unification. It also means connection to the rest of the systems for plant data capturing.

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 maintenance management. 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 maintenance management tool [26]. During the last five years, we have seen the percentage of plants using these tools for maintenance management increase enormously, from 15% to 85%, as indicated by a survey of 1500 American plants [26]. However, much higher benefits can be obtained when one simultaneously uses these tools for all three purposes. Configured in this manner, a system for maintenance management would be expected to raise substantially the likelihood of materializing the following benefits:

- Preventing catastrophic failures while increasing plant throughput by 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 labour hours and the stock of spare parts;
- Identifying the machine problems before equipment disassembly 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 equipment to cover critical stops and reduction in insurance costs.

According to Moubray [28] 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 stress). For a complete set of methods the reader is referred to the handbooks published by the ASNT (American Society of Non-destructive Testing).

2.4.2 Functions of the ME Pillar

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

In Baldín *et al.* [29], 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;
3. Techniques used to control and assess maintenance performance.

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

2.4.2.1 Design of the Maintenance Plan and its Process of Continuous Improvement

Maintenance engineering is actually an analytical function with a highly methodical development carried out during the preparatory and the operational phases of 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 behaviour 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 previous system assessment. The selection of the failure analysis method depends on a system's available technical and qualitative data. 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 [30] classifies them according to the following concepts:

- *Type of reasoning*. Inductive and deductive methods. Inductive methods begin the study departing from specific events with the idea to reach overall systems 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:

  1. FMEA, Failure Modes and Effects Analysis;
  2. FMECA, Failure Modes Effects and their Criticality Analysis;
  3. HAZOP, Hazards and Operability Analysis;
  4. MA, Markov Analysis;
  5. Event Sequence Analysis.

  By contrast, deductive reasoning methods begin 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 Reliability Centred Maintenance (RCM) help accomplish this sub-function. According to Rausand [31], RCM identifies the functions of a system, the way these functions may fail and then establishes, *a priori*, a set of applicable and effective preventive maintenance tasks, based on considerations of system safety and economy. According to Campbell and Jardine [32], RCM specifically allows: a) detection of failures early enough to ensure minimum interruptions to a system's operation, b) elimination of the causes of some failures before they appear, c) elimination of the causes of some failures through changes in design, and d) identification of those failures that may occur without any decrease in system's safety;

• *Ensuring employee involvement in maintenance.* This aids the pursuit of continuous improvement. Total Productive Maintenance (TPM) is an example of this sub-function. TPM was formally defined in 1971 by the JIPE (Japan Institute of Plant Engineers, predecessor of the Japan Institute of Plant Maintenance) as a methodology. TPM helps the plant to accomplish systematically productive maintenance activities (preventive maintenance activities, reliability centred 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 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 [33];

- *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 decent estimate of the required number of maintenance personnel by skills, Shenoy and Bhadury [34] found that queuing theory models offer very good results, especially those that help minimize equipment unavailability and labour cost. The Monte Carlo simulation is also used for this purpose (see for instance [35, 36]). 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 [37]);
    - *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), FSN (Fast slow and non-moving) analysis and SDE (Scarce, difficult, and easy to procure). These in turn lead to appropriate heuristics;
    - *MRP/MRPII* (Material Requirements Planning/Manufacturing Requirements Planning) applied to maintenance. This technique has been used mostly for spare parts procurement in scheduled maintenance.

Besides the need to manage effectively 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 labour cost. *Managing* maintenance contracts require both a process and a framework. Good guidelines to ensure proper maintenance contract management may be found in new European pre-standards [38]. In these standards the practitioner will 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.

2.4.2.2 Optimization of the Maintenance Policy

In the last five decades we have seen rapid growth in the use of statistical and operational research techniques that help managers, engineers, and others pursue optimization in maintenance policy making [39]. We therefore feel that this work deserves a separate functional identity within the broad area of maintenance engineering. The overall activities at this point may be divided as follows:

- *Analysis and preparation of reliability and availability data of the system*. In maintenance management two categories of micro-level data are needed: failure rates (which are possibly time dependent) and repair/restoration and preventive maintenance times. Several different sources may provide failure rate information [40]: (1) public data books and databanks, (2) performance data from the actual plant, (3) expert opinions, or (4) laboratory testing. A review of reliability data collection and its management is given in EuReDatA [41];
- *Data quality.* Regarding source type (1), reliability databanks, much still remains to be done in terms of quality of the data available in these banks. In addition to the materials used, design and surface treatment, detailed studies [42] 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 [43] supplies data for the repair times and different failure modes. The data supplied is at best the average values with certain confidence levels. Moreover, most data sources present only constant failure rates;
- *Laboratory testing.* Laboratory testing [40] 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, components 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 cases, laboratory 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; 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 into discrete time units as explained by Hoyland and Rausand ([40], pp 22—23). In cases where the possibility of changing a current preventive maintenance strategy in a system is to be analysed, information regarding failure distribution functions for the failure modes under analysis is normally difficult to find — within the available historic plant data. This is due to the fact that the preventive actions may impact the failure rate distribution (this effect is explained

by Tsuchiya [59]; see also the explanations in Resnikoff Conundrum [28]).

- *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, one must consider the cost of engineering and the possible cost of lost production due to maintenance (see, for instance, British Standard BS6143 [44]). For example, a particular preventive maintenance strategy might require a certain cost in labour, spare parts, tools, information systems, and human resources to support the program. At the same time, preventive maintenance would require a certain downtime of 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;
- *Modelling systems for maintenance policy optimization.* The integral process for the utilization of optimization models in maintenance has been discussed by some authors [45] who described the necessary aspects to take into account in order to consider the modelling of a scientific and exhaustive maintenance problem. 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 maintenance management. According to Campbell and Jardine ([32], p276), 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 [46]. Baker and Christer [47] 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 [48], or block replacement with/without minimal repair type models [49] are enthusiastically used in practice [46]. At the same time,

difficulty in developing good maintenance optimization models has been growing as modern industrial systems increase in complexity. The significant bibliographical reviews of maintenance quantitative models include Pierskalla and Voelker [50]; Osaki and Nakagawa [51]; Sherif and Smith [52]; Valdez-Flores and Feldman [53]; and Cho and Parlar [54]. Each of these reviews classifies the optimization models according to certain criteria.

2.4.2.3 Measurement and Control of Maintenance Engineering Activities

A complete set of indicators for the control and improvement of maintenance management may be found in Coetzee [55], Campbell and Jardine [32] and Wireman [17]. For instance, Wireman [17] defines a set of indicators divided by groups: a) Corporate, b) Financial, c) Efficiency end effectiveness, d) Tactical and e) Functional performance. He states that people have to use those indicators properly connected to corporate indicators. Objectives 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, - identify possible solutions to the problems. A more specific set of indicators dedicated to the assessment of the different maintenance engineering tools may be found in Wireman [17].

Table 2.3 summarizes the different functions that constitute the Maintenance Engineering pillar.

Table 2.3. Classification of functions within the ME methods pillar

Functions of the ME methods pillar	Design of the maintenance plan and its process of continuous improvement	• 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 continuous improvement
		• Management of maintenance resources
	Optimization of the maintenance policy	• Analysis and preparation of reliability and availability data of the system
		• Analysis and preparation of maintenance financial data of the system
		• Modelling systems for their maintenance policy optimization
	Measurement and control of maintenance engineering activities	

2.4.3 Functions of the Organizational Pillar

In many organizations, the maintenance management 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 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.* [18]. 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 [6]. 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 [18] 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 accordance 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 2.4).

Some techniques fostering flexibility within the maintenance organization are given by the Japan Institute of Plant Maintenance [56] and by Nakajima [33]. They present, for instance, techniques to use 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 of reaching 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 preventive maintenance.

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 [57] and their integration with ERP systems.

Table 2.4. The functions of the organizational techniques pillar

<table>
<tr><td rowspan="7">Functions of the organizational techniques pillar</td><td rowspan="3">Providing flexibility to the maintenance organization</td><td>• Develop multi-skilling</td></tr>
<tr><td>• Small group development</td></tr>
<tr><td>• Foster team work</td></tr>
<tr><td rowspan="2">Supporting communication and coordination with other functional areas (intra)</td><td>• Extensive use of CMMS</td></tr>
<tr><td>• Integration of CMMS into ERPs</td></tr>
<tr><td rowspan="2">Improve external (inter) relationships</td><td>• Improve relationships with OEMs</td></tr>
<tr><td>• Improve understanding and response to customer needs</td></tr>
</table>

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 [58]. Everyone from raw material suppliers to local distributors and dealers in the supply chain share a common destiny, and they commit effort, 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 maintenance management and personnel in a modern manufacturing firm will have to develop techniques and processes that help accomplish the following objectives:

- Maintain a proper relationship with the OEMs (Original Equipment Manufacturers) 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 of any possible external non-conformity of the product rejected or returned by the 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 product quality audits and be responsible for executing 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 alternatives to outsourcing like selective outsourcing or out-tasking [12] is a must in modern organizations.

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