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The Maintenance Management Framework

Models and Methods for Complex Systems Maintenance

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To Professor Rafael Ruiz Usano

Foreword

The importance of prevention of failures in industrial facilities, and their timely identification and correction, if they occur, cannot be overstated. An indication of the amount of attention various aspects of maintenance have attracted in recent years is the number of scholarly publications and books published. For example, a quick search of the journal *Reliability Engineering and System Safety* reveals that 274 articles have been published since 1988. These papers deal with diverse aspects of maintenance such as mathematical models of specific strategies, human factors, utilization of operating experience, organizational issues, industrial case studies, and many others. And this, of course, is only one journal in which such articles are published.

In a broad sense, establishing a good maintenance program is an interdisciplinary enterprise that requires both managerial/organizational expertise and quantitative analysis that utilizes mathematical models. A good example of the significance of the utilization of quantitative information is the impressive improvement in performance at nuclear power plants in the United States in the last 15 years. Quantitative results from probabilistic risk assessments (PRAs) have been used to convince the regulators that certain kinds of maintenance can be performed during power operations without undue risk to public health and safety. PRAs have also made it possible to define quantitative goals for the availability of systems and components, thus giving freedom to the owner utility to create the organizational processes that are best suited to satisfying these goals. This performance-based system has been beneficial from both the safety and the power production perspectives.

Writing a book on an interdisciplinary subject is not easy. It is to the credit of Professor Crespo Márquez that he deals with both the managerial and the analytical aspects of maintenance with equal enthusiasm. The book contains an impressive set of mathematical maintenance models. Yet, the author is careful to introduce these models in a systematic way so that a reader unfamiliar with a particular model can understand its intent and assumptions; only knowledge of elementary probability theory is required. This part could be useful to researchers and practitioners in other fields as well, such as reliability and risk assessment.

In spite of the mathematical rigor, the organizational aspects of maintenance are never neglected. In addition, several case studies are very helpful in demonstrating the applicability of models and processes to practical settings.

This book is a valuable addition to the literature and will be useful to both practitioners and analysts.

George E. Apostolakis
Massachusetts Institute of Technology

Preface

This manuscript deals with the maintenance management process, defined as the course of action and the series of stages to follow in order to manage maintenance properly, and specifically with the maintenance management framework, that refers to the essential supporting structure and the basic system needed to manage maintenance effectively. The work is divided into three major parts:

- Part 1. Maintenance management definition and characterization;
- Part 2. Basic concepts for complex systems maintenance;
- Part 3. Developing the maintenance management framework.

Each of these three parts covers different contents with the following intentions:

- To characterise, in detail, the maintenance management process and framework (Part 1).
- To review the basic concepts and models needed for the design, development and implementation of tools within the maintenance management and maintenance engineering fields (Part 2).
- To offer a practical view of the maintenance management process, identifying the key decision areas where specific modelling tools can be of great help (Part 3, in Chapter 7).
- To develop the basic pillars of the maintenance management framework, providing the reader with a consistent background in practical modelling tools and engineering methods for maintenance management (Part 3).

Part 1 is basically an up-to-date review of the maintenance management concept, process and framework. It shows different points of view about these topics that can be found in the literature.

Part 2 is about the failure concept and models as well as the maintenance concept and models. It is common to see a lack of “the maintenance concept” development in modern organizations. Probably the most relevant aspect of this part of the book is the definition of the maintenance policy. This concept is frequently badly structured in many organizations, producing confusion and lack of management effectiveness and efficiency.

Part 3 is obviously the core part of the work and develops a practical view of the maintenance management framework. The scope of this part is to offer to the reader a practical vision of the set of activities composing the management of maintenance, grouping them into a series of management blocks, each of which has a clear function within the maintenance management process.

Inside each of the management blocks, different tools — models, techniques and methods of maintenance engineering — are included. Every chapter of the third part of the book provides a detailed description of each of the tools, offering the reader a brief synthesis of its conceptual and analytical foundations. This is something that is required to understand the implementation of the tools that can be appreciated in many case studies provided throughout the book.

Often we present different tools to deal with the same problem. The idea is to offer flexibility to face problems considering different degrees of imperfect information, or showing different complexity levels in systems and in their operation. Therefore, some of the models will have a very qualitative appearance while others will be seen as extremely quantitative. At the same time, some tools will be very analytical tools while others will be highly empirical.

The author has carried out a selection of tools and has decided a level of penetration inside the features and characteristics of each one. This has been done following a very personal criterion, resulting from his applied research and practical applications within this field in numerous projects and engagements with many organizations during the last 17 years of professional experience. Most case studies illustrate these experiences and offer a real perspective of the use of the tools defining a framework for modern maintenance management.

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Rafael Ruiz-Usano has been for many years the Head of the Research Group “Organización Industrial” at the School of Engineering of the University of Seville. Within this group, several colleagues have found an amicable and friendly working atmosphere where the area of maintenance management and engineering could develop. We all thank Rafael for his support and this book is dedicated to him.

Pedro Moreu de León has been a great help in many of the issues related to maintenance and maintenance management concepts. He is currently Chairman of the Committee for Maintenance Standardization (AEN/CTN 151 “Mantenimento”) of AENOR (Asociación Española de Normalización y Certificación), and Convenor of the European Working Group for Maintenance Management Standardization (CEN WG8/TC 319 “Maintenance”) of CEN (Committee for European Standardization, Brussels).

Carlos Parra (from IngeCon, Venezuela) provided several case studies related to his consulting activities with organizations in different parts of the world. His support was especially valuable with material regarding Criticality Analysis, RCFA, RCM and LCCA. Carlos is a leading international expert in the field of Operational Reliability.

Marcelo Tardelli, from Heineken, provided extremely valuable input regarding the practical implementation of the maintenance concept, the assessment of critical equipment, the planning and improvement of preventive maintenance, and the set-up of TPM programs to optimize the organizational efficiency for maintenance. Marcelo is an extremely experienced and knowledgeable maintenance engineer, responsible for many maintenance improvement projects in his company in Europe.

Benoit Iung and Alexandre Muller from CRAN (Centre de Recherche en Automatique de Nancy, France) co-authored a recent review of e-maintenance, from where the contents of Chapter 18 were extracted. Benoit also led the edition of a special issue about e-maintenance for the journal *Computers in Industry*, which served as the main source for that review.

Colleagues at the School of Engineering, Rafael Ruiz-Usano and Miguel Angel Muñoz, helped with different contents of Chapter 14 related to maintenance activities scheduling.

As well as people contributing different materials to this work, there are also other colleagues who reviewed many of the concepts and case studies in the book. In this sense, I would like to thank Antonio Sola and Luis Plaza from Iberdrola, Lauro Benito and Tomás Ruiz from Ibermansa, Ricardo Conde from GE Plastics and Jatinder Gupta (from the University of Alabama Huntsville).

There were also several interviews that were very valuable in order to understand how the maintenance management concept and system are implemented in different companies and industrial sectors. Thanks to Fernando Diz-Lois from Sevillana-Endesa, Alfonso Pascual from Ertisa and James Ignizio from Intel Corporation, amongst others.

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Finally, a special thank you to the author's wonderful family: Lourdes, Lourdes Jr, Adolfo Jr and Gonzalo, who offered him their love, support and precious time, enabling this work to be accomplished.

To all of them, thanks.

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PART 1. Maintenance Management Definition and Characterization

1

On the Definition of Maintenance Management

1.1 A Definition of Maintenance Management

According to Webster's Dictionary, *management* characterises the process of leading and directing all or part of an organization, often a business one, through the deployment and manipulation of resources (human, financial, material, intellectual or intangible). One can also think of management functionally as the action of measuring a quantity on a regular basis and adjusting an initial plan and the actions taken to reach one's intended goal. This applies even in situations where planning does not take place. Situational management may precede and subsume purposive management.

Maintenance management will therefore characterise the process of leading and directing the maintenance organization. Before describing this process, let us make sure that we understand what a maintenance organization, with the resources belonging to it, is pursuing.

Maintenance is defined [1] 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 (function or a combination of functions of an item which are considered necessary to provide a given service).

This definition clarifies the objective of maintenance and can help us to understand what part of an organization is, somehow, devoted to maintenance. Now we can define maintenance management as follows [1]:

> *"All the activities of the management that determine the maintenance objectives or priorities (defined as targets assigned and accepted by the management and maintenance department), strategies (defined as a management method in order to achieve maintenance objectives), and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods including economical aspects in the organization."*

This definition of maintenance management is closely aligned to other such notions found in modern maintenance literature [2-4]. Further definitions consider maintenance management as the management of all assets owned by a company, based on maximizing the return on investment in the asset [5]. Another approach [6] indicates 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 configured well and working reliably 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).

In this work we will follow the above-mentioned maintenance management definition established in the European standards for maintenance terminology [1], and we will review the main aspects of that definition, *i.e.*:

- The determination of maintenance objectives or priorities;
- The determination of strategies (and responsibilities);
- Their implementation by means such as maintenance planning, maintenance control and supervision, and;
- Improving methods including economical aspects in the organization.

We will show how, in order to manage maintenance effectively and efficiently, we can summarize these four points by clearly understanding the following two:

- The maintenance management process, the course of action and the series of stages or steps to follow and;
- The maintenance management framework — the essential supporting structure and the basic system — needed to manage maintenance.

1.2 Effectiveness and Efficiency of Maintenance Management

The maintenance management process can be divided into two parts: the definition of the strategy, and the strategy implementation.

The first part, definition of the maintenance strategy, requires the definition of the maintenance objectives as an input, which will be derived directly from the business plan. This initial part of the maintenance management process conditions the success of maintenance in an organization, and determines the effectiveness of the subsequent implementation of the maintenance plans, schedules, controls and improvements. However, this very important point is sometimes forgotten. The ability to deal with this problem, reaching an effective maintenance strategy, shows our ability to foresee the correct maintenance requirements over time, our ability to anticipate these requirements in congruence with the production requirements. This will allow us to arrive at a position where we will be able to minimize the maintenance indirect costs [7], those costs associated with production losses, and ultimately, with customer dissatisfaction.

Clearly effectiveness emphasizes how well a department or function meets its goals or company needs, and is often discussed in terms of the quality of the service provided, viewed from the customer's perspective.

In the case of maintenance, effectiveness can represent the overall company satisfaction with the capacity and condition of its assets [5], or the reduction of the overall company cost obtained because production capacity is available when needed [8]. Effectiveness concentrates then on the correctness of the process and whether the process produces the required result.

The second part of the process, the implementation of the selected strategy has a different significance level. Our ability to deal with the maintenance management implementation problem (for instance, our ability to ensure proper skill levels, proper work preparation, suitable tools and schedule fulfilment), will allow us to minimize the maintenance direct cost (labour and other maintenance required resources). In this part of the process we deal with the efficiency of our management, which should be less important. Efficiency is acting or producing with minimum waste, expense, or unnecessary effort. Efficiency compares the quantity of service provided to the resource expended. It measures how well the task is being performed, not whether the task itself is correct. Efficiency is then understood as providing the same or better maintenance for the same cost.

It is curious, however, that most of the research done within the area of maintenance management is mainly devoted to improving the implementation part of the management process (planning, scheduling, controlling and improving), while it seems that less effort has been spent studying the process of reaching an effective maintenance strategy. That's why frequently we find ourselves doing "the wrong thing right" in our maintenance organizations. In the following section we will pay special attention to this issue.

1.3 Maintenance Objectives, Strategy and Responsibilities

1.3.1 Setting Maintenance Objectives

Business objectives take into consideration what the needs and wants of the customers, shareholders, and other stakeholders are [3]. These general business objectives can be grouped [9] into four groups: profitability, growth, risk and social objectives. Let us review each one of these aspects and see how they relate to maintenance:

- Profitability is, as a general rule, a priority. It is the necessary condition that allows us, in the long run, to reach the other objectives. Maintenance therefore should clearly contribute to the profitability and the competitiveness of the business, or to the effectiveness of the administration and public services;

- Growth can be important at different moments of the product life cycle, for instance, in high-growth markets gaining share is easier and more valuable, it reduces pressure on price, it ensures access to technology, it deters subsequent entrants in the market, *etc.*;
- People, environment and asset safety is another priority in current businesses. Although laws and regulations establish a certain framework for safety, risk may always show up as a consequence of new equipment installation, interdependence of new and existing equipment, *etc.*;
- Many companies claim that they have social objectives to fulfil. They actively want to contribute to the discussion of socially relevant issues by engaging in dialogue with interested sections of society.

Achieving these business objectives requires a business strategy. Said strategy, in conjunction with the current asset environment, helps us to translate business objectives into maintenance objectives. When doing so, it is normal to find typical goals for maintenance management in many organizations [9-10], goals that can be generally classified into three groups:

- Technical objectives. These depend on the business sector operational imperatives. In general, operational imperatives are linked to a satisfactory level of equipment availability and people safety. A generally accepted method to measure the fulfilment of this goal is the Overall Equipment Effectiveness (OEE), as described in TPM method [11];
- Legal objectives/Mandatory regulations. Normally it is a maintenance objective to fulfil all these existing regulations for electrical devices, pressure equipment, vehicles, protection means, *etc.*;
- Financial objectives: to satisfy the technical objective at the minimum cost. From a long term perspective global equipment life cycle cost should be a suitable measure for this.

Achieving each objective will probably have a different level of outcome. It is therefore desirable to evaluate the different maintenance goals, to make sure that those goals are realistic, in accordance with the current asset situation, and then start planning for strategies to achieve those goals.

It is extremely important at this time to see what “other people are doing”, to review sector best practices. This will help us to set up realistic goals, or to test potential strategies.

We cannot forget that maintenance objectives are targets assigned and accepted by the management and maintenance department. The process of assigning targets is critical, typically recursive, and often a time consuming process.

1.3.2 Formulating Strategy

The strategy setting process may follow standard organizational planning methods, which normally include (see Figure 1.1):

- Deriving from corporate goals the policies and objectives for maintenance. These objectives may include: equipment availability, reliability, safety, risk, maintenance budget, *etc*., and should be communicated to all personnel involved in maintenance, including external parties;
- Determination of current factory/facilities performance;
- Determination of the target performance measures (Key Performance Indicators —KPIs). Improvements will be made based on accepted business, user and maintenance management performance indicators;
- Establishing principles to guide strategy implementation by means of planning, execution, assessment, analysis and improvement of maintenance.

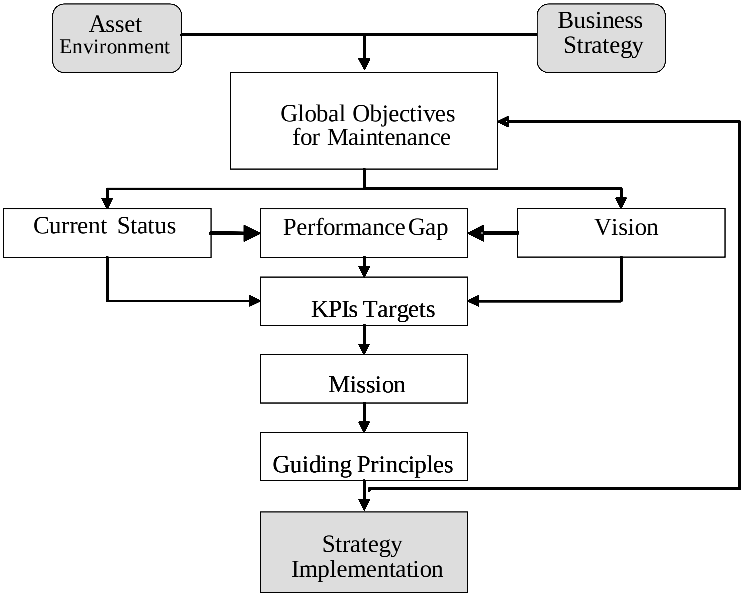

Figure 1.1. Maintenance Strategy Model

1.3.3 Establishing Responsibilities

The adopted maintenance strategy will lead to the determination of different maintenance management responsibilities at different activity levels. These responsibilities will be held by different participants that will play different management roles in each specific scenario. As the participant we normally find: the equipment manufacturer, the equipment vendor, the buyer of the equipment (who normally uses it and becomes "the user" of the equipment) and third/external parties providing any type of maintenance service. Typical scenario examples are as follows:

- A first example is the scenario in which the equipment manufacturer is required to provide complete maintenance and maintenance support services as an integrated component of the delivery of the product. These services are either provided on a contractual basis or accessed as needed by the user. In these cases, once this outsourcing strategy is in place and the contract with the equipment manufacturer (or representative) is signed, the primary responsibility remains with the manufacturer (or a vendor or other outsourced support organization contacted by the manufacturer). The user of the equipment primarily depends upon this network to be supplied with total support services during the operation and maintenance phase of the equipment. The maintenance management is mainly held by the maintenance provider (the manufacturer or contacted organization under his responsibility) and the maintenance management system at user level is reduced to what is more or less an administrative chain to connect its organization with the provider;
- A second example is probably the most common scenario. In this case the equipment manufacturer or their vendors provide only basic or standardized maintenance support planning, such as recommendations for maintenance, the maintenance handbook, spare part lists, and other general documentation (see Standard EN 13460 regarding maintenance documentation). Users then provide the required maintenance and maintenance support for their specific case often using internal resources. This occurs especially when existing equipment is combined into complex systems by another vendor or organization and is then supplied to an end user. The responsibility for developing maintenance, for maintenance support and thus for maintenance management needs to be established between the vendor and user, and in the majority of cases, the user takes the main role and work load;
- As a final and common example, the maintenance service to be provided is completely, or partially, outsourced to another company (independent from the equipment manufacturer). In this case, the maintenance management is shared between the maintenance service provider and the user, but the user normally reduces its activity to performance control and the setting of maintenance goals.

Obviously, in any case or possible scenario, functions and responsibilities within the maintenance organization should be identified, assigned and communicated to equipment users, relevant parts of the organization and external participants.

Prior to this assignment of responsibilities, the personnel qualification requirements (or third party qualification requirements) of each identified function should be studied and determined. Maintenance management should ensure that the maintenance is aware of these requirements and that all responsibilities for processes and activities are included in the job description for each position and/or in the corresponding third party contracts.

The objective will always be to ensure that the functions will be performed properly, efficiently, in a safe way and taking into account relevant environmental aspects.

1.4 Strategy Implementation at the Three Levels of Activity: Strategic, Tactical and Operational

Maintenance management must align actions at three levels of business activities —strategic, tactical, and operational.

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 measured items such as the incidence of the plant equipment breakdowns as these would impact the plant's operational targets (for instance, by using criticality analysis). Maintenance management 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 example, 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 fulfil the maintenance plan. As a result, a detailed program would materialize with all the tasks specified and the resources assigned. Moreover, during the process of detailed maintenance requirements planning and scheduling, this level of activity must develop a level of competence 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 failure 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 rely heavily on the maintenance information systems that provide information about all the work done on each piece of equipment.

Finally, by capturing collective management experience at the three levels, and adapting best practices from within and outside the maintenance organization, we will be able to arrive at a maintenance management system that is continuously improved, and that automatically adapts to new and changing organization targets.

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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]).

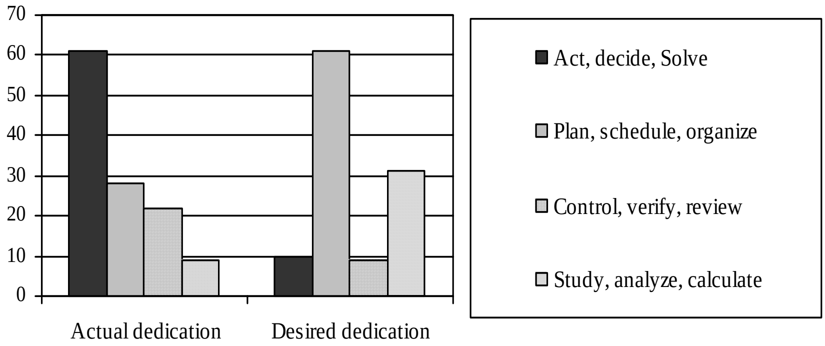

Figure 2.1. What maintenance managers do *vs* what they think they should do

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.

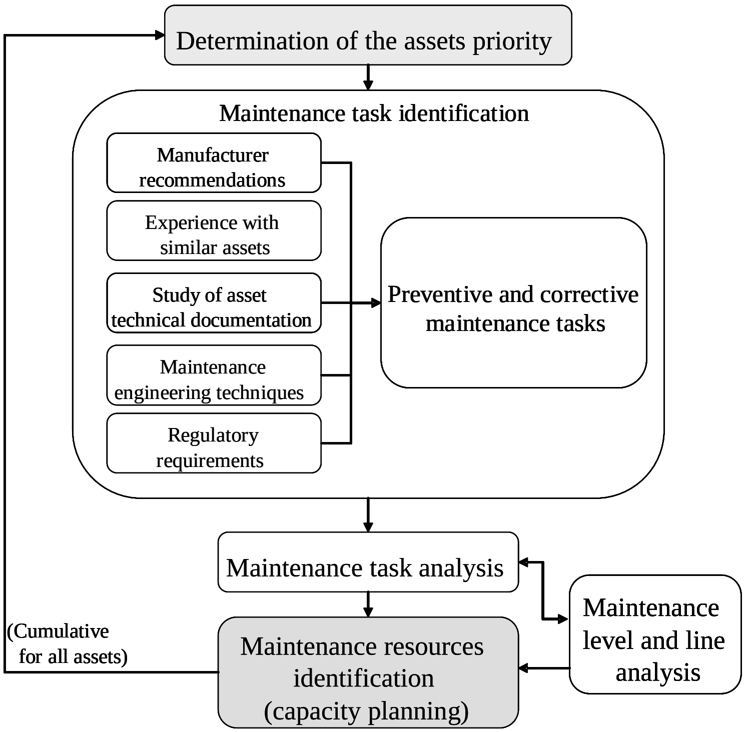

Figure 2.2. Maintenance task and capacity planning model

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.

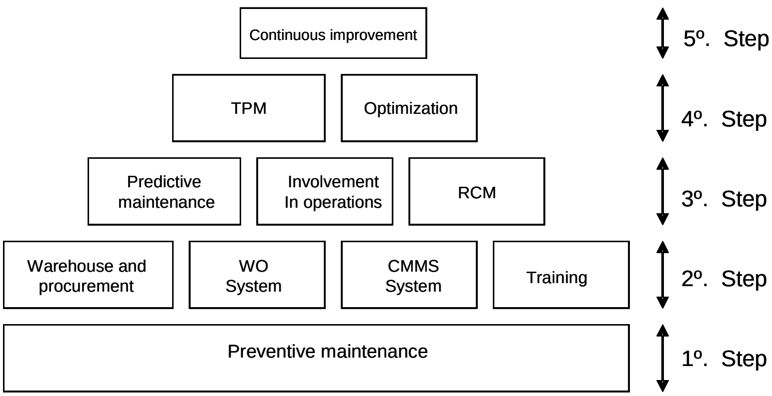

Figure 2.3. Maintenance framework according to Wireman [17]

[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.

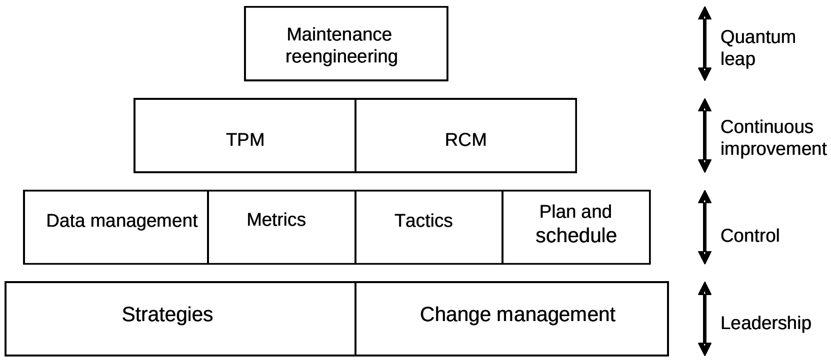

Figure 2.4. Maintenance Framework according to Campbell [18]

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.

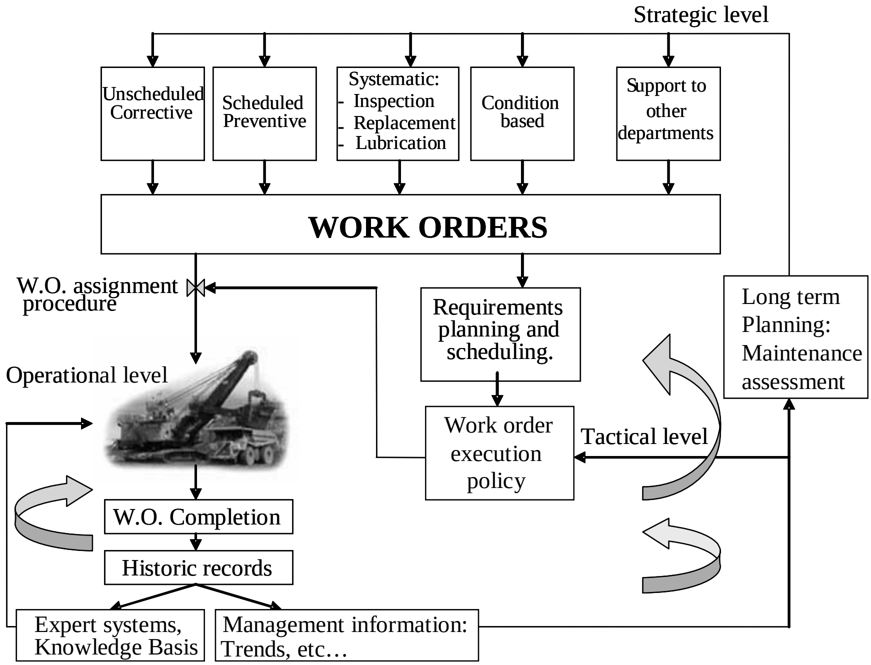

Figure 2.5. Maintenance process, course of action and feedback operating at the three levels of business activities (from Crespo Márquez *et al.* [60])

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

<table>
<tr><td rowspan="8">Functions of the ME methods pillar</td><td rowspan="4">Design of the maintenance plan and its process of continuous improvement</td><td>• Failure analysis, reliability analysis and risk analysis of the system’s operation</td></tr>
<tr><td>• Design of the maintenance plan</td></tr>
<tr><td>• Ensure the total employees involvement in maintenance, to pursue continuous improvement</td></tr>
<tr><td>• Management of maintenance resources</td></tr>
<tr><td rowspan="3">Optimization of the maintenance policy</td><td>• Analysis and preparation of reliability and availability data of the system</td></tr>
<tr><td>• Analysis and preparation of maintenance financial data of the system</td></tr>
<tr><td>• Modelling systems for their maintenance policy optimization</td></tr>
<tr><td colspan="2">Measurement and control of maintenance engineering activities</td></tr>
</table>

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

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

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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PART 2. Basic Concepts for Complex Systems Maintenance

3

The Failure Concept

3.1 Failure Event and Related Terms

Failure[8] is the termination of the ability of equipment to perform a required function (function or combination of functions which are considered necessary for the equipment to provide a given service). After a failure the equipment has a *fault* which may be complete or partial. Notice that failure is an event, while fault is a state. Failures can occur for different reasons. A *cause of failure* can be one, or a combination, of the following: design failure, manufacturing failure, installation failure, mishandling failure and/or maintenance related failure. In addition to the cause, every failure has a *mechanism*, *i.e.* a physical, chemical or other type of process which leads to the failure occurrence. Note that while the cause of failure shows "why" the equipment fails, the failure mechanism shows "how" the equipment fails to perform the required function. For instance, a hydraulic cylinder may be stuck in one position. The cylinder has failed to stroke or provide linear motion. The mechanism of failure — "how" the equipment fails — is the loss of lubricant properties that keep the sliding surfaces separated, but there are countless possibilities for "why" it fails. The reason for failure could be a problem with the fluid due to contamination, a wrong selection, dirt, *etc*.

A failure in a certain element can be:

- *A primary failure.* When it is not caused either directly or indirectly by a failure or a fault of another element;
- *A secondary failure.* When it is caused either directly or indirectly by a failure or a fault of another element.

[8] Terms and definitions used in this chapter take into consideration the international standards regarding maintenance, dependability and quality of service published by the European Committee for Standardization (CEN) [1] and the International Electrotechnical Commission (IEC) [2].

Moreover, the probability of occurrence of a failure may increase with:

- *The passage of time.* When this happens, independently of the operating time of the equipment, we refer to the failure as an *aging failure*, where aging is understood as a physical phenomenon which involves a modification of the physical and/or chemical characteristics of the material;
- *The equipment operating time, or the number of operations or its applied stresses.* In these cases we refer the failure as *wear-out failure*, where wear-out is understood as a physical phenomenon which results in a loss or deformation of material.

The above-mentioned causes, passage of time and the equipment use, as well as other external causes (for instance, environmental causes) may lead the equipment to suffer an irreversible process that is called *degradation*. Degradation may lead to failure and by monitoring the degradation process we may anticipate some failure of equipment. However, there are failures that cannot be anticipated by prior examination or monitoring; these failures are known as *sudden* failures.

3.2 Fault State and Related Terms

As we have mentioned above, failure is the transition from a state of equipment characterised by the fact that it can perform a required function (assuming that external resources are provided if required) — *up state* — to another state characterised by equipment inability to perform that function — *fault*. In some cases the fault can be *partial* when the equipment can perform some, but not all, the required functions. But let us review the possible states of the equipment:

- *Down state.* State characterised by:
    - A *fault*;
    - The inability to perform a required function during *preventive maintenance*.
- *Up state.* State of the element characterised by the fact that it can perform a required function, assuming that the external resources, if required, are provided. As subsets of the *up state* we find:
    - *Operating state.* State when an item is performing its required function;
    - *Standby state*. Non-operating up state during the required time of the equipment;
    - *Idle state.* Non-operating state, during non-required time;
    - *External disable state*. The element is in an up state, but lacks required external resources, or there are some planned actions other than maintenance.

Note that the fault state excludes the cases of equipment inability to perform the required functions due to preventive maintenance activities or other planned actions, or due to lack of external resources. In some cases it may be possible to use equipment which has a partial fault with reduced performance. A fault can also be *latent*, existing but not yet detected.

Table 3.1. Equipment states

<table>
<tr><td colspan="4">Up state</td><td colspan="2">Down state</td></tr>
<tr><td colspan="3"></td><td colspan="3">Disabled state</td></tr>
<tr><td rowspan="2">Idle</td><td rowspan="2">Operation</td><td rowspan="2">Standby</td><td rowspan="2">External disabled</td><td colspan="2">Internal disabled state</td></tr>
<tr><td>Subject to preventive maintenance</td><td>Fault</td></tr>
</table>

In Table 3.1 we have added the *disabled state*, which is the state of the equipment characterised by its inability to perform a required function, for any reason.

Once we have defined the possible states of the equipment, it is easier to identify the times when the equipment is in every state, as follows:

- *Down time.* The interval during which the equipment is in a down state;
- *Up time.* The interval during which the equipment is in an up state. As subsets of the *up time* we find:
    - *Operating time.* Time interval during which the equipment performs its required function;
    - *Standby time*. Time interval during which the equipment is in a standby state;
    - *Idle time.* Time interval during which the equipment is in an idle state;
    - *External disable time*. Time interval during which the equipment is in an external disabled state.

3.3 The Maintenance Time

It is important to note that maintenance may be carried out when the equipment is performing the required function (this will be defined as *on-line maintenance*), and therefore the *maintenance time,* or the time interval during which maintenance is carried out on the equipment (either manually or automatically and including technical and logistic delays) can be higher than the down time. The *maintenance time* can be divided into preventive and corrective maintenance time as follows:

- *Preventive maintenance time*. Time during which preventive maintenance is carried out on the equipment, including technical and logistic delays inherent in preventive maintenance;
- *Corrective maintenance time*. Time during which corrective maintenance is carried out on the equipment, including technical and logistic delays inherent in corrective maintenance.

The *maintenance time* can also be divided into active time and logistic delay as follows:

- *Active time*. Period of the maintenance time during which active maintenance is is carried out on the equipment either manually or automatically, excluding logistic delays. Corrective active time is normally called *repair time*;
- *Logistic delay*. Accumulated time during which maintenance cannot be carried out due to the need to acquire maintenance resources, excluding any administrative delay. Logistic delays can be due to traveling to unattended installations, pending arrival of spare parts, specialist, test equipment or information and unsuitable environmental conditions.

Table 3.2. Equipment times

<table>
<tr><td colspan="3">Up time</td><td colspan="5">Down time</td><td>Up time</td></tr>
<tr><td colspan="3"></td><td colspan="6">Disabled time</td></tr>
<tr><td></td><td colspan="5">Maintenance time</td><td>Undetected fault time</td><td>Admin. delay</td><td>External disabled time</td></tr>
<tr><td></td><td colspan="3">Preventive maintenance time</td><td colspan="2">Corrective maintenance time</td><td colspan="3"></td></tr>
<tr><td colspan="2"></td><td colspan="3">Active maintenance time</td><td></td><td colspan="3"></td></tr>
<tr><td></td><td>Preventive logistic delay</td><td colspan="2">Active preventive time</td><td>Active corrective time</td><td>Corrective logistic delay</td><td colspan="3"></td></tr>
</table>

In order to carry out the maintenance to the equipment, adminsitrative delays may also appear. These delays are accumulated time during which maintenance cannot be carried out due to the need to solve administrative processes. Administrative delays can be due to the need for access authorization to the areas where the maintenance is carried out, or due to the need to solve any legal or official paperwork before starting the work. Note that we do not consider these administrative delays as maintenance time. For a similar reason, *undetected fault time*, *i.e.* the time interval between failure and recognition of the resulting fault, is a down time of the equipment not included within the maintenance time. See Table 3.2 for a complete definition of the equipment times.

If we now pay specific attention to the active corrective maintenance time, this time can be divided into four components as follows (see Table 3.3):

Table 3.3. Equipment active corrective times

<table>
<tr><td colspan="4">Active corrective maintenance time</td></tr>
<tr><td>Technical delay</td><td>Fault localization time</td><td>Fault correction time</td><td>Check-out time</td></tr>
<tr><td></td><td colspan="3">Repair Time</td></tr>
</table>

- *Technical delay*. The accumulated time necessary to perform auxiliary technical actions associated with the maintenance action itself.
- *Fault localization time.* The part of the active corrective mantenance time during which fault localization is performed.
- *Fault correction time.* The part of the active corrective mantenance time during which fault correction is performed.
- *Check-out time*. The part of the active corrective mantenance time during which function check-out is performed.

3.4 References

[1] EN 13306:2001, (2001) Maintenance Terminology. European Standard. CEN (European Committee for Standardization), Brussels.
[2] IEC 60050-191-am2, (2002) Amendment 2 - International Electrotechnical Vocabulary. Chapter 191: Dependability and quality of service. Edition 1.0, Geneva.

4

Failure Models

4.1 The Importance of Failure Data

Like failures, many physical events and measures of practical interest are known by the general term of *stochastic processes*. Such processes refer to events that cannot be predicted *a priori* in a concise form, but for which it is possible to determine their probability to take place at a certain moment. We cannot predict when the failures will happen, but we can determine, on the basis of our best information, the times to carry out preventive maintenance, or the most suitable maintenance strategy in the long term.

Reliability data existing in industrial plants becomes, therefore, a fundamental asset for their maintenance management. Nevertheless, it is common to observe situations where:

- No importance is given to this data;
- Suitable tools to gather data are not in place;
- Data is not filtered adequately;
- Data is neither processed nor used for maintenance improvement.

A reliability study will require:

- The correct register of the equipment operating time (or the unit of use chosen for the maintenance control);
- The correct register of the time when failures take place, and;
- A proper screening of the failures causes.

A maintainability study will require the recording of:

- The necessary time to repair the different failures, and;
- The reasons why these time delays occur.

4.2 Basic Functions to Model Failures

One must take into account four basic functions related to the failures of the equipment:

- The failure probability density function *f(t)*;
- The failure probability distribution function *F(t)*;
- The reliability function *R(t)* and;
- The failure rate $\lambda(t)$.

Let us see, with the help of an example, the meaning of each one of these functions. In this example we will calculate the histogram of the failures relative frequency.

An earthmoving company is launching a new project with five trucks, all identical models, bought at the same date to start operations. After approximately ten months, a failure analysis of the trucks is carried out. It was found that certain rubber straps, in some power take-off of the diesel system had experienced an important number of failures. After an investigation in the CMMS of the company, the following information corresponding to the same cause of failure of the straps was obtained (in Table 4.1).

Table 4.1. Failure histogram in straps

Period	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5
1	-	Failure	-	Failure	-
2	-	-	Failure	Failure	-
3	-	-	-	-	Failure
4	Failure	Failure	-	Failure	Failure
5	-	-	Failure	-	-
6	-	-	Failure	-	-
7	Failure	-	Failure	-	-
8	-	Failure	-	Failure	Failure
9	-	-	-	.	-
10	Failure	Failure	-	.	-

Table 4.2 is obtained from Table 4.1 by arranging data in a different form. The idea is to group failures in the data base according to the estimated lifetime of the straps (four periods). From Table 4.2, it is easy to build an estimation of the failure distribution fucntion and failure rate of the straps, according to Table 4.3.

Notice how, given that $f(t)=R(t-1)-R(t)$, that $\lambda(t)=f(t)/R(t-1)$, and that $F(t)=1-R(t)$, once we know one of these four functions we can obtain the other three.

Table 4.2. Number of failures during the strap lifetime per truck

Strap lifetime period	Number of failures per truck and period of strap lifetime. Assuming same cause of failure					
	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5	**TOTAL FLEET**
1º	-	1	2	2	1	**6**
2º	-	1	1	1	-	**3**
3º	2	1	1	-	1	**5**
4º	1	1	-	1	1	**4**
						18

Table 4.3. Obtaining the basic functions

Strap lifetime period	*f(t)*	*F(t)*	*R(t)=1–F(t)*	*λ(t)=f(t)/R(t–1)*
1º	6/18 = 1/3	1/3	12/18 = 2/3	1/3
2º	3/18 = 1/6	1/2	9/18 =1/2	1 /4
3º	5/18	7/9	4/18 = 2/9	5/9
4º	4/18= 2/9	1	0	1

From Table 4.3 we can obtain a graphical representation of such functions that is presented in Figure 4.1.

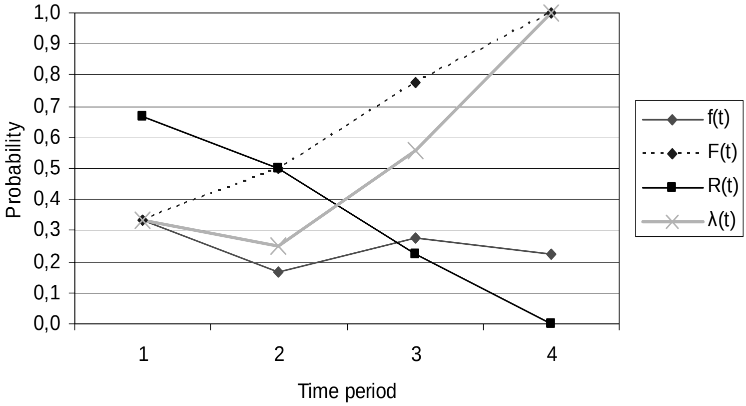


Figure 4.1. Graphical representation of basic functions

Transforming previous estimations of discrete time intervals into probability functions in continuous time, we can define them as follows:

R(t) is the probability to survive until time *t*.

$\lambda(t)dt$ is the failure probability in the interval *t*, *t+dt* assuming that the equipment survives until time t; therefore according to conditioned probability formulations:

$$\lambda(t)dt = f(t)dt/R(t) \tag{4.1}$$

where *f(t)dt* is the probability of failure in the interval *t*, *t+dt*, with *f(t)* as failure probability density function. Therefore

$$\lambda(t) = f(t)/R(t) \tag{4.2}$$

And since

$$\int_0^t f(t)dt = 1 - R(t) \tag{4.3}$$

Taking derivatives in both sides of the equation:

$$f(t) = \frac{-dR(t)}{dt} \tag{4.4}$$

Substituting Equation (4.4) in (4.2) leads to

$$-\lambda(t) = \frac{dR(t)}{dt}\frac{1}{R(t)} \tag{4.5}$$

And then by taking the integral in Equation (4.5):

$$-\int_0^t \lambda(t)dt = \int_1^{R(t)} \frac{dR(t)}{R(t)} \tag{4.6}$$

Note that the integration limits of the failure rate are between 0 and *t*, while 1/*R(t)* is integrated with respect to *R(t)*, and therefore when *t*=0, *R(t)*=1, and in *t* by definition the reliability is *R(t)*. Therefore, if we integrate Equation (4.6) the result is

$$-\int_0^t \lambda(t)dt = \ln R(t)\Big|_1^{R(t)} = \ln R(t) - \ln 1 = \ln R(t) \tag{4.7}$$

Hence

$$R(t) = \exp\left\{-\int_0^t \lambda(t)dt\right\} \tag{4.8}$$

Note how, in case we have a constant failure rate over time, *i.e.* the failure has a totally random behaviour, we have that $R(t)=e^{-\lambda t}$ (see Figure 4.2).

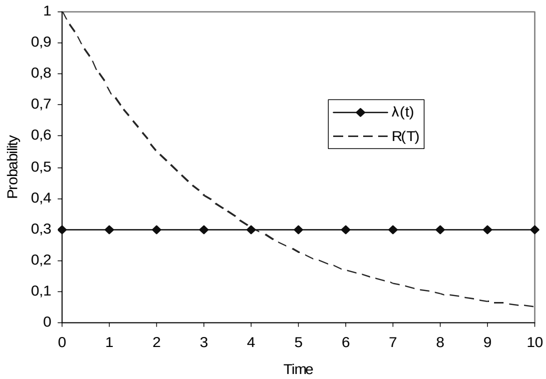


Figure 4.2. Reliability *R(t)* and failure rate *λ(t)*, when *λ(t)* is constant

4.3 Empirical *vs* Theoretical Failure Distribution Functions

Let us now see how to find a theoretical reliability function that is suitable to represent failure behaviour of a real element of our physical system. In general, two approaches exist to solve this problem:

- Estimating the reliability function by obtaining a curve that fits existing data regarding the life cycle of the element (this is normally done when an important number of data are available);
- In a second approach, the reliability function of the element is estimated by means of statistical sampling. The parameters corresponding to theoretical functions of the failure distribution, and the corresponding confidence intervals of that function, are established.

It is common for real data about equipment operating time before the failure suitably to fit some of the following distribution functions: Weibull, exponential, log-normal or normal.

At present, Weibull analysis is the most used method to fit reliability data to a formal representation or mathematical model [1]. This is because the Weibull distribution can represent failures of components fitting the normal, exponential, and many other probability distribution functions, and only by changing the value of its parameters. Therefore we will briefly review this technique in the following section.

4.4 Weibull Distribution Function and Weibull Analysis

Weibull analysis is a great tool for failures modelling and analysis. We can also produce good predictions on future failures, and from very small size samples.

But let us see a brief introduction to Weibull distribution function, explaining the meaning of its parameters.

As we proved above, in Equation (4.8):

$$R(t) = \exp\left\{-\int_0^t \lambda(t)dt\right\}$$

Since the relationship between the failure rate and the time to failure can take many different forms, the analytical solution of Equation (4.8) can turn out to be extremely complicated. In practice, previous relationship can be described by a three parameter distribution function known as the Weibull distribution:

$$R(t) = \exp\left\{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right\} \tag{4.9}$$

This function was developed by the Swedish researcher Waloddi Weibull in a study concerning metal fatigue [2], and is characterised by three parameters: β shape parameter, η scale parameter and γ origin parameter. Weibull's distribution function enjoys great acceptance due to three differential facts:

1. With this unique function three types of failure probability distribution functions can be modelled: the decreasing hazard function (*infant mortality*), the constant hazard function (*random*) or the increasing hazard function (*wearout*);
2. The parameters obtained in the analysis provide significant information regarding the equipment cause of failure;
3. Finally, the adjustment can be done using conventional graphical tools, very attainable in their practical application.

The Weibull function expressed in Equation (4.9) can be reduced to a straight line by taking logarithms twice in that equation, where *1–F(t)=R(t),* as follows:

$$1 - F(t) = \exp\left\{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right\} \tag{4.10}$$

$$\frac{1}{1-F(t)} = \exp\left(\frac{t-\gamma}{\eta}\right)^{\beta} \tag{4.11}$$

And therefore

$$\ln\frac{1}{1-F(t)} = \left(\frac{t-\gamma}{\eta}\right)^{\beta} \tag{4.12}$$

Taking logarithms again:

$$\ln\ln\frac{1}{1-F(t)} = \beta\ln(t-\gamma) - \beta\ln\eta \tag{4.13}$$

If we substitute *t–γ* by *t’* in Equation (4.13) and we also put:

$$y = \ln\ln\frac{1}{1-F(t)} \tag{4.14}$$

$$x = \ln t' \tag{4.15}$$

$$a = \beta \tag{4.16}$$

$$b = -\beta\ln\eta \tag{4.17}$$

Then Equation (4.13) is transformed into the form $y=ax+b$, which is the equation of a straight line with a slope β —Weibull shape parameter— and cutting the x axis (y=0) when

$$\ln\ln\frac{1}{1-F(t)} = 0 \tag{4.18}$$

Then

$$\ln\frac{1}{1-F(t)} = 1 \tag{4.19}$$

Which is equivalent to:

$$\frac{1}{1-F(t)} = e \tag{4.20}$$

Then $F(t)=0.632$ and

$$\beta\ln t' = \beta\ln\eta \tag{4.21}$$

Hence $t' = \eta$.

That means that if we initially assume that $\gamma=0$, then $t=\eta$ — Weibull scale parameter — and therefore this parameter gives us information about the moment in time of the equipment life cycle, before which this element will fail with a probability of *63.2%*. This parameter is, for this reason, known also as the *Weibull characteristic life parameter*.

The hypothesis $\gamma=0$ is sometimes not correct; certain equipment (*e.g*. bearings), even in an infant-mortality state, will continue to operate for some time before failing. In those cases we do require a time shift in the equation, $\gamma>0$ and represents the guaranteed life of the equipment. That is why γ is also known as the *Weibull guaranteed life parameter*.

As a summary:

- The *guaranteed life time* γ, normally shows up in those wearout failure models where failures are produced after a certain time γ. Failure rate is initially zero and increases only after that time.
- The *shape parameter* β characterises the form of the failure pdf, and is a measure of the regularity of the failure occurrence:
  - $\beta<1$: Burn-in or infant-mortality failure;
  - $\beta \cong 1$: Random failure;
  - $\beta>1$: Wearout failure, although for $1<\beta<3$, random component of the failure is still considered high.
- *The characteristic life parameter* η, is the time interval between the *guaranteed life time* γ and the time for which we may expect the equipment to have failed with 63.2% probability.

In Figure 4.3 the Weibull distribution function with different parameters values is presented.

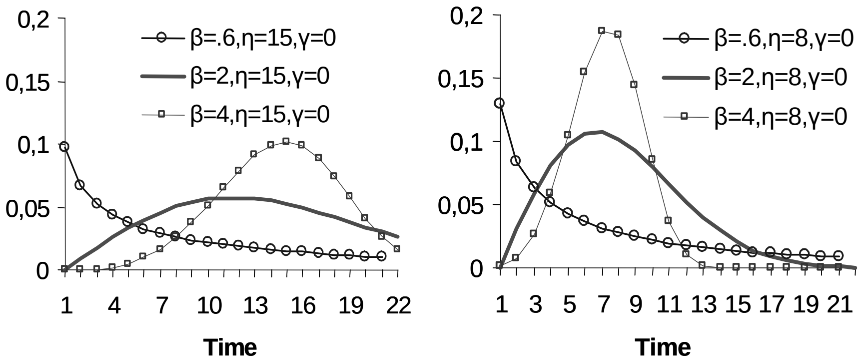


Figure 4.3. Sample Weibull functions with different parameters values

4.5 Weibull Analysis

The process to carry out a Weibull analysis is simple and consists of the following steps:

1. Group the data in increasing order of time to failure;
2. Estimate the failure distribution function *F(t)* using the *Median Rank Method* for each time and considering data censoring;
3. Plot F(t) on Weibull probability paper — double logarithmic paper — *vs* failure time of each group of observations;
4. Fit the points to a straight line, obtaining the value of the Weibull distribution function parameters (at this time assuming bi-parametric distribution, or with parameter $\gamma=0$);
5. Check for a better adjustment to a curve with downwards concavity. If that is possible, use a procedure (that we will study later) to find the value of γ, producing a better adjustment of the data points (this will be the case of tri-parametric Weibull function);
6. Check for goodness-of-fit test;
7. Obtain the confidence intervals.

Let us look at each of these steps in one example (taken from Crespo Márquez *et al.* [3]). Let us again use the example of the strap failure in the trucks that was presented at the beginning of this section. Suppose that we would have more precise data (for times to failures) for the first five strap failures in the trucks. Let us assume that the table for the first three operating periods (months) of the five trucks can be expressed as below (we suppose that every truck works approximately 300 h a month, and that data is recorded until the end of the third month).

Table 4.4. Failure times —in hours— of straps for the first three operating periods (months). In bracket — time to failure of the straps

Operating period	Truck 1	Truck 2	Truck 3	Truck 4	Truck 5
1	-	100	-	250	-
2	-	-	350	450(200)	-
3	-	-	-	-	850

In Table 4.4 we find in brackets the operating hours of the strap when it fails (the time to failure), in case the failure is not the first one to take place in this truck.

The number of operating hours of the straps, at the end of the test, is presented in Table 4.5.

Table 4.5. Operating time of the straps at the end of the test third month

Truck 1	Truck 2	Truck 3	Truck 4	Truck 5
900	800	550	450	50

Let us consider, in a first instance, the information that we have regarding the straps that have failed. There were five straps that failed: two in truck number 4 and one in trucks number 2, 3 and 5. If we group the data in increasing order of time to failure we have Table 4.6.

Table 4.6. Data grouping in increasing order of time to failure (in hours)

Chronological order of the strap failure	Truck where the failure takes place	Operating time of the strap at failure
1	2	100
2	4	200
3	4	250
4	3	350
5	5	850

Once we have finished *step 1* of the Weibull method, we move to *step 2* that is related to the estimation of *F(t)*.

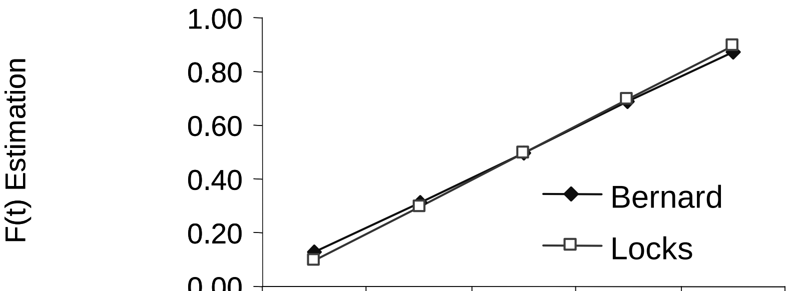
A fast, but not good, estimation of *F(t)* could be taken directly from Table 4.6; we would then say that, for instance, 60% of the straps (3/5) would fail before 250 operating hours. Notice that that would be the equivalent of saying that *F(850)=1*, and we know that this is not true. We just have to check the data in Table 4.4, to observe that there are failures taking place over 900 operating hours of the straps. Definitively, when we handle a small sample of failures, we cannot make such statements we have to rely on other methods to calculate approximations of the function *F(t)*. The *median rank method* is a way of making such approximations. This method fixes *F(t)=0.5* as the median value of the distribution, which is later organized taking into account said consideration [4]. In order to do so, we will calculate the failure probabilities using mathematical estimators such as Bernard's estimator in Equation (4.22) [5]:

$$\hat{F}_i = \frac{i-0.3}{n+0.4} \tag{4.22}$$

or Locks' estimator [6] in Equation (4.23).

$$\hat{F}_i = \frac{i - \frac{1}{2}}{n} \tag{4.23}$$

where i is the failure chronological order, n is the sample size and $\hat{F}_i$ is the corresponding estimation of $F(t)$. By applying above-mentioned estimators we reach Figure 4.4.



	100	200	250	350	850
Bernard	0.13	0.31	0.50	0.69	0.87
Locks	0.10	0.30	0.50	0.70	0.90

Time (hrs)

Figure 4.4. *F(t)* estimation using Bernard and Locks formulation

Step 2 of the Weibull analysis cannot be finished without considering the data censoring problem. What is data censoring? What does it mean for reliability estimations? Let us now try to answer these two questions.

Sometimes, when we finish capturing data, there is no equipment failure recorded. We may know the operating time of the units that are working (Table 4.5), but we may not know when those units will fail. In many other cases, units may be replaced in preventive maintenance when they were in good operating conditions (this does not happen in our example) and, therefore, we do not know either when they would have failed. These are called *right censoring* cases, or cases where the data of the elements is truncated or censored to the right. There are also cases where censoring is said to be *to the left*, for instance those cases in which it is not known what moment the elements began to work. Data censoring should always be considered for suitable estimations of *F(t)* [7]. Otherwise, we might underestimate equipment reliability and, consequently, we may *over maintain* it.

The process that we suggest to consider data censoring in our $\hat{F}_i$ calculation is the so-called Kaplan-Meier estimation process [8] and it is as follows:

a) Order the actual failure times from t_1 through t_r, where there are r failures;
b) Corresponding to each t_i, associate the number n_i, with n_i = the number of operating units just before the the i-th failure occurred at time t_i ;
c) Estimate $R(t_1)$ by $(n_1 - 1)/n_1$;
d) Estimate $R(t_i)$ by $R(t_i - 1) \times (n_i - 1)/n_i$;
e) Estimate $F(t_i)$ by $1 - R(t_i)$.

Note that censored units only count up to the last actual failure time before they were removed. They are included in the n_i counts up to and including that failure time, but not after.

Table 4.7. Operating times including censored units

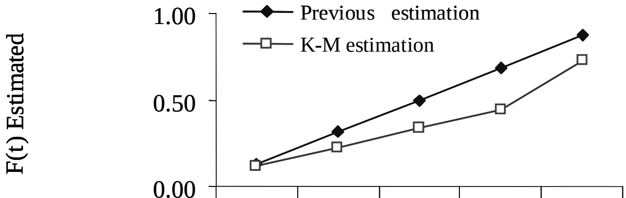
I	Failure (F) Censored (C)	Truck	Strap operating hours	t_r	n_i	$\hat{F}_i = 1-R(t_i)$
1	C	5	50	-	-	
2	F	2	100	$t_1=100$	9	0.111
3	F	4	200	$t_2=200$	8	0.222
4	F	4	250	$t_3=250$	7	0.333
5	F	3	350	$t_4=350$	6	0.444
6	C	4	450	-	-	
7	C	3	550	-	-	
8	C	2	800	-	-	
9	F	5	850	$t_5=850$	2	0.722
10	C	1	900	-	-	

The result of the process can be appreciated in Table 4.7 and in Figure 4.5, where it can be verified how the new estimation of the $F(t)$ offers higher values of strap reliability when considering its total operating hours in the test.

Let us now move to *step 3* and prepare the data to be plotted in a double logarithmic scale. According to Equations (4.13)—(4.17), and once we have obtained our final estimation of F(t) which tales into account the censored data (Figure 4.5), we now prepare now the data for their graphical representation (Table 4.8).

Later we present them so that in the x axis we represent the third column of Table 4.8, and in the y axis the fourth column. In this form, the representation of the points must adjust to a straight line $y=ax+b$, so that this straight line will have an equal slope to the shape parameter β of the Weibull distribution, and its intersection the x axis ($y=0$) will be in $t=\eta$ (scale parameter or characteristic life).

Let us select an XY (dispersion) graph in our spreadsheet, which compares every couple of values of our Table 4.8. Then, we can obtain the representation of the cloud of points shown in Figure 4.6, and also the straight line which has the best fit — selecting linear trend in the software. Note that this is automatically calculated by the spreadsheet selecting that option, which also offers the equation of the line.



	100	200	250	350	850
Previous estimation	0.13	0.31	0.50	0.69	0.87
New K-M estimation	0.11	0.22	0.33	0.44	0.72

Time (h)

Figure 4.5. Previous *vs* new *F(t)* estimation including censored data

Table 4.8. Data preparation (x,y) for the Weibull plot

t	*F(t)*	*x*=ln *t*	*y*=lnln(1/(1–*F(t)*))
100	0.11	4.61	–2.14
200	0.22	5.30	–1.38
250	0.33	5.52	–0.90
350	0.44	5.86	–0.53
850	0.72	6.75	0.25

Then we obtain the two-parameter Weibull function, completing *step 4* of the analysis, representing the failures of our element. That function is characterised by the following parameters:

$\beta = 1.13$

$\eta = e^{(7.28/1.13)} = 627.96$

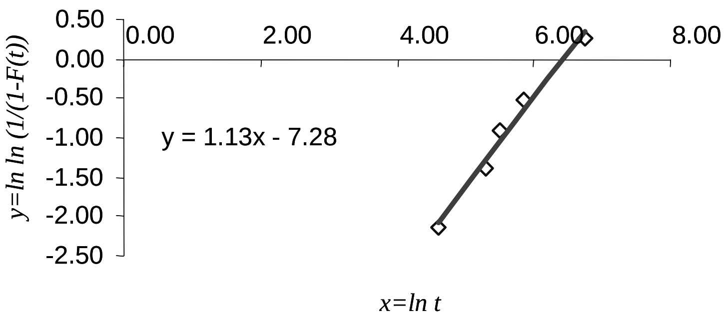


Figure 4.6. Straight line fitting points in Table 4.8

A simple sight of the points of the graph if Figure 4.6 offers the impression that a concave downwards curve could be a better fit option, such it appears in Figure 4.7.

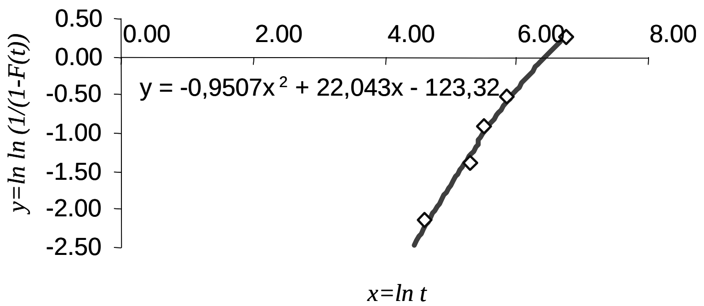


Figure 4.7. Curve (quadratic) line fitting points in Table 4.8

Concavity of the curve in Figure 4.7 indicates the possibility of achieving a better adjustment of the Weibull function parameters by introducing the origin parameter, or guaranteed life parameter γ, with positive value. To determine the value of γ, we can help ourselves by referring to the spreadsheet, checking the sensitivity of the curve to variations of the x axis coordinates, and by doing so changing the value of γ, as we saw in Equation (4.13).

To begin this exercise, let us initially suppose that the guaranteed life equals the time that it takes the first failure to show up (100 h in our example). If we do this coordinates variation (*t'=t–100*), we would create the graph in Figure 4.8. Clearly the concavity of the curve has changed and is now upwards. This indicates that the period of guaranteed life must be shorter than our initial supposition. Obviously, the period of guaranteed life must mean that the resultant representation of referred the curve tends again to a straight line.

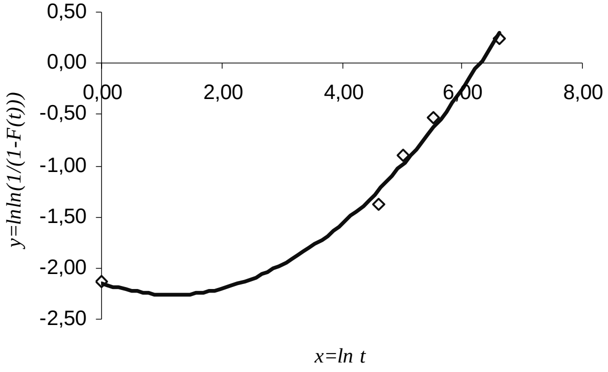


Figure 4.8. Points fit for coordinates change with $t' = t - 100$

To find the solution to the problem of our example, we have changed the value of the parameter obtaining a good result for γ =75. Then the data that we will use for the graphical representation is the one presented in Table 4.9.

Table 4.9. Data for the graphical representation with γ=75

t–γ	F(t)	x=Ln (t–γ)	y=LnLn(1/(1–F(t)))
25	0.11	3.22	–2.14
125	0.22	4.83	–1.38
175	0.33	5.16	–0.90
275	0.44	5.62	–0.53
775	0.72	6.65	0.25

With the data in Table 4.9 we can represent the curve obtaining a good adjustment to a straight line (Figure 4.9).

Once we come to the straight line, and obtain its equation (also automatically in our spreadsheet), we can easily calculate the three parameters of the Weibull function, completing *step 5* of the analysis, that in our example take the following values:

β = 0.70

$\eta = e^{(4.53/0.70)} = 621.93$

γ = 75

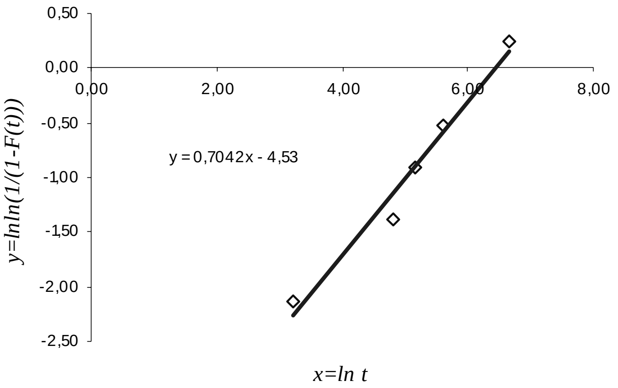


Figure 4.9. Points fit for coordinates change with $t'=t-75$

Step 6 of the Weibull analysis has to do with the assessment of the goodness of fit. In order to do so we can follow the Kolmogorov-Smirnov test, consisting of the following steps:

a) Select the distribution to assess;
b) Determine the significance level of the test (α usually at 1, 5, 10 or 20%), which is the probability of rejecting the hypothesis that the data follows the chosen distribution assuming the hypothesis is true;
c) Determine $F(t_i)$ using the parameters assumed in step a);
d) From the failure data compute the $\hat{F}(t_i)$ using the median ranks or the Kaplan-Meier estimate if applicable;
e) Determine d, where

$$d = Max_i \left\{ \left| F(t_i) - \hat{F}(t_i) \right|, \left| F(t_i) - \hat{F}(t_{i-1}) \right| \right\};$$

f) If $d>d_\alpha$, where d_α is obtained from the K-S statistic table, we reject the hypotheis that data can be adjusted to the distribution selected in step a).

Table 4.10. Data for the Kolmogorov-Smirnov test of the Weibull (0.7, 621.93, 75)

t_i	$F(t_i)$	$\hat{F}(t_i)$	$F(t_i)-\hat{F}(t_i)$	$F(t_i)-\hat{F}(t_{i-1})$	d_i
25	0.020	0.111	–0.090		
125	0.134	0.222	–0.087	0.023	0.087
175	0.194	0.333	–0.138	–0.027	0.138
275	0.310	0.444	–0.133	–0.022	0.133
775	0.723	0.722	0.001	0.279	0.279

We have applied the Kolmogorov–Smirnov test to values in Table 4.9, obtaining Table 4.10, where $d=0.279<d_{\alpha}=0.5$, and therefore we cannot reject the hypothesis that the selected distribution fits our data.

After the goodness of fit test we have a better idea about the validity of our failure data model, However, it is still convenient to move to *Step 7* before we take any action based on our statistical analysis. *Step 7* will help us to measure the risk of these actions,

In step 2 we proposed using the *median rank method* to make approximations of the function *F(t).* This means that for 50% of the time the true probability of failure lies above or below this approximation. In the same way (see Table 4.11), we can use the 5% and 95% rank tables (in Tables 4.12 and 4.13) to measure the confidence in our model [5]. If we use the 95% rank table to estimate *F(t),* for 95% of the time the probability of failure will be below this value. Similarly, if we use the 5% rank table to estimate *F(t),* for 95% of the time the probability of failure will be above this value.

Table 4.11. Data for the confidence levels graphical representation

t–γ	*95% Rank*	*K-M Est.*	*5% Rank*	*ln t*	*Lnln(1/(1–F (t)))*		
					95% Rank	*K-M Est.*	*5% Rank*
25	0.45	0.111	0.01	3.21	–0.51	–2.14	–4.58
125	0.65	0.222	0.07	4.82	0.07	–1.38	–2.53
175	0.81	0.333	0.19	5.16	0.51	–0.90	–1.56
275	0.92	0.444	0.34	5.61	0.94	–0.53	–0.87
775	0.99	0.722	0.55	6.65	1.52	0.25	–0.23

According to previous considerations, and checking the values in Table 4.11, we can conclude that, for instance, for ***t–γ***=775 h, *F(t)* will have a value between 0.55 and 0.772 with a confidence of 90%. This is equivalent to say that the reliability of the component for that time is between 0.228 and 0.54 for 90% of the time. Figure 4.10 contains the graphical logarithmic representation of data in Table 4.11.

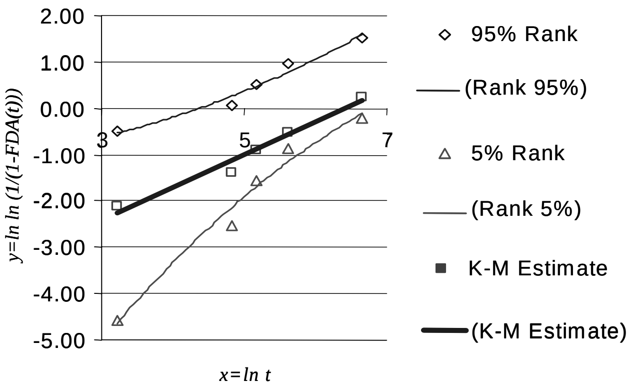


Figure 4.10. Graphical representation of the confidence intervals

Table 4.12. 5% Ranks

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	5.00	2.53	1.70	1.27	1.02	0.85	0.71	0.64	0.57	0.51	0.47	0.43
2		22.36	13.54	9.76	7.64	6.28	5.34	4.62	4.10	3.68	3.33	3.05
3			36.84	24.86	18.92	15.31	12.88	11.11	9.78	8.73	7.88	7.19
4				47.24	34.26	27.13	22.53	19.29	16.88	15.00	13.51	12.29
5					54.93	41.82	34.13	28.92	25.14	22.24	19.96	18.10
6						60.70	47.91	40.03	34.49	30.35	27.12	24.53
7							65.18	52.90	45.04	39.34	34.98	31.52
8								68.77	57.09	49.31	43.56	39.09
9									71.69	60.58	52.99	47.27
10										74.11	63.56	56.19
11											76.16	66.13
12												77.91

Table 4.13. 95% Ranks

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	95.00	77.64	63.16	52.71	45.07	39.30	34.82	31.23	28.31	25.89	23.84	22.09
2		97.47	86.46	75.14	65.74	58.18	52.07	47.07	42.91	39.42	36.44	33.87
3			98.31	90.24	81.08	72.87	65.87	59.97	54.96	50.69	47.01	43.81
4				98.73	92.36	84.68	77.47	71.08	65.51	60.66	56.44	52.63
5					98.98	93.72	87.12	80.71	74.86	69.65	95.02	60.90
6						99.15	94.66	88.89	83.13	77.76	72.88	68.48
7							99.27	95.36	90.23	85.00	80.04	75.47
8								99.36	95.90	91.27	86.49	81.90
9									99.43	96.32	92.12	87.22
10										99.46	96.67	92.81
11											99.54	96.95
12												99.57

4.6 References

[1] Abernethy RB, (1996) The New Weibull Handbook. 2^{nd}. Edition. Gulf Publishing.
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5

The Maintenance Concept

5.1 Maintenance Types

5.1.1 Maintenance Type Classification

According to the maintenance definition that we offered in the first chapter, maintenance is a combination of actions intended to retain an item in, or restore it to, a state in which it can perform the function that is required for the item to provide a given service. This concept leads to a first classification of the maintenance actions in two main groups or types[9]: actions oriented towards retaining certain operating conditions of an item and actions dedicated to restoring the item to said conditions.

"Retention" and "restoration" are denominations for action types that are then converted into "preventive" and "corrective" maintenance types in the maintenance vocabulary. Following this criterion, the European standard for maintenance terminology [1] presents the different types of maintenance classified according to Figure 5.1.

In this chapter we will first define the different maintenance types. By doing so, we define a very important adjective or attribute of the maintenance action; however, the maintenance type is not the maintenance action definition. The definition of the most common maintenance actions or activities is then offered in Section 5.2. Sections 5.3 and 5.4 help us to understand the relationship between maintenance actions and equipment complexity. From the point of view of the maintenance actions, the more complex the item, the more need for the technical subdivision of the item. Complex items maintenance will therefore require the item subdivision into so-called indenture levels. It is common to find that maintenance

[9] Terms and definitions used in this chapter take into consideration the international standards regarding maintenance, dependability and quality of service published by the European Committee for Standardization (CEN) [1] and the International Electrotechnical Commission (IEC) [2].

needs — resources, qualification of resources, and so on — for each indenture level vary importantly. This leads us to the definition of maintenance levels, which are associated to indenture levels of the items. Notice that this association normally involves resource assignments and therefore resources needs to be properly organized and managed at different positions in our organization. These positions are called, as we will see in Section 5.5, maintenance lines, and they will be responsible for the accomplishments of different maintenance levels of different items.

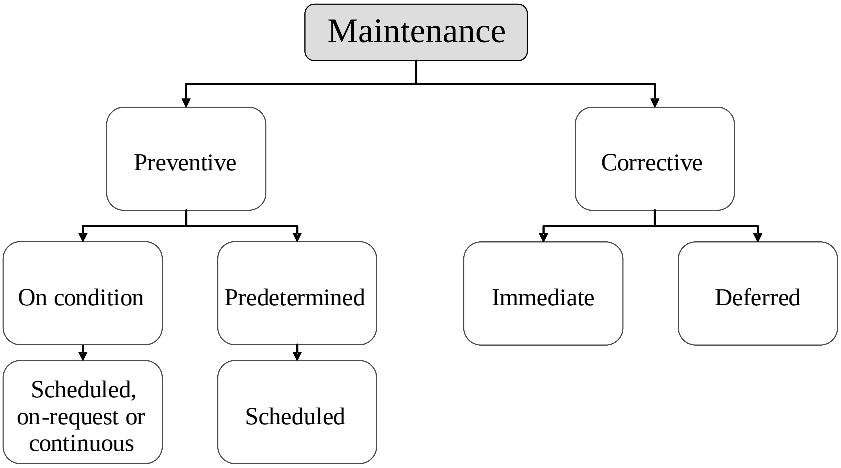

Figure 5.1. Maintenance tpes according to EN 13306:2001 [1]

Previous paragraphs help us to understand the existing complexity for the definition of the so-called maintenance policy of an organization, as explained with an example in Section 5.6.

5.1.2 Preventive Maintenance

Preventive maintenance is defined as maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of the equipment. Preventive maintenance can be predetermined or condition based:

- *Predetermined maintenance*. Preventive maintenance carried out in accordance with established intervals of time or number of units of use (*i.e. scheduled maintenance*) but without previous item condition investigation;
- *Condition based maintenance*. Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. Performance and parameter monitoring may be *scheduled*, *on-request* or *continuous*. Within the condition based maintenance we include the predictive maintenance, that can be defined as follows:

- *Predictive maintenance*. Condition based maintenance carried out following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the equipment.

5.1.3 Corrective Maintenance

Corrective maintenance is maintenance carried out after fault recognition and intended to put the equipment into a state in which it can perform a required function. Corrective maintenance can be immediate or deferred:

- *Immediate maintenance.* Maintenance which is carried out without delay after a fault has been detected to avoid unacceptable consequences;
- *Deferred maintenance.* Corrective maintenance which is not immediately carried out after a fault detection but is delayed according to given maintenance rules.

5.2 Maintenance Activities

Maintenance types consist of a set of maintenance activities in a given sequence. Most common maintenance activities can be listed and defined as follows:

- *Inspection*. Check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item. Generally, inspection can be carried out before, during or after other maintenance activity:
    - *Compliance test*. Test used to show whether or not a characteristic or a property of the equipment complies with the stated specification;
- *Monitoring*. Activity performed either manually or automatically intended to observe the actual state of the equipment. Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameters of the equipment with time. Monitoring may be continuous, over an interval of time, or after a given number of operations. Monitoring is usually carried out in the operating state;
- *Routine maintenance*. Regular or repeated elementary maintenance activities which usually do not require special qualification, authorization(s) or tools. Routine maintenance may include, for example, cleaning, tightening of connections, checking liquid level, lubrication, *etc.*;
- *Overhaul*. A comprehensive set of examinations and actions carried out in order to maintain the required level of availability and safety of the equipment. An overhaul may be performed at prescribed intervals of time or number of operations, and may require a partial or complete dismantling of the item;
- *Rebuilding*. Action following the dismantling of the equipment and the repair or replacement of those components that are approaching the end of their useful life and/or should be regularly replaced. The objective of

rebuilding is normally to provide the equipment with a useful life that may be greater than the lifespan of the original equipment. Rebuilding differs from overhaul in that the actions may include improvements and/or modifications, understood as follows:

- *Improvement*. Combination of all technical, administrative and managerial actions intended to ameliorate the dependability of the equipment, without changing its required function;
- *Modification*. Combination of all technical, administrative and managerial actions intended to change the required function of the equipment. Modification, in fact, is not a maintenance action but concerns changing the required function of the equipment to a new required function. The changes may have an influence on the dependability or on the performance of the equipment, or both;

- *Repair*. Physical action taken to restore the required function of faulty equipment. Within a repair we can normally find the following actions:
  - *Fault diagnosis*. Actions taken for fault recognition, fault localization at the appropriate indenture level and cause identification;
  - *Fault correction.* Actions taken after fault diagnosis, to put the equipment into a state in which it can perform a required function;
  - *Function check-out.* Action taken after maintenance actions to verify that the equipment is able to perform the required function. Function check is usually carried out after down state.

5.3 The Indenture Level

Many of the modern industrial systems are complicated in their structure which consists of many interconnected elements. The cause and effect relationships between these elements will normally be difficult to capture because of their extent, their time delay, or simply because of their rare impact in system behaviour patterns. Also, the history of these systems will be important for their behaviour analysis. If we try to carry out complex systems maintenance we have to take into account the considerations above before starting the implementation of our maintenance strategy. When trying to understand causes of equipment functional failure, we need to describe the different parts of the equipment structure, the different subfunctions and the possible causes of the function loss. Maintenance is always trying to eliminate these causes of functional failures that will be located at different levels of the equipment structure. The level of subdivision of an item from the point of view of the maintenance action is called the indenture level. Examples of indenture level could be a system, a subsystem, a component (Figure 5.2). There are several factors that may influence the equipment indenture level:

- The complexity of the equipment construction;
- The accessibility to the different subsystems;

- The required skill level of the maintenance personnel;
- The requirements for test equipment facilities;
- The need for specific safety considerations;
- *Etc.*

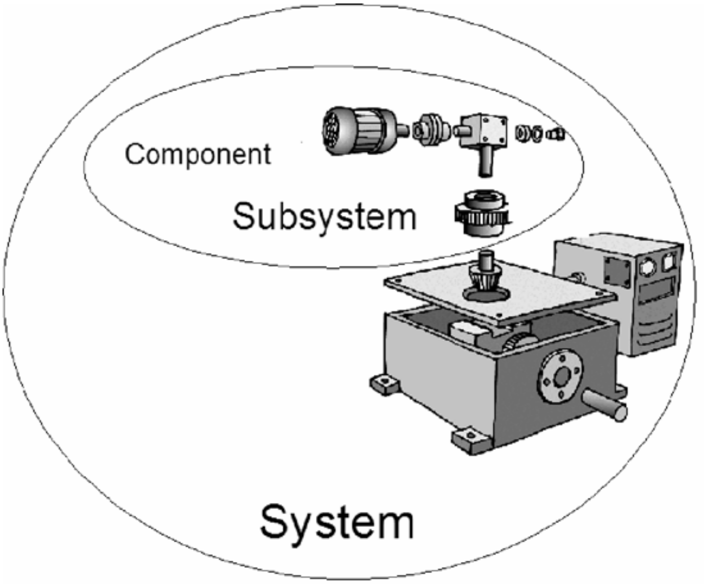

Figure 5.2. Equipment indenture level

5.4 The Maintenance Level

European standard defines a level of maintenance as the set of maintenance actions to be carried out at a specific indenture level. With this is mind, examples of maintenance actions at different indenture level would be replacing a system, a subsystem or a component.

However, in many real plants and factories, the levels of maintenance are not necessarily related to the indenture levels (item subdivisions) and this may, sometimes, induce confusion. The level of maintenance is commonly characterised by the complexity of the maintenance task. Therefore, different maintenance levels are not necessarily related to actions at different indenture levels but to actions of different technical complexity.

To illustrate this point, let us see the following example, where the maintenance levels of a real assembly plant are defined. This plant belongs to a well known multinational company that considers maintenance development to be a clear driver of their business competitive advantage. The plant started a TPM program several years ago with considerable success, and the current definition of the maintenance levels is as follows:

- Level 1. Autonomous management:
  - Cleaning, inspection and lubrication standards;
  - Simple repairs and replacements;
  - Adjustments and format changes;
- Level 2. Corrective maintenance:
  - Equipment cards removal (solving equipment anomalies);
  - Fault diagnosis;
  - Repairs;
- Level 3. Preventive maintenance:
  - Preventive (including predictive) maintenance;
  - Overhauls;
  - Training and standardization;
- Level 4. Maintenance prevention:
  - Improvements;
  - Early equipment management;
  - New equipment, techniques and systems;
- Level 5. Contracted Maintenance:
  - Maintenance providers interventions;
  - Important suppliers activities.

In this example, as the reader may perceive, maintenance levels seem to be more related to technical and/or managerial complexity than to indenture levels. However, it is obvious that preventive operations at level 3, or corrective operations at level 2, may deal with different indenture levels than those carried out at level 1.

In industry it is also common to assign higher maintenance levels to more complex maintenance tasks. In our example, maintenance task in levels 2 or 3 would require higher maintenance skills than those in level 1. However, this could not be applicable for levels 3 and 5.

5.5 The Maintenance Line or Echelon

The line of maintenance is a concept that links the level of maintenance to the existing maintenance organization. Note that the maintenance level concept is not related to the maintenance organization, but to the item maintenance complexity, through the indenture level concept. The maintenance line concept, however, establishes the position in an organization where specified levels of maintenance are to be carried out on an item. Examples of line of maintenance are: field repair shop, maintenance provider shop or manufacturer.

The lines of maintenance are characterised by their location and their maintenance support, that is to say, the place where the maintenance is carried out and the resources, services and management necessary to carry out a certain level of maintenance activities. Support may include, for example, personnel, test equipment, work rooms, spare parts, documentation, tools, *etc*.

When maintenance is carried out at the location where the equipment is used we refer to this maintenance as *on-site maintenance*. Other maintenance activities will be off-site, for instance at the shop of a certain manufacturer. But it is also possible that, with the equipment on-site, maintenance is carried out off-site, *i.e.* without the physical access to the item — *remote maintenance*.

Regardless of the number of maintenance lines defined by a certain organization, the maintenance terminology standard defines *maintenance supportability* as the ability of a maintenance organization to have the right maintenance support at the necessary place to perform the required maintenance activity at a given instant of time during a given time interval. Maintenance supportability is therefore concerned with the effectiveness of an organization to provide the correct maintenance support, but an organization has to provide the right support in an efficient manner. The same standard defines the term *maintenance support efficiency* as the ratio between the planned or expected resources necessary to fulfil the required maintenance task and the resources actually used.

5.6 The Maintenance Policy

Previous sections show that, for maintenance purposes, items have subdivisions named indenture levels. Maintenance actions at different indenture levels can then be classified in different maintenance levels. Maintenance levels will be then carried out at different positions of the maintenance organization named maintenance lines or echelons.

Once all these concepts are clear and established in an organization we may say [2] that the organization has established a maintenance policy. A maintenance policy is therefore defined as the interrelationship between its maintenance echelons or lines, the items indenture levels and the maintenance levels to be applied for the maintenance of an item.

Figure 5.3 presents the maintenance lines (3) where actions of the different maintenance levels (5 – in circles) of the example presented in Section 5.4 are to be carried out. As we can see in that figure, the first level of maintenance is accomplished by operators of the production lines or cells. They are the first maintenance line. The second maintenance line is the maintenance department of each production unit. They are responsible for the corrective activities within the second level of maintenance. A maintenance department at a higher level, common support for all production units, is the third maintenance line which is responsible for the other three levels of maintenance: preventive maintenance, maintenance improvement and contracted maintenance.

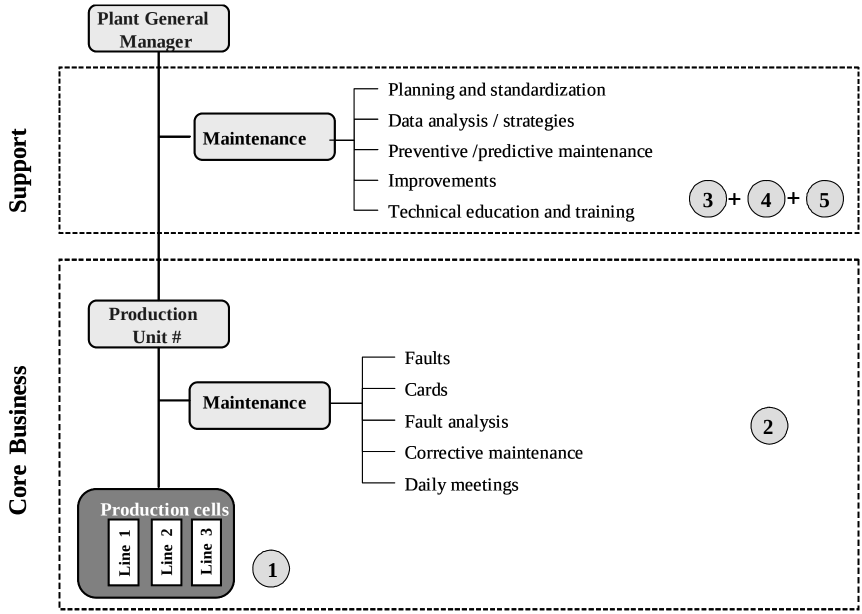

Figure 5.3. Example of a maintenance policy definition

The definition of the maintenance policy is important for an organization. The maintenance policy develops the maintenance concept within the organization and sets up solid foundations for the excellence in maintenance management.

5.7 References

[1] EN 13306:2001, (2001) Maintenance Terminology. European Standard. CEN (European Committee for Standardization), Brussels.
[2] IEC 60050-191-am2, (2002) Amendment 2 - International Electrotechnical Vocabulary. Chapter 191: Dependability and quality of service. Edition 1.0, Geneva.

6

Basic Maintenance Models

6.1 Introduction to Maintenance Policy Modelling

Modelling a specific maintenance policy requires the formal representation of the maintenance action applied, by a certain maintenance line or echelon, to avoid the ocurrence of a failure at a given indenture level of an item (see maintenance policy definition in Section 5.6).

What then are the inputs that we need in order to build a formal maintenance policy model? We answer this question by characterizing the components of a maintenance policy model as follows:

- *The failure model.* In Chapter 3 we explained that the failure occurrence process is a *stochastic process*. That is to say, we cannot predict when the failures will happen, but we can determine, on the basis of our best information, the probability that they will appear during a certain period of time. In Chapter 3 we also reviewed how to make such a prediction by building an appropriate failure model from the existing reliability data. Once a maintenance policy addresses a certain cause of failure, the model of that cause of failure is a requirement, a fundamental input to build the maintenance policy model;
- *The maintenance action characterization.* Maintenance actions can be preventive or corrective. Both actions may require a modelling of their maintenance time — there are models where some of these times are ignored .

  Preventive actions will require the characterization of their predetermined time intervals — or prescribed criteria. Regardless of the preventive strategy that we may follow, failures can always occur and corrective actions also need to be formalized. Repair activities can be of a different extent. After a repair — sometimes after an important preventive maintenance — equipment can be as good as new, as bad as old, or something in between. This needs to be conveniently formalized in our maintenance model;

- *The line of maintenance.* The line of maintenance is characterised by its location and maintenance support, that is to say, the place where the maintenance is carried out and the resources used. On many occasions, the maintenance line is related to the cost of the maintenance actions and/or a certain delay time for the action to be accomplished;
- *The indenture level consideration.* Sometimes we may want to model a maintenance policy for equipment consisting of several indenture levels. In these models we may need to formalize partial preventive actions carried out only at certain — normally lower — equipment indenture levels (for instance, in a component of a system). The relationship between partial and global actions carried out on the equipment, and their impact on equipment behaviour needs to be properly captured and formalized.

In the following sections we review different approaches to maintenance policy modelling. It is not the intention to present a complete review of the modelling possibilities found in the literature ([1—7]) but to offer the reader a variety of examples that can be used to solve the problem.

Some of the following examples include not only the maintenance policy model but also the policy optimization model. At this point we call reader attention to the fact that complex problems may require the use of diverse and complex optimization techniques that need further study. Attention should now be paid to the way the maintenance policy is formalized and the manner of considering the different points listed above.

The order of the following sections is taken from previous reviews and maintenance model classifications found in the literature.

6.2 Total Replacement Models

In classic total replacement models [8] we assume that the equipment is always replaced completely, the replacement is done instantaneously, *i.e.* consumes no time, and the equipment failure is detected as soon as the failure takes place. Normally there are two types of replacement options:

- Preventive replacement (*PR*). Following a predetermined preventive maintenance policy;
- Corrective replacement (*CR*). Following the equipment failure.

Basic total replacement models normally consider the following PR policies:

- Constant interval replacement (*CIR*). Replacement is done after a certain constant time interval;
- Age based replacement (*ABR*). Replacement is done when the equipment reach a certain operating time — age.

Let us now formalize these options in the following sections.

6.2.1 Constant Interval Replacement (CIR)

Replacement is done after the failure (CR) or after a certain constant time interval t_p (PR) (see Figure 6.1). The model is built to determine the optimal time interval between two preventive replacements. The optimization criteria is to minimize the total expected cost per unit time.

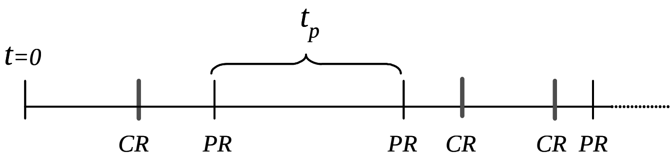

Figure 6.1. Equipment maintenance over time

We will use the following notation:

C_p	: PR unit cost ;
Cc	: CR unit cost;
t_p	: PR time;
$F(t)$	: Time to failure probability distribution function;
$f(t)$	: Time to failure probability density function;
$N(t_p)$	: Expected number of failures[10] within the time interval (0,tp);
$TEC(t_p)$	: Total expected cost per unit time.

If a failure is produced, it will take place within the time interval (0, t_p), and the total expected cost per unit time $TEC(t_p)$, for the interval t_p, will be as follows:

$$TEC(t_p) = \frac{TEC(0,t_p)}{Length(0,t_p)} = \frac{C_p + C_C N(t_p)}{t_p} \tag{6.1}$$

If we follow this policy, and the number of failures is appreciable, notice that many preventive replacements could be done when the operating time of the equipment is below t_p, which of course could make this policy less efficient.

Suppose that we have to maintain certain equipment which has the time to failure probability density function $f(t)$ following a uniform distribution within the time interval [0,20] weeks. Also suppose that the cost for the replacements are Cc=500 € and Cp =40 €. Imagine that we want to calculate the best t_p to minimize the total expected cost per time of the equipment maintenance when following CIR policy. We look for a t_p that will minimize the function in Equation (6.1). In order to do so, let us show Equation (6.1) as a function of t_p.

[10] Barlow and Hunter [8] showed that $N(t_p) = \int_0^{tp} \lambda(t)dt$, where $\lambda(t)$ is the failure rate.

The expected number of failures for the time interval t_p will be

$$N(t_p) = \int_0^{tp} \lambda(t)dt = \int_0^{tp} \frac{f(t)}{1-F(t)}dt \qquad (6.2)$$

where *f(t)* is defined as follows:

$$f(t) = \begin{cases} 1/20 & 0 \le t \le 20 \\ 0 & \text{otherwise} \end{cases}$$

Hence

$$N(t_p) = \int_0^{tp} \lambda(t)dt = \int_0^{tp} \frac{\frac{1}{20}}{1-\frac{1}{20}t}dt = \int_0^{tp} \frac{1}{20-t}dt = \left[-\ln(20-t)\right]_0^{tp} = \ln\frac{20}{20-t_p}$$

The total expected cost per time unit will then be

$$CTE(t_p) = \frac{40 + 500\ln\frac{20}{20-t_p}}{t_p}$$

Figure 6.2 represents $TEC(t_p)$ for values of t_p between 1 and 20. The minimum value of $TEC(t_p)$ is achieved for t_p=6 weeks, with $TEC(6)$=36.39 € of minimum cost per week.

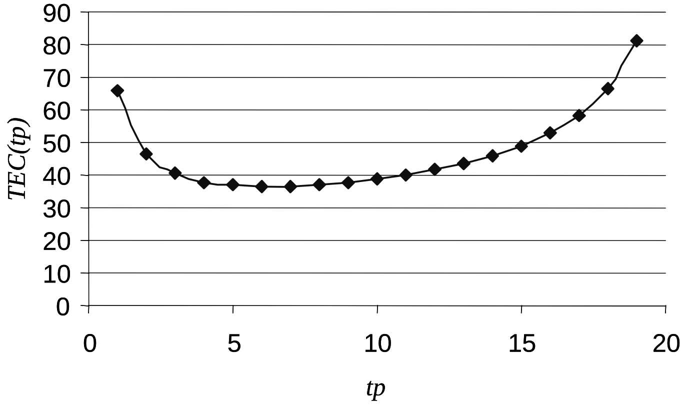

Figure 6.2. *TEC(tp)* plot to find the optimum t_p value

6.2.2 Age Based Replacement (ABR)

In this case (Figure 6.3), the PR is done after the equipment reaches a certain operating time — age, t_p. In case of equipment failure a CR is done and the next PR is scheduled after t_p units of time. We again want to calculate the best t_p which minimizes $TEC(t_p)$.

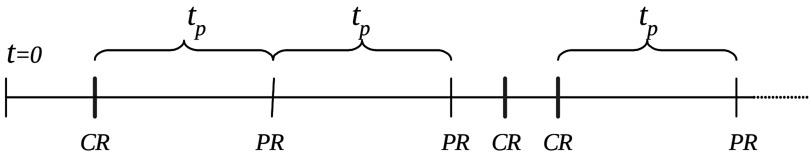

Figure 6.3. Age based policy and equipment maintenance over time

This time the equipment may reach the PR time t_p; this will happen with a probability equal to $R(t_p)$, or fail before that time, with a probability equal to $F(t_p)$. The expected cost for the interval $(0,t_p)$ is now equal to $C_pR(t_p)+C_cF(t_p)$, and the expected length of the cycle is equal to t_p times the probability of the preventive cycle $R(t_p)$, plus the expected length of the failure cycle times the probability of the failure $F(t_p)$.

The length of the failure cycle can be estimated calculating the expected value of the failure distribution now truncated in t_p as follows:

$$M(t_p) = \int_{-\infty}^{tp} \frac{tf(t)dt}{F(t_p)} \tag{6.3}$$

$$TEC(t_p) = \frac{C_pR(t_p) + C_cF(t_p)}{t_pR(t_p) + M(t_p)F(t_p)} \tag{6.4}$$

Then the optimum of $TEC(t_p)$ will be obtained by minimizing Equation (6.4) with respect to t_p. If we take the same example than for the *CIR* policy, Equation (6.3) will then be

$$M(t_p) = \frac{\int_0^{tp} tf(t)dt}{1 - R(t_p)} = \frac{\int_0^{tp} t\frac{1}{20}dt}{\frac{1}{20}t_p} = \frac{t_p}{2}$$

Hence Equation (6.4) can be expressed as follows:

$$TEC(t_p) = \frac{40(1-\frac{1}{20}t_p)+500\,\frac{1}{20}t_p}{t_p(1-\frac{1}{20}t_p)+\frac{t_p}{2}\frac{1}{20}t_p} = \frac{40+23t_p}{t_p - t_p^2(\frac{1}{40})}$$

If we plot this function, Figure 6.4, for different values of t_p, the minimum $TEC(t_p)$ value is obtained for t_p=7 weeks, with $TEC(7)$=34.8 € of minimum maintenance cost per week. In Figure 6.4 we compare results for *TEC* in cases of *CIR* and *ABR* policies[11] and for selected t_p values.

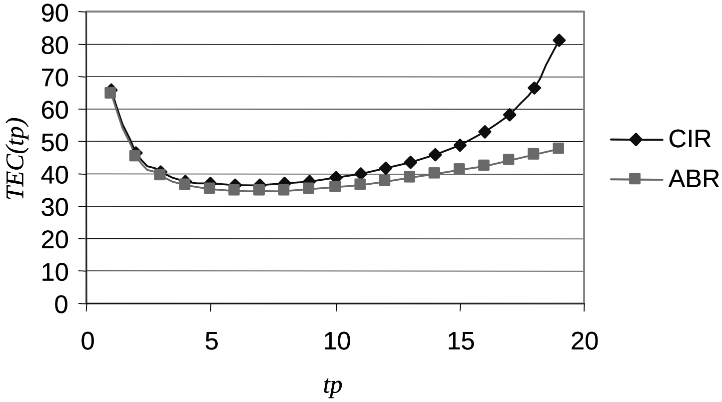

Figure 6.4. $TEC(t_p)$ plot for *CIR* and *ABR* policies

6.3 Partial Replacement Models

These models are extensions of those presented above in Section 6.2. Their formulation [9] is motivated by the idea of possible partial replacement of equipment consisting of lower indenture levels.

In these models we will assume that, in our equipment, partial preventive replacements (PPR) of lower indenture level components can be done, at certain operating times T_i, restoring the entire equipment to its initial failure rate. However, it is also common that after a certain number of PPR*s*, these will be more expensive than a complete preventive equipment replacement (PR).

Basic PPR models normally consider two options concerning corrective maintenance:

- Minimal repairs, inexpensive but without failure rate restoration capabilities;

[11] ABR policy will more suitable [10] when the failure rate is increasing with time, *i.e.*, when the probability of failure of the equipment increases with its operating time.

- Normal repairs, more expensive but with failure rate restoration capabilities.

Let us now formalize each of these options in the following sections.

6.3.1 PPR with Minimal Repairs

In this policy we assume that the total preventive replacement of the equipment (PR) is done after (*k–1*) partial preventive replacements PPR. For equipment subject to (*i–1*) PPR*s* with (*i*<*k*), the next PPR will be done after T_i units of operating time since the last PPR (or PR in case *i=1*). In case of failure, a minimal repair will be carried out, which will take the equipment back to operation but without restoring its failure rate (Figure 6.5). PPR and PR, unlike minimal repairs, will restore the equipment failure rate to initial conditions.

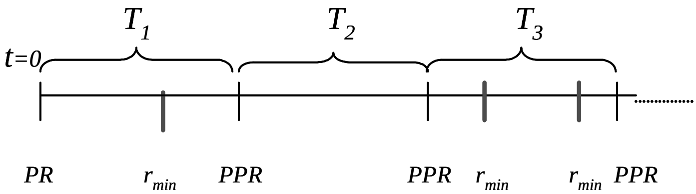

Figure 6.5. Equipment maintenance with PPR and minimal repairs option

We will now use the following additional notation:

C_{pp} : PPR unit cost;
C_p : PR unit cost;
C_{rm} : Minimal repair unit cost;
T_i : Time to carry out the PPR;
$\lambda i(t)$: Failure rate at *t* for equipment with *(i–1)* PPR*s*;
$TEC(k, T_1, \ldots, T_k)$: Total expected cost per unit time.

Then the total expected cost per time unit will be

$$TEC(k,T_1,\ldots,T_k) = \frac{(k-1)C_{pp} + C_s + C_{rm}\sum_{i=1}^{k}\int_0^{T_i}\lambda_i(t)dt}{\sum_{i=1}^{k} T_i} \tag{6.5}$$

The problem to solve is to find the optimal number *k* of PPR*s* and the time since the last replacement to do these PPR*s* — T_i , with *i=1…k*, minimizing the total expected cost per time $TEC(k, T_1, \ldots, T_k)$.

6.3.2 PPR with Normal Repairs (NR)

In this policy we again assume that the total preventive replacement of the equipment (PR) is done after $(k–1)$ partial preventive replacements — PPR. For equipment that went through $(i–1)$ PPR*s*, with $i<k$, a normal repair — NR — will be carried out in case of a failure, or another PPR will be done after T_i units of time since the last maintenance (notice that now with that maintenance we restored the failure rate of the equipment), whichever it comes first (Figure 6.6).

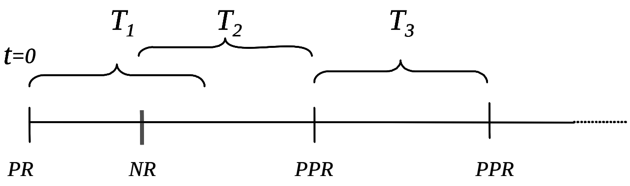

Figure 6.6. Maintenance activities over time with PPR*s* and NR*s*

We will use the following additional notation:

C_c : NR unit cost;
C_{ec} : NR extra unit cost (exceeding PPR unit cost);
$Mi(T_i)$: Mean of the truncated distribution in T_i , equipment with $(i–1)$ PPR´*s*.

If we suppose that

$$C_c=C_{pp}+ C_{ec}$$

then the expected unit cost for a PPR for equipment with $(i–1)$ PPR*s* since last PR:

$$CE(T_i) =C_cF_i(T_i)+C_{pp}R_i(T_i)=(C_{pp}+ C_{ec})F_i(T_i)+C_{pp}R_i(T_i)=C_{pp}+C_{ec}F_i(T_i) \qquad (6.6)$$

and the total expected cost for a PR cycle of the equipment will be

$$TEC(k,T_1,...,T_k) = (k-1)C_{pp} + C_p + C_{ec}\sum_{i=1}^{k} F_i(T_i) \qquad (6.7)$$

The length of the *PR* cycle is

$$L(k,T_1,...,T_k) = \sum_{i=1}^{k} \{T_iR_i(T_i) + M_i(T_i)F_i(T_i)\} \qquad (6.8)$$

with

$$M_i(T_i) = \int_{-\infty}^{Ti} \frac{t f_i(t) dt}{F_i(T_i)} \tag{6.9}$$

and the total expected cost per time unit is given by:

$$CTE(k, T_1, ..., T_k) = \frac{(k-1)C_{pp} + C_s + C_{eic} \sum_{i=1}^{k} F_i(T_i)}{\sum_{i=1}^{k} \{T_i R_i(T_i) + M_i(T_i) F_i(T_i)\}} \tag{6.10}$$

Our problem will be to determine the optimal number of PPR*s*, and the moment when they should be carried out, in order to minimize the total expected cost in Equation (6.10).

Notice that models in the last two sections are extensions of the models presented in the previous sections. Also notice that those models are the result of having $k=1$ in our last formulation.

6.4 Replacement Models with Imperfect Maintenance (IPM)

In the replacement models that we presented in previous sections we have assumed that equipment is “as good as new” after preventive replacements PR or PPR. In many other cases, the failure pattern of the equipment may change after the preventive maintenance activities. Modelling these cases will require that, after the preventive maintenance, we set the failure rate of the equipment to a point between “as good as new” and “as bad as old”. This concept is known as imperfect preventive maintenance (IPM) and the corresponding model is then known as the *IPM* model.

In the basic *IPM* model [11], the IPM*s* are carried out at fixed time h_k ($k=1,2,...,N-1$) and the equipment is replaced (PR) after $N-1$ IPMs. In case of equipment failure between IPM*s*, a minimal repair is carried out. We will assume that, if we do the k-th IPM at t operating time of the equipment, after that k-th IPM the equipment age will be set to $b_k t$, (see Figure 6.7).

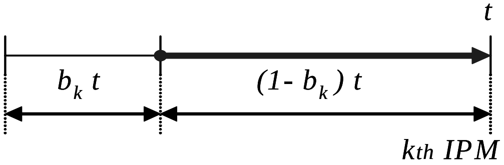

Figure 6.7. IPM impact on equipment age

In the IPM model we make the following assumptions:

1. IPM*s* are carried out at times h_1, h_1+h_2, ..., where h_i is the length of the i-th interval ($i=1,2,...,N-1$) and the PR of the equipment is carried out after the interval N;
2. Failures between two *IPM*s are solved with minimal repairs. After k IPM*s* equipment life is reduced $b_k t$, with $0=b_0<b_1<b_2<\ldots<b_{N-1}<1$;
3. After PR the equipment is as good as new and its failure rate is totally restored;
4. $\lambda(t)$ is continuous and strictly increasing with time;
5. Times to carry out *IPM* , minimal repair and PR are ignored;
6. After N time intervals the cycle ends with a PR.

We have to find the size of the intervals (h_k), and the number of *IPMs* ($N-1$) before PR to minimize the total expected cost per time unit. We will use the following notation:

y_i : equipment age when the i-th *IPM* is carried out;
C_{ipm} : IPM unit cost;
C_p : PR unit cost;
C_{rm} : Minimal repair unit cost.

The equipment age when we do the k-th IPM is obtained as

$$y_k = h_k + b_{k-1}\, y_{k-1} \tag{6.11}$$

Therefore, during the kth time interval, the equipment age is within $[b_{k-1}y_{k-1}, y_k]$.
The total expected cost per cycle is

$$TC(y_1, y_2, ..., y_N) = C_{rm}\sum_{k=1}^{N}\int_{b_{k-1}y_{k-1}}^{y_k}\lambda\,(t)dt + (N-1)C_{ipm} + C_p \tag{6.12}$$

The cycle expected length will be

$$LE\,(T) = \sum_{k=1}^{N-1} h_k \tag{6.13}$$

and the total expected cost per time unit is

$$TEC\;(y_1,...,\,y_N) = \frac{TC\;(y_1,...,\,y_N)}{LE\,(T)} =$$

$$= \frac{C_{rm}\sum_{k=1}^{N}\int_{b_{k-1}y_{k-1}}^{y_k}\lambda\;(t)dt + (N-1)C_{ipm} + C_p}{\sum_{k=1}^{N-1} h_k} \tag{6.14}$$

6.5 Shock Based Replacement Models

In the literature we can find other replacement model approaches. This is the case of shock models. Shock models are models in which equipment deterioration is accumulated according to shocks, and replacement is decided according to equipment deterioration. These models generally consider the following assumptions:

- Equipment receives shocks at random times;
- Each shock causes a certain random deterioration;
- Deterioration is accumulated until equipment replacement or failure;
- Time between shocks and deterioration caused by a shock are random variables with distribution functions, $F_{X(t)}$ and $G_{X(t)}$, respectively. These are functions of the accumulated equipment deterioration at time t, $X(t)$;
- After the failure, equipment is replaced by an identical new one, with a cost $c(\Delta)$, where Δ refers to failure;
- The equipment can be replaced before the failure, with a cost $c(X) \leq c(\Delta)$, if the deterioration of the equipment reaches the level X;
- The replacement cost function $c(\mathrm{X})$ will never decrease when X increases;
- Replacement time is ignored;
- When the accumulated deterioration of the equipment at t is X, and then suffers a shock of magnitude Y, the equipment probability of failure is a function of $(X + Y)$;
- After the equipment replacement a new cycle starts.

Let us now use the following notation:

ζ : The time at failure;
T : The time at replacement;
$(\zeta \wedge T)$: Minimum of $\{\zeta, T\}$.

Then the total expected cost per time unit can be expressed as follows:

$$TEC(T) = \frac{P\{\mathrm{T} < \zeta\}E[c(X(T))] + P\{\mathrm{T} = \zeta\}c(\Delta)}{E[T \wedge \zeta]} \tag{6.15}$$

6.6 Inspection Models

The purpose of these models is to define the optimal inspection schedule, or to find the best moments in time to check the equipment condition. Inspection models will normally consider other possible preventive activities and corrective maintenance. In inspection models, and according to a certain mathematical formulation, inspections, preventive replacements (PR) and corrective replacements (*CR*) will be combined with the idea of reaching the minimum total expected cost per unit time.

Inspection models were introduced by Barlow *et al.* [12]. Initial formulation of the problem was an age based inspection model, where there are no preventive maintenance replacements and the equipment is replaced only after a failure. This model considers the following assumptions:

- Equipment failure is known only after an inspection;
- Inspections do not deteriorate the equipment;
- Equipment cannot fail during the inspection;
- Each inspection has a unit cost C_i;
- The cost, per time unit, associated to a non-detected failure is C_f;
- The corrective replacement cost is C_s.

The inspection policy in this model considers that an inspection is done at times x_1, x_2, x_3,..... x_n, until a failure is found, then the equipment is replaced, and another cycle starts (Figure 6.8).

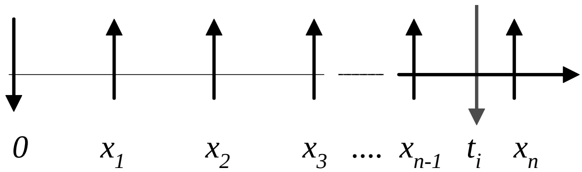

Figure 6.8. Equipment inspections and failure

When there is a failure between x_{n-1} and x_n, at time t_i, the cost per inspection cycle is

$$C(t_i, x_n) = nC_i + (x_n - t_i)C_f + C_s \tag{6.16}$$

Note that Equation (6.16) supposes that equipment fails at t_i and then suffers a performance loss, associated with the failure, until it reaches x_n. At x_n the inspection takes place, then the failure will be found and the replacement done. We carry out therefore n inspections and a corrective (total) replacement per cycle.

The expected cost of this policy is expressed in Equation (6.17).

$$CE(t, x) = \int_{x_{n-1}}^{x_n} \left[nC_i + (x_n - t_i)C_f + C_s\right] f(t)dt \tag{6.17}$$

If we now add for all *n* values, we can obtain the total expected cost as follows:

$$\sum_{n=1}^{\infty} \int_{x_{n-1}}^{x_n} \left[nC_i + (x_n - t_i) C_f + C_s \right] f(t) dt \tag{6.18}$$

To achieve this cost per time unit we have to calculate the cycle expected length:

$$LE(x_1, x_2, ..., x_n) = \int_0^{\infty} tf(t) dt + \sum_{n=1}^{\infty} \int_{x_{n-1}}^{x_n} (x_n - t) f(t) dt + T_s \tag{6.19}$$

where T_s is the replacement time. Then, the total expected cost per time unit is

$$CTE(x_1, x_2, ..., x_n) = \frac{\sum_{n=1}^{\infty} \int_{x_{n-1}}^{x_n} \left[nC_i + (x_n - t) C_f + C_s \right] f(t) dt}{\int_0^{\infty} tf(t) dt + \sum_{n=1}^{\infty} \int_{x_{n-1}}^{x_n} (x_n - t) f(t) dt + T_s} \tag{6.20}$$

6.7 References

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PART 3. Developing the Maintenance Management Framework

7

A Review of Key Decision Areas in Maintenance Management Modelling

7.1 Introduction

What is the process — the course of action and the series of stages or steps — to follow in order to manage maintenance properly? What are the different tools that can be used to support this process? Chapters 1 and 2 reviewed these questions. A definition of maintenance management process and framework was given, as well as a classification of the tools that can be used to support the maintenance management process.

In this part of the book a practical vision of the maintenance management process and framework is offered. A generic maintenance management model is presented with the idea of:

- Structuring the maintenance management process by grouping management activities within a series of so-called management building blocks;
- Structuring the framework grouping techniques that can be used to support decisions to be taken within each of these building block.

After presenting the model, different chapters will sequentially introduce basic management principles and methods that may be used to improve each building block decision making process.

7.2 A Generic Model for Maintenance Management

The generic model for maintenance management that will now be proposed and defined integrates other models found in the literature (see for instance [1,2]) for built and in-use assets, and consists of eight sequential management building blocks, as presented in Figure 7.1.

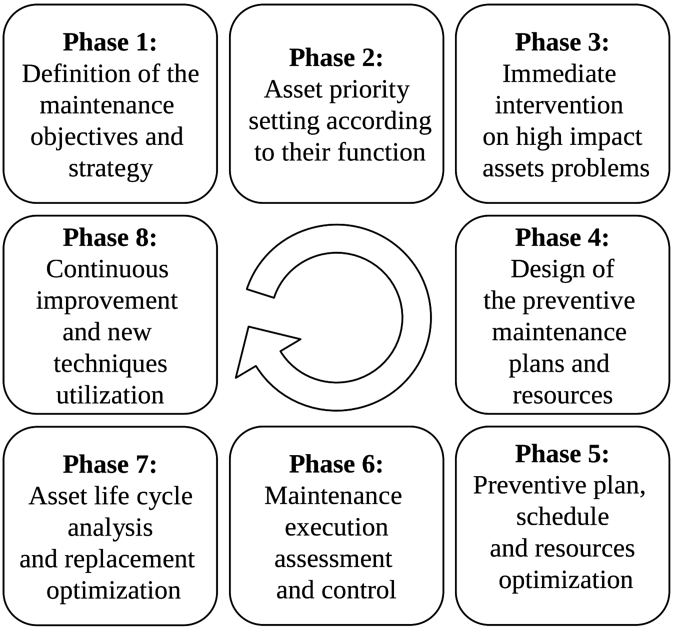

Figure 7.1. Maintenance management model

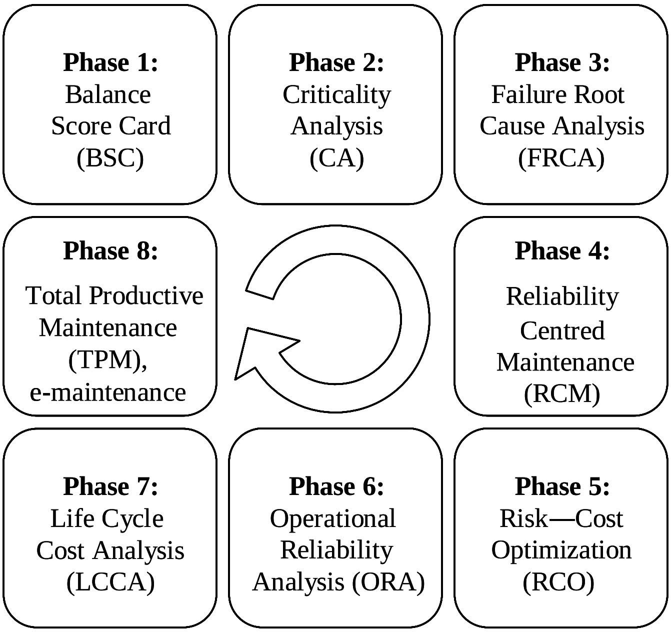

Figure 7.2. Sample methods and models within each management building block

Each building block is, in fact, a key decision area for asset maintenance and life cycle management. Within each of these decision areas we can find methods and models that may be used to order and facilitate the decision making processes, some of which are presented in Figure 7.2.

7.3 Definition of Maintenance Objectives and Strategy

It is a common belief in industry that strategic planning is important for ensuring an organization's future success. However, very often the operational objectives and strategy, as well as the performance measures, are inconsistent with the declared overall business strategy [3]. This unsatisfactory situation can indeed be avoided by introducing the Balanced Scorecard (BSC) [4].

The BSC is specific for the organization for which it is developed and allows the creation of key performance indicators (KPIs) for measuring maintenance management performance which are aligned to the organization's strategic objectives. Unlike conventional measures which are control oriented, the Balanced Scorecard puts overall strategy and vision at the centre and emphasizes on achieving performance targets. The measures are designed to pull people toward the overall vision. They are identified and their stretch targets established through a participative process which involves the consultation of internal and external stakeholders, senior management, key personnel in the operating units of the maintenance function, and the users of the maintenance service. In this manner, the performance measures for the maintenance operation are linked to the business success of the whole organization [5].

In Chapter 8 we will explore how the Balance Score Card can be used for maintenance management purposes.

7.4 Asset Priority and Maintenance Strategy Definition

There are a large number of quantitative and qualitative techniques which attempt to provide a systematic basis for deciding what assets should have priority within a maintenance management process, a decision that should be taken in accordance with the existing maintenance strategy.

Most of the quantitative techniques use a variation of a concept known as the "probability/risk number" (PRN) [6]. A PRN is derived by attaching a numerical value to the probability of failure of an asset (the higher probability, the higher the value), and attaching another value to the severity of the different categories of failure consequences (the more serious consequences for each category, the higher the value). The two numbers are multiplied to give a third which is the PRN. Of course, assets with the higher PRN will be analysed first. The criteria and the relative weighting to assess severity and probability may vary widely for different companies according to their maintenance objectives and KPIs. On some occasions, there is no hard data about historical failure rates, but the maintenance organization may require a certain *gross assessment* of assets priority to be carried out. In these cases, qualitative methods may be used and an initial assets assessment, as a way to start building maintenance operations effectiveness, may be obtained.

Once there is a certain definition of assets priority, we have to set up the strategy to be followed with each category of assets. Of course, this strategy will be adjusted over time, but an initial starting point must be stated.

In Chapter 9 we will discuss quantitative and qualitative criticality analysis techniques. Later, in the same chapter we will study possible examples of strategy definitions for the different category of assets.

7.5. Immediate Intervention on High Impact Weak Points

Once the assets have been prioritized and the maintenance strategy to follow defined, the next step would be to develop the corresponding maintenance actions associated with each category of assets. An initial point of departure would be, for instance, the design of the maintenance preventive plan, and the resources required to accomplish it, for those assets considered of high criticality impact. This would be an inductive process that will take both time and resources to be fully developed. Note that each failure mode of the critical assets will have to be ranked according to their criticality and the corresponding maintenance policy selection analysis to be carried out.

Before doing so, we may focus on certain repetitive — or chronic — failures that take place in high priority items. Finding and eliminating, if possible, the causes of those failures could be an immediate intervention providing a fast and important initial payback of our maintenance management strategy. The entire and detailed equipment maintenance analysis and design could be accomplished, reaping the benefits of this intervention if successful.

There are different methods developed to carry out this weak point analysis, one of the most well known being root-cause failure analysis (RCFA). This method consists of a series of actions taken to find out why a particular failure or problem exists and to correct those causes. Causes can be classified as physical, human or latent. The physical cause is the reason why the asset failed, the technical explanation on why things broke or failed. The human cause includes the human errors (omission or commission) resulting in physical roots. Finally, the latent cause includes the deficiencies in the management systems that allow the human errors to continue unchecked (flaws in the systems and procedures). Latent failure causes will be our main concern at this point of the process.

In Chapter 10 we will present several approaches to carry out a formal root-cause failure analysis process. Note that although informal RCFA techniques are usually used by individual or goups to determine corrective actions for a problem, they have limitations that can make the development of long-term solutions difficult [7].

7.6 Design of the Preventive Maintenance Plans and Resources

With the idea of designing the preventive maintenance plan for a certain system, we will have to identify its functions, the way these functions may fail and then establish a set of applicable and effective preventive maintenance tasks, based on considerations of system safety and economy. A formal method to do this, as we explained in Part 1, is the RCM (Reliability Centred Maintenance). As previously stated, RCM will allow the detection and elimination of causes of some failures before they show up through a set of maintenance proactive actions and plans, the elimination of the causes of some failures through changes in design, and the identification of those failures that may happen without any decrease in the system's safety.

The design of maintenance preventive plans will be a requirement in order to approach the maintenance capacity planning problem. Dealing with this problem means ensuring that the correct number of resources are engaged, and that we plan their best possible utilization.

The RCM method will be presented in Chapter 11. Chapter 12 will then introduce a set of models that, under certain conditions, can be used to improve maintenance activities planning. Models to deal with the maintenance capacity planning problems will then be reviewed in Chapter 13.

7.7 Preventive Plan, Schedule and Resources Optimization

Optimization of maintenance planning and scheduling can be carried out to enhance the effectiveness and efficiency of the maintenance policies resulting from an initial preventive maintenance plan and program design. The utilization of the maintenance optimization models requires previous knowledge and proper handling of the basic failure and maintenance models reviewed in Part 2 of this work. Models to optimize maintenance plan and schedules will vary depending on the time horizon of the analysis. Long-term models address maintenance capacity planning, spare parts provisioning and the maintenance/replacement interval determination problems, mid-term models may address, for instance, the scheduling of the maintenance activities in a long plant shut down, while short term models focus on resources allocation and control [8].

Modelling approaches, analytical and empirical, are very diverse. The complexity of the problem is often very high and forces the consideration of certain assumptions in order to simplify the analytical resolution of the models, or sometimes to reduce the computational needs.

Chapter 14 is dedicated to presenting several modelling approaches to solve different maintenance planning and scheduling problems, for different time horizon and decision process assumptions.

7.8 Maintenance Execution Assessment and Control

The execution of the maintenance activities — once designed, planned and scheduled using techniques described for previous building blocks, has to be evaluated and deviations controlled to continuously pursue business targets and approach stretch values for key maintenance performance indicators as selected by the organization.

Many of the high level maintenance KPIs, are built or composed using other basic level technical and economical indicators. Therefore, it is very important to make sure that the organization captures suitable data and that that data is properly aggregated/disaggregated according to the required level of maintenance performance analysis.

Chapter 15 presents a process to ensure that basic level — technical and economical — maintenance indicators are properly estimated for a certain item.

7.9 Asset Life Cycle Analysis and Replacement Optimization

A life cycle cost analysis calculates the cost of an asset for its entire life span. The analysis of a typical asset could include costs for planning, research and development, production, operation, maintenance and disposal.

Costs such as up-front acquisition (research, design, test, production, construction) are usually obvious, but life cycle cost analysis crucially depends on values calculated from reliability analyses such us failure rate, cost of spares, repair times, and component costs. A life cycle cost analysis is important when making decisions about capital equipment (replacement or new acquisition) [7], it reinforces the importance of locked in costs, such as R&D, and it offers three important benefits:

- All costs associated with an asset become visible. Especially: Upstream; R&D, Downstream; Maintenance;
- Allows an analysis of business function interrelationships. Low R&D costs may lead to high maintenance costs in the future;
- Differences in early stage expenditure are highlighted, enabling managers to develop accurate revenue predictions.

Chapter 16 is devoted to introducing different aspects related to asset reliability within the life cycle cost analysis (LCCA), and we describe three basic models which include in their evaluation process the quantification of the impact that could cause the diverse failure events in the total costs of a production asset.

7.10 Continuous Improvement and New Techniques Utilization

Continuous improvement of maintenance management will be possible due to the utilization of emerging techniques and technologies in areas that are considered to be of higher impact as a result of the previous steps of our management process.

Regarding the application of new technologies to maintenance, the “e-maintenance” concept is put forward as a component of the e-manufacturing concept[12] [9], which profits from the emerging information and communication technologies to implement a cooperative and distributed multi-user environment. E-Maintenance can be defined [10] as a maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support not only includes e-technologies (*i.e.* ICT, Web-based, tether-free, wireless, infotronic technologies) but also, e-maintenance activities (operations or processes) such as e-monitoring, e-diagnosis, e-prognosis…*etc*.

Besides new technologies for maintenance, the involvement of maintenance people within the maintenance improvement process will be a critical factor for success. Of course, higher levels of knowledge, experience and training will be required, but at the same time, techniques covering the involvement of operators in performing simple maintenance tasks will be extremely important to reach higher levels of maintenance quality and overall equipment effectiveness.

Chapters 17 and 18 present a a set of techniques that can be used to improve maintenance people involvement in maintenance improvement programs, and a review of new technologies arising in maintenance, respectively.

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8

Definition of Maintenance Objectives and Strategy

8.1 Introduction

The Balanced Scorecard (BSC) proposed by Kaplan and Norton [1] is a model that translates a business unit's mission and strategy into a set of objectives and quantifiable measures built around four perspectives:

1. Financial (the investor's point of view);
2. Customer (the performance attributes valued by customers);
3. Internal processes (the long and short-term means to achieve the financial and customer objectives); and
4. Learning and growth (capability to improve and create value).

It directs managers towards focusing on a handful of measures that are most critical for the continual success of the organization. The BSC has been implemented in a number of major corporations in the engineering, construction, microelectronics and computer industries [2]. Experience in these pioneering organizations indicates that the Scorecard will have its greatest impact on business performance only if it is used to drive a change process. Countless times the BSC has allowed the development of strategic management systems that link long-term strategic objectives to short term actions [3].

8.2 BSC and Maintenance

The BSC approach provides a holistic framework for establishing performance management systems at the corporate or business unit level. When the approach is applied to managing the performance of maintenance operations, a process involving the following steps can be followed [4]:

1. Formulate strategy for the maintenance operation. Strategic options such as developing in-house capability, outsourcing maintenance, empowering

frontline operators to practise autonomous maintenance, developing a multi-skilled maintenance workforce, and implementing condition-based maintenance are considered and decisions made through a participative process;

2. Operationalize the strategy. The maintenance strategy is translated into long-term objectives. The relevant Key Performance Indicators (KPIs) to be included in the BSC are then identified and performance targets established. The measures are designed to pull people towards the overall vision. They are identified and their stretch targets established through a participative process which involves the consultation of internal and external stakeholders, senior management, key personnel in the operating units of the maintenance function, and the users of the maintenance service. This way, the performance measures for the maintenance operation are linked to the business success of the whole organization;
3. Develop action plans. These are means to the ends stipulated in the targets established in step (2), taking into account any necessary changes in the organization's support infrastructure, such as structuring of maintenance work, management information systems, reward and recognition, resource allocation mechanisms, *etc.*;
4. Periodical review of performance and strategy. Progress made in meeting strategic objectives is tracked and the causal relationships between measures are validated at defined intervals. The outcome of the review may necessitate the formulation of new strategic objectives, modification of action plans and revision of the scorecard.

Mission & Strategy

Strategic Objectives	**Measures (KPIs)**	**Targets**	**Action**	**Perspective**
				Financial
				Customer
				Internal Processes
				Learning & Growing

Figure 8.1. The Balanced Score Card

8.3 Proper Selection of Maintenance KPIs

KPIs selection is an important decision making process that may have many potential implications. In order to reinforce positive implications of our measurement system and to reduce the negative ones, a set of suggestions [5] are as follows:

- The role of KPIs should be forward-looking prediction and insight, rather than backward-looking record keeping to forward-looking prediction and insight;
- Use KPIs to provide feedback, build understanding and encourage intrinsic motivation, rather than as a tool for top-down management control;
- Focus on systematic thinking, fundamental structural change and organisational learning, instead of mindless target-setting, continual fire-fighting or the rigorous allocation of blame;
- Make KPIs become a framework for everyone to understand and align with the top-level objectives of the organisation, and enable them to participate actively and enthusiastically in continuous improvement.

Mission & Strategy

Strategic Objectives	Measures (KPIs)	Targets	Action Plans	Perspective
Improve maintenance cost effectiveness	- Maintenance cost (%) per unit produced	- Current: 10% - Target: 7%	- Ensure proper data acquisition - Criticality analysis - PM compliance	**Financial**
Improve equipment availability	- MTBF - MTTR	- ↑ 20% MTBF - ↓ 10% MTTR	- RCM Program - Improve maintenance materials management	**Customer**
Improvement of maintenance process & documentation	- ISO 9001 compliance	Maintenance certification before 31.12.2007	- Develop all remaining procedures and technical specifications	**Internal Processes**
Ensure suitable training levels to fulfill the mission	- Training level per each maintenance level	Definition of the precise maintenance training level per maintenance level	- Definition of the training level per maintenance level - Training level assessment	**Learning & Growing**

Figure 8.2. The Balanced Scorecard for maintenance. An example

Taking into account these suggestions, KPIs should be developed in areas where improvement is desired. Each KPI should have a targeted performance level. The KPI and target should, where possible, be specific, measurable, achievable (but require stretch), realistic and time-based (*i.e.* can track performance improvement over time). The frequency at which the KPI is measured will be determined by the realistic amount of time that it would be expected for a corrective action to have an impact on the performance level. Thus, one does not want to measure and analyse the parameters when there is no change from one measurement to the next, but this needs to be balanced against not regularly measuring those parameters that can be out of control for long periods. Time, cost and resources necessary to develop, maintain and manage the KPIs must be considered as this will also determine how many robust KPIs need to be used.

In Figure 8.1 we present an example of BSC development for a certain maintenance department. The mission of this department is to provide very high value oriented assets maintenance; non competitive maintenance sections could be later outsourced. With that purpose, the mission has been translated into action plans according to the table in Figure 8.2.

8.4 From Key Performance Indicators to Functional Indicators

Let us now look at the table within Figure 8.2. The financial perspective key performance indicator is "maintenance cost of unit produced". With this KPI we are trying to find out how we are doing with respect to achieving our goals in the area of cost effectiveness [5]. Notice that we may have a range of additional metrics in the areas of maintenance planning, scheduling, quality or learning, supporting this indicator (see Figure 8.3). Therefore, if we notice a problem in cost effectiveness, we can easily drill down to see what else is going on. In the real-world, more functional level indicators would even support these further.

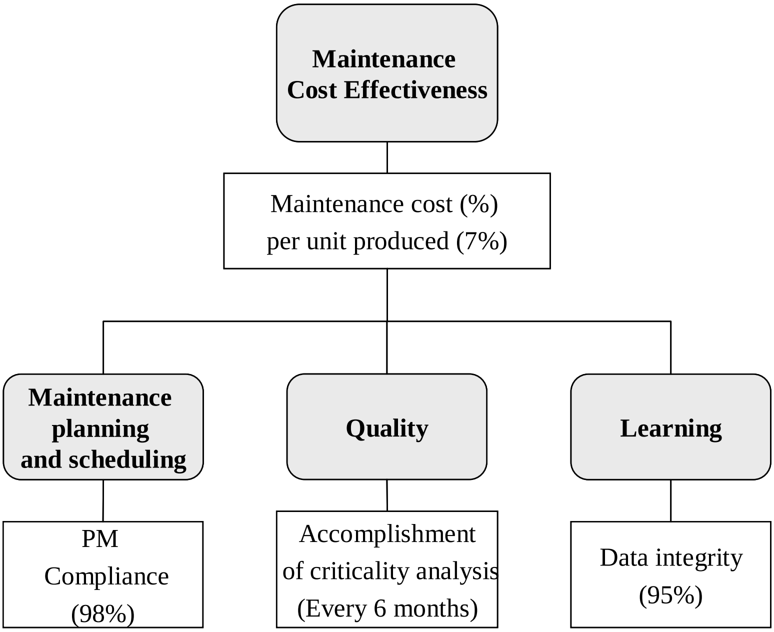

Figure 8.3. From KPIs to functional indicators

Another example could be the development of performance indicators to improve time to repair (MTTR) through a better maintenance materials management process, according to Figure 8.2. The design of maintenance indicators could be as in Figure 8.4 where the assessment of the maintenance support program is obtained through audits to suppliers, suitable spare parts levels design, improved maintenance materials requirements planning and better maintenance planning. Performance indicators to monitor these action plans could be: supplier lead time and lead time variability, spare parts service level, spare parts turnover and urgent purchase orders released, respectively. These functional indicators allow drilling down further into the real causes of the problems [6].

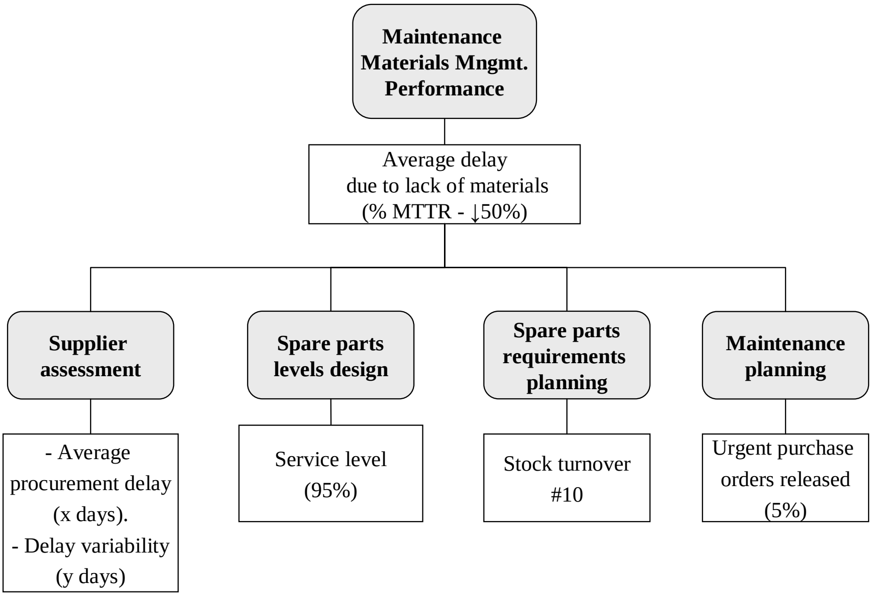

Figure 8.4. Indicators to improve maintenance materials management performance

Note that when drilling down in maintenance KPIs to obtain functional performance indicators, it is important to make sure that all action plans within the maintenance scored card are reasonably taken into account.

In a third example we show possible indicators to consider when measuring performance of an action suggesting the implementation of RCM to ensure time to repair and equipment reliability improvements. Indicators in Figure 8.5 are examples of those suggested by Wireman [7] to help monitor RCM. In our case, extra attention is paid to the maintenance effectiveness through the RCM program. Therefore, we will follow the permanent assets criticality assessment and root failure cause analysis, together with the preventive maintenance effectiveness and the prevention of maintenance activities. These actions will be monitored through the follow-up of the number of critical assets, the number of repetitive failures for those assets, the total number of failures and the reduction in preventive maintenance tasks.

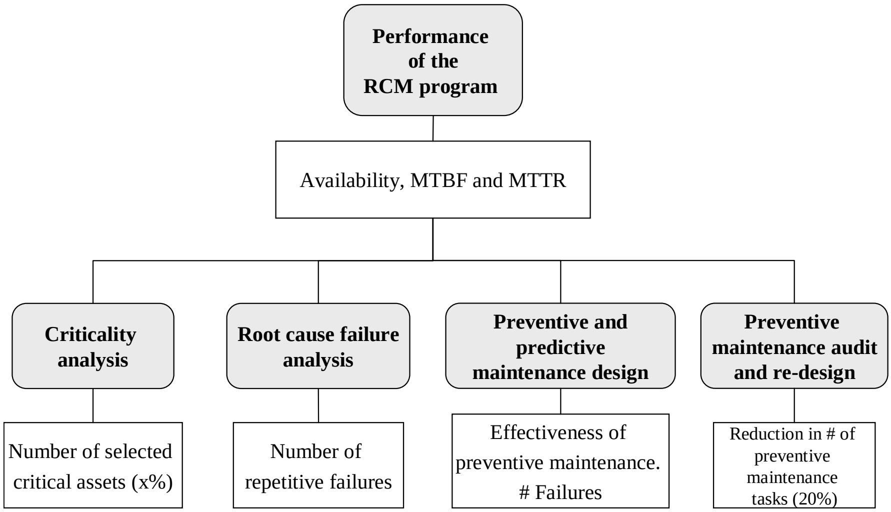

Figure 8.5. Indicators to improve RCM program performance

8.5 References

[1] Kaplan RS, Norton DP, (1992) The Balanced Scorecard - measures that drive performance. Harvard Business Review, 70(1): 71-9.
[2] Kaplan RS, Norton DP, (1993) Putting the Balanced scorecard to work. Harvard Business Review, 71(5): 134-42.
[3] Kaplan RS, Norton DP, (1996) Using the Balanced Scorecard as a strategic management system. Harvard Business Review, 74(1): 75-85.
[4] Tsang AHC, (1998) A strategic approach to managing maintenance performance. Journal of Quality in Maintenance Engineering, 4(2): 87-94.
[5] Meekings A, (1995) Unlocking the potential of performance measurement: a practical implementation guide. Public Money and Management, October-December: 5-12.
[6] Mather D, (2005) The maintenance scorecard. New York: Industrial Press, Inc.
[7] Wireman T, (1998) Developing performance indicators for managing maintenance. New York: Industrial Press, Inc.

9

Criticality Analysis for Asset Priority Setting

9.1 Introduction

In the previous chapter we have seen methodologies to transform business priorities into maintenance priorities by establishing critical targets in key performance drivers for current maintenance operations. Short term action plans can then be derived to ensure that maintenance function is aligned to business targets and priorities at any time. These actions will always require structuring the maintenance work and developing a course of strategic actions to address specific issues for the emerging critical items under the new business conditions.

Determining equipment criticality is understanding how crucial a certain piece of equipment is to the business [1]. The answer is generally determined by the consequences in the case of failure. Therefore maintenance decisions and actions will always involve the possibility of a certain deviation from business targets, a certain loss, a certain amount of risk.

In the following sections we explore the process of assets criticality analysis. Three methods for assets criticality will be presented. Each of these methods assumes certain information and knowledge of the system to analyse. Of course, the more information and data, the more quantitative the analysis can be. On some ocasions, however, pure qualitative assessment is required as an initial point for the maintenance strategy setting process.

9.2 Criticality Analysis Using Qualitative Techniques

Qualitative criticality analysis relies strongly on people's opinions, experience, and intuition. It uses a variety of polling, interview, and questionnaire techniques to rank assets by their perceived criticality. Qualitative analysis is a simple, easily understood approach. As long as the right people are on the team expressing their opinions it may identify significant critical areas. It avoids the need to retrieve processes and determines quantitative data like incidents frequency or incidents severity data besides performing the calculations associated with quantitative analysis.

A qualitative analysis can prove to be a fairly good evaluation that, conducted with due diligence, yields satisfactory results. However, obviously a qualitative analysis has disadvantages. One of the most serious criticisms of the approach is that it is difficult to enforce any degree of consistency and uniformity. People may be asked to weigh assets in the light of terms such as "critical," "semi-critical" and "non-critical". The terms' specific meaning and application may vary widely. The team may actually agree on how the asset in question fits into the overall business process and what the impact of its loss would be, but their personalities drive them to use different words. That is why defining the language as clearly as possible will greatly help matters.

The use of qualitative *vs* quantitative techniques to assess criticality will largely depend on the company culture and management's comfort level with numbers *vs* opinions. A quantitative approach will have a firmer basis in fact, but will typically expend more resources (*e.g*., more people time, more cost) to perform the analysis. A qualitative analysis, on the other hand, is simpler. It will be completed more quickly and expend fewer resources, but these benefits are gained at the cost of a lack of precision. This choice however does not need to be binary. Rather than seeing these two approaches as opposites, they should be viewed as two extremes on a continuum. The quantitative approach is used when numbers are readily available and can be trusted, and the qualitative approach is used when the asset is not quantifiable or the numbers are either not readily available or not to be trusted.

9.2.1 Case Study: Manufacturing Plant Criticality Flowchart

The method that we will present now is used, with certain variations, in many manufacturing plants worldwide. For our particular example, however, the process is applied to a beer factory. The procedure to follow in order to carry out an assets criticality analysis flowchart as follows:

1. Define the purpose and scope of the analysis;
2. Establish the work team. Success of this method, and others presented in this work, will hardly depend on the induction and training processes of the people who are involved in the teams. These processes will have to motivate the team and generate the necessary commitment for an efficient methodology implementation;
3. Establish the questionnaire in the form of a flowchart. The flowchart orders the priority of each criterion;
4. Decide on the characteristics of the assets falling within categories A, B and C of each specific question in the flowchart;
5. Determine the priorization of the assets by answering the questionnaire. The method requires that the teams arrives at a consensus when answering the questionnaire.

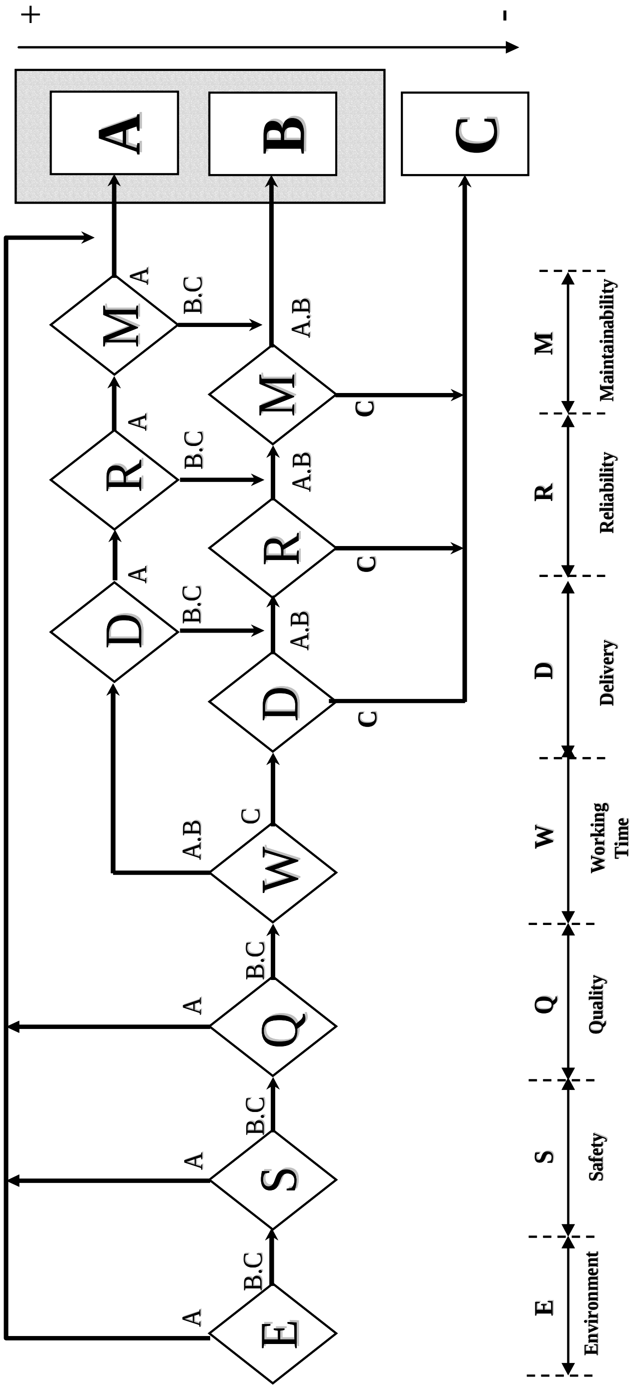

Figure 9.1. Flowchart criticality

A very important aspect of this method is the design of the flowchart that is used during the process. A flowchart is a schematic representation of a process. They are commonly used in business/economic presentations to help the audience visualize the content better, or to find flaws in the process. The flowchart orders the sequence of the questions that the team needs to answer for each secific asset considered for the analysis (see Figure 9.1). Note that the flowchart only allows the classification of the assets within one of the three groups A, B or C that are defined per each criterion question. Notice that the final asset ranking will also have three categories named A, B and C, for this particular case study.

Let us see how the business unit in our case study has decided regarding the questions and the characteristics of the assets falling within categories A, B and C of each specific criterion:

- Environmental impact of a certain production equipment or asset is the first aspect to be considered in the flowchart of our case study. With respect to environment, an asset falling within category “A” may cause an important and “business external” environmental impact in case its maintenance is not planned and carried out properly. By external impact we mean, for instance, that the business unit may have to inform local authorities about the incident and adopt specific contingency plans. An example can be a failure in a cooling system producing a gas leak to the atmosphere with high ammonia content. Category “B” is reserved for those assets whose failures may produce environmental problems that can be solved internally. For instance, this would be the case of a failure producing the leak of a certain liquid that can be treated within the water network of the company, producing no external consequences to the community water network. Finally, assets falling within category “C” are assets whose failures might create no environmental consequences;
- Safety issues are considered next. Category “A” assets are now assets whose failures may produce accidents causing temporal or permanent worker absence to the work place. Category “B” assets failures would cause only minor damage to people at work, producing no work absence. Again, assets falling within category “C” are assets whose failures might create no consequences related to safety;
- Quality is the next issue to be evaluated. The procedure for this assessment is very similar to what we have already carried out for the equipment environmental assessment. Quality failures may also produce an important external impact, or a very negative market image, when the failing product, or series of products, reach the final customer (consumers in our case study). Category A would now be dedicated to assets that could suffer this type of failure. Category “B” and “C” would be for assets that, when not properly maintained, could suffer failures producing only internal impact or no impact respectively;
- Working time of an asset may also condition its criticality. In this case study, assets which have three shifts working time fall within “A” category. Those assets with two shifts working time will be under “B” category. Finally when the production assets have ony one shift working time per day

they will fall within category "C". On some occasions extra labour required for the asset corrective maintenance, as an average, can be also considered within this criterion. Assets requiring a high amount of extra hours to be repaired would fall within "A" category, and so on;

- Delivery is a criterion related to the operational impact of an asset failure. "A" category assets are now those producing a stoppage in the entire factory when they fail. Assets whose failures may stop only a production line will fall within the "B" category. Finally assets producing no significant production stoppage would fall within category "C";
- Reliability criterion is related to the frequency of failures that may exist in an asset which is not properly maintained. In our case study, the business unit catalogue as category "A" assets those assets with a failure frequency less than 5 h. Assets with failure frequencies higher than 5 h and less than 10 h would be included in category "B". Finally for failures frequencies above 10 h, the assets category would be "C". Its is normal to consider a frequency criteria that produces 20% of the assets to be of category "A", 30% of them to be of categeory "B", while 50% would fall within "C" category.
- Maintainability is the last criterion to be observed. This criterion is related to the mean time required to repair an assets failure. Assets requiring a mean time of repair longer than 90 min are catalogued as "A". Between 45 and 90 min would be in "B" category. Finally those assets whose mean time of repair is less than 45 min would fall within "C" category.

9.3 Criticality Analysis Using Risk Assessment Techniques

Risk is the potential impact (positive or negative) to an asset or characteristic of value that may arise from some present process or from some future event. In everyday usage, "risk" is often used synonymously with "probability" and restricted to negative risk or threat.

Risk management is the ongoing process of identifying these risks and implementing plans to address them. Some industries manage risk in a highly-quantified and numerate way. These include, for instance, the nuclear power and aircraft industries, where the possible failure of a complex series of engineered systems could result in highly undesirable outcomes.

Often, the number of assets potentially at risk outweighs the resources available to manage them. It is therefore extremely important to know where to apply available resources to mitigate risk in a cost-effective and efficient manner. Risk assessment is the part of the ongoing risk management process that assigns relative priorities for mitigation plans and implementation. In professional risk assessments, risk combines the probability of an event occurring with the impact that event would cause. The usual measure of risk for a class of events is then $R=PxC$, where P is probability and C is consequence. The total risk is therefore the sum of the individual class-risks.

Risk assessment techniques can be used to prioritize assets and to align maintenance actions to business targets at any time. By doing so we ensure that maintenance actions are effective, that we reduce the indirect maintenance cost, the most important maintenance costs, those associated to safety, environmental risk, production losses, and ultimately, to customer dissatisfaction.

The procedure to follow in order to carry out an assets criticality analysis following risk assessment techniques could be then depicted as follows:

1. Define the purpose and scope of the analysis;
2. Establish the risk factors to take into account and their relative importance;
3. Decide on the number of asset risk criticality levels to establish;
4. Establish the overall procedure for the identification and priorization of the critical assets.

Notice that assessing criticality will be specific to each individual system, plant or business unit. For instance, criticality of two similar plants in the same industry may be different since risk factors for both plants may vary or have different relative importance.

9.3.1 Case Study: A Petrochemical Plant

This case study considers a certain plant within an oil refinery. The criticality assessment was conducted within a calendar week, with the purpose of redirecting maintenance efforts according to new business targets. Time employed for this analysis includes collecting required data from the plant information system and team meetings. The team was composed of six members including the facilitator and people from the following departments: maintenance management, operations management, process engineering, maintenance engineering and operations planning. For maintenance purposes, the analysis level was decided to be the plant subsystems level.

Risk factors considered in the analysis were: employees' safety, environment affection, operation downtime, maintenance and direct and indirect cost of operations, failure frequency and mean time to repair.

The assessment of risk for each asset considered was

$$R = F x C \tag{9.1}$$

where F is the frequency factor or number of failures in a certain time period (year) and C is consequence of the failure measured as follows:

$$C = (OI \ x \ OF) + MC + ISE \tag{9.2}$$

with:

OI : Operational Impact factor;
OF : Operational flexibility factor;
MC : Maintenance Cost factor;
ISE : Impact on Safety and Environment factor.

Concerning the frequency of failures (*F*), the team decided to establish the classification and scale in Table 9.1, to rank the different assets.

Table 9.1. Failure frequency classification and scale

Failure frequency (F)	Failures per year	Model value
Poor	> 4	4
Average	2-4	3
Good	1-2	2
Excellent	< 1	1

Regarding the different consequence factors (defining *C*), they were classified and scaled as in Tables 9.2 — 9.5.

Table 9.2. Operational impact factor, classification and scale

Operational Impact (OI)	Consequence	Model scale
Extremely high	Immediate plant shut down	10
Very high	Partial plant shut down	6
High	Impact production levels or quality	4
Average	Operational cost associated with unavailability	2
Low	No significant impact on operations	1

Table 9.3. Operational flexibility factor, classification and scale

Operational Flexibility (OF)	Consequence	Model scale
High	No spare nor alternative operation	4
Average	Spare function shared	2
Low	Spare function available	1

Table 9.4. Maintenance cost factor, classification and scale

Maintenance cost (OF)	Consequence	Model scale
High	≥ 20.000 €	2
Low	< 20.000 €	1

Table 9.5. Impact on safety and environment factors, classification and scale

Impact on safety and environment (ISE)	Consequence	Model scale
Extremely high	Impact on internal and external human safety requiring notification to public institutions	8
Very high	Irreversible environmental affection	6
High	Impact operation facilities causing severe damage	4
Average	Minor accidents and incidents	2
Low	Environmental affection without laws violation	1
Very low	No impact to human, environment nor operation facilities	0

As a result of the above mentioned classification, maximum value for an asset risk was set to 200 risk dimensionless units (notice that 200=4x[(10x4)+2+8] when substituting in Equations 9.2 and 9.1). The team established three levels of assets criticality as in Table 9.6.

Table 9.6. Levels of assets criticality

Asset criticality level	Adimensional risk value
Critical	$R > 100$
Semi-critical	$40 < R < 100$
Non-critical	$R < 40$

Once the overall criteria for the criticality analysis of the plant was established, a list of the plant systems and subsystems was obtained, data was conveniently gathered for the analysis and a document similar to the one presented in Table 9.7 was obtained.

In Table 9.7, a total of 16 subsystem of the plant are presented already sorted by their priority resulting from their estimated risk. A number of 4 subsystems out of 16 were found to be critical, 9 semi-critical and 3 non-critical.

Table 9.7. Assets (subsystems) priority according to their risk assessment

ASSET	F	OI	OF	MC	ISE	C	R	PRIORITY
REACTOR	3	9	4	2	6	44	132	CRITICAL
REGENERATOR	3	9	4	2	6	44	132	CRITICAL
POWER R.TRAIN	3	9	4	2	5	43	129	CRITICAL
H.GAS COMPRESSOR	3	8	4	2	3	37	111	CRITICAL
PRES. CONTROL VALVES	2	8	4	2	4	38	76	SEMI CRÍTICAL
MAIN COLUMN	2	8	4	2	4	38	76	SEMI CRÍTICAL
PRIMARY ABSORBER	3	6	3	2	4	24	72	SEMI CRÍTICAL
SECONDARY ABSORBER	3	5	3	2	4	21	63	SEMI CRÍTICAL
H2S INHIBITOR	3	4	3	2	4	18	54	SEMI CRÍTICAL
PRECIPITATOR	2	6	3	3	3	24	48	SEMI CRÍTICAL
3 STAGE SEPARATOR	2	5	4	2	1	23	46	SEMI CRÍTICAL
BOILER	2	6	3	2	3	23	46	SEMI CRÍTICAL
PRE-WARMING TRAIN	2	6	3	2	3	23	46	SEMI CRÍTICAL
NAFTA DESPOILER	1	5	4	2	3	25	25	NON CRITICAL
ALC. DESPOILER	1	4	4	2	3	21	21	NON CRITICAL
APC DESPOILER	1	4	4	2	3	21	21	NON CRITICAL

Critical and semi-critical assets were later located within the criticality matrix as shown in Figure 9.2. From the moment this analysis was carried out, preventive maintenance actions were also prioritized according to the resulting ranking and resource allocation for sudden corrective activities would also be prioritized using the matrix.

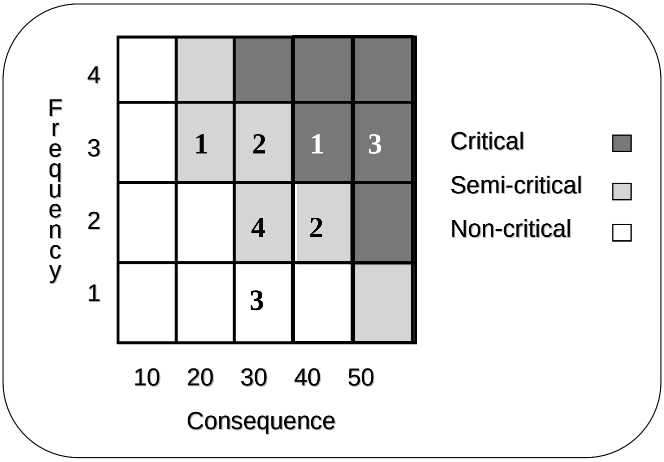

Figure 9.2. Criticality matrix and assets location

9.4 Criticality Analysis Using AHP

Another method that may be used to prioritize assets according to their criticality is the analytical hierarchy process (AHP). This approach was developed at the Wharton School of Business by Thomas Saaty [2] and allows the decision makers to model a problem in a hierarchical structure showing the relationship of the goal, objectives (criteria), sub-objectives and alternatives. Alternatives that are deficient with respect to one or more objectives can compensate by their performance with respect to other objectives. AHP was composed departing from several previously existing but unassociated techniques and concepts such as hierarchical structuring of complexity, pairwise comparisons, redundant judgments, and the eigenvector method for deriving weights and consistency considerations. The resulting method may crucially help when dealing with complex technological, economic, and sociopolitical problems.

AHP is built on a solid yet simple theoretical foundation based on three basic principles:

- Decomposition;
- Comparative judgments; and
- Hierarchy composition or synthesis of priorities.

The decomposition principle is applied to structure a complex problem into a hierarchy of clusters, sub-clusters and so on (Figure 9.3).

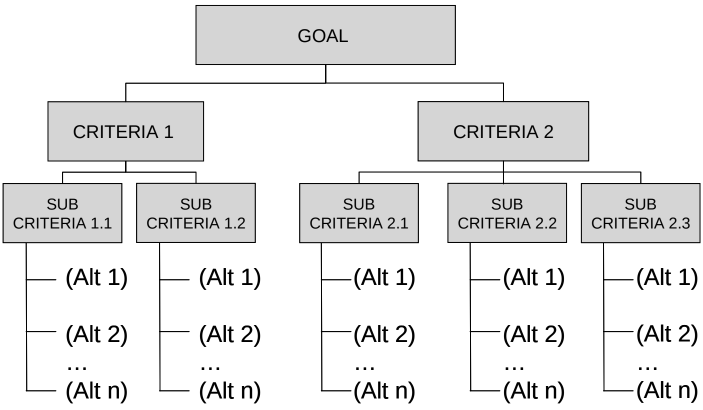

Figure 9.3. Example of decision hierarchy

The pairwise comparisons are used to derive local priorities of the elements in a cluster with respect to their parents. AHP uses a set of one-to-one comparisons to evaluate alternatives under each criterion. These pair-wise comparisons are the smallest in decisions. Alternative comparisons and criteria weighting is done in separate steps. Criteria weights combine both objective measures and subjective preferences. AHP aims at quantifying relative priorities for a given set of alternatives on a ratio scale [3] (see Table 9.8).

Table 9.8. Judgments ratio scale [3]

Judgments	Score
Equal	1
	2
Weak	3
	4
Strong	5
	6
Very strong	7
	8
Absolute	9

This scale, from one to nine, is used to give the relative preference between two alternatives, is able to capture a great deal of information, and has proven to be extremely useful due to the fact that the AHP is somewhat scale independent [4]. Reasons defending this scale are the following [2]:

- The human ability to make qualitative distinctions is well represented by five attributes: equal, weak, strong, very strong, and absolute. Compromises between adjacent attributes can be made when greater precision is needed. The totality requires nine values and they may be consecutive;
- The human brain has a psychological limit for simultaneous comparisons of 7 ± 2 items. This mental capacity has something to do with the number of fingers. Therefore, a nine-point scale will be sufficient to do the comparisons between items.

The principle of hierarchic composition of synthesis is applied to multiply the local priorities of elements in a cluster by the global priority of the parent element, producing global priorities for the lowest level elements (the alternatives) [2].

AHP has many advantages over conventional scoring methods such as an increase in accuracy and consistency, and that the subjective consideration is quantified in a structured framework. However, the major drawback in the use of AHP is the effort required to make all pair-wise comparisons [5]. As the size of the hierarchy increases, the number of required pair-wise comparisons increases exponentially. Also the AHP is complex in terms of higher levels of detail required by the evaluators when asked for their preferences.

Let us see, in the next section, details of the procedure to follow in order to carry out an assets criticality analysis following AHP.

9.4.1 Case Study: AHP Applied to the Petrochemical Plant

In this example the decision making process behind the determination of the assets priority illustrates AHP and the associated mathematics used to derive weights and priorities. The process to follow to model the problem would be as follows:

1. *State the goal:*
   - Prioritize the equipment of a plant according to their criticality;
2. *Define the criteria:*
   - Failure frequency (FF);
   - Failure detection (FD);
   - Failure severity (FS);
   - Failure costs (FC);
3. *Identify the alternatives:*
   - Reactor (RE1);
   - Regenerator (RG1);
   - Separator (SP1);
   - Power R. train (TR1);
   - H. Gas Compressor (GC);
   - Pre-warming train (TH1);
   - Pressure control valve (PV1);
   - Boiler (B1);

Information in the first three steps can be arranged in a hierarchical tree as follows:

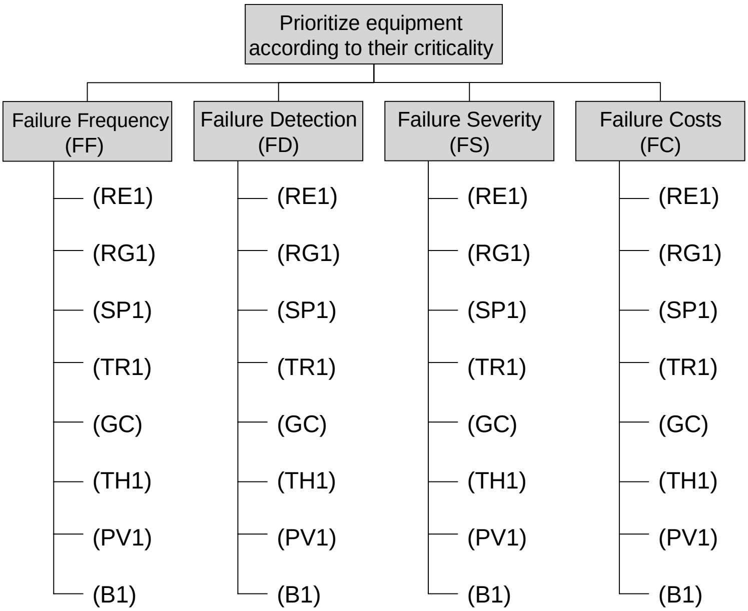

Figure 9.4. Equipment criticality decision hierarchy

4. *Define the scale for each criteria.* Notice that the defined scale for each criteria may require a search for certain equipment historical data. For instance, in order to score each equipment regarding FF criteria (see Table 9.9), a review of the equipment failure records will be required.

Table 9.9. FF criteria scale

FF	Failure frequency level	Level definition
10	Very high: Almost unavoidable	An occurrence each week
9		An occurrence each month
8	High: Continuously	An occurrence every three months
7		An occurrence every six months
6	Moderate: Occasionally	An occurrence every nine months
5		An occurrence every year
4	Low: Few failures	An occurrence every two to three years
3		An occurrence every four to six years
2	Remote: Failure very unlikely	An occurrence every seven to nine years
1		An occurrence every ten or more years

Failure detection (FD) criteria (Table 9.10) are more related to the protection, control and warning systems available for a safe detection of the failure events. In order to score certain equipment with respect to this criteria, information regarding aspects related to instrumentation, control, safety and protection systems will be required.

Table 9.10. FD criteria scale

FD	Failure detection (control) level	Level definition
10	Absolutely uncertain	Equipment is not inspected nor controlled. Failure events are not detected
9		
8		
7	Low	Control is reduced to visual inspection of the equipment
6		
5	Moderate	Equipment is statistically controlled and inspected. One inspection point. (25% automated inspection)
4		
3	High	Equipment is statistically controlled and inspected. Two inspection points (75% automated inspection)
2	Very high	Equipment is statistically controlled and inspected. Total inspection (100% automated inspection)
1	Totally controlled	Equipment is statistically controlled and inspected. Total inspection and permanent test equipment calibration (100% automated inspection)

Failure severity (FS) scale (Table 9.11) is related to the impact of equipment failures on safety, environment and operations. For the assessment of this criterion for the assets considered, it is necessary to know their potential failure effects within the existing operational context.

Table 9.11. FD criteria scale

FS	Failure Severity level	Level definition
10	Dangerously high	Failures may cause loss of human life
9		Failures may create complications with existing laws and regulations
8		Failures producing function loss and inoperable equipment
7	High	Failures causing important decrease in customer satisfaction
6		Failures impacting a production subsystem decreasing service quality
5	Low	Failures causing efficiency loss and customer complaint
4		Failures that can be avoided with minimal modifications and with low service impact
3	Very low	Failures creating small inefficiencies to the customer that the same customer could correct
2		Failures difficult to be recognized by the customer and whose effects are not significant for the process
1	Non-existent	Failures that cannot be detected by the customer and not impacting process efficiency

Finally failure cost (FC) scale (Table 9.12) is related to the economical impact of equipment failures on safety, environment and operations.

Table 9.12. FC criteria scale

FC	Failure costs level	Level definition
10	Dangerously high	Failures may cause high indemnification cost
9		
8	Very high	Failures causing total production loss
7		
6	High	Failures causing high maintenance direct cost – repair cost
5		
4	Moderate	Failures causing significant operation or maintenance cost
3		
2		
1	Very low	Failures causing no significant cost to production process

5. *Alternatives evaluation for each of the selected criteria.*

Table 9.13 presents this evaluation.

Table 9.13. Alternatives (assets) evaluation for each criteria

Asset	Criteria							
	FF	$\frac{FF_i}{\sum_i FF_i}$	***FD***	$\frac{FD_i}{\sum_i FD_i}$	***FS***	$\frac{FS_i}{\sum_i FS_i}$	***FC***	$\frac{FC_i}{\sum_i FC_i}$
(RA1)	2	0,0833	2	0,0606	**10**	0,2041	**10**	0,2000
(RG1)	2	0,0833	6	0,1818	6	0,1224	7	0,1400
(SP1)	3	0,1250	2	0,0606	2	0,0408	4	0,0800
(TR1)	**6**	0,2500	2	0,0606	9	0,1837	8	0,1600
(GC1)	2	0,0833	2	0,0606	5	0,1020	6	0,1200
(TH1)	1	0,0417	**8**	0,2424	2	0,0408	3	0,0600
(PV1)	5	0,2083	5	0,1515	6	0,1224	4	0,0800
(BO1)	3	0,1250	6	0,1818	9	0,1837	8	0,1600
Total	24		33		49		50	

6. *Quantify judgments on pair alternative criteria*. The quantified judgments on pairs of criteria alternatives, C_i and C_j, (criteria in our case study are FF, FD, FS and FC) are represented by an n-by-n matrix, known as a judgments matrix. This judgments matrix can be represented by

$$A=(a_{ij}) \tag{9.3}$$

The entries a_{ij} are defined by the following entry rules:

> **Rule 1**. If $a_{ij}=\alpha$, then $a_{ji}= 1/\alpha$, $\alpha\neq 0$;
> **Rule 2**. If the criteria C_i is judged to be of equal relative importance as criteria C_j, then $a_{ij}=a_{ji}=1$. Obviously $a_{ii}=1$ for all i.

Thus the matrix A has the form

$$A=\begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \tag{9.4}$$

where a_{ij} represents how many times the criteria C_i is more important for equipment criticality than criteria C_j (see Table 9.14 for our case study).

Table 9.14. The judgments matrix (A) for the criticality analysis

a_{ij}	FF	FD	FS	FC
FF	-	3	1	1
FD	1/3	-	1/2	1/3
FS	1	2	-	½
FC	1	3	2	-

7. *Determine the criteria weighting and its consistency*. Having recorded the quantified judgments of comparisons on pairs (C_i, C_j) as numerical entries a_{ij} in the matrix A, what is left is to assign to the n contingencies C_1, C_2, C_3, ..., C_n a set of numerical weights w_1, w_2, w_3,..., w_n that should reflect the recorded judgments.

Saaty proved that the eigenvector of the comparison matrix provides the best approximation to the priority ordering (weight) of the different criteria, and the eigenvalue is a measure of consistency (to find the priority vector or the weight of each factor included in the priority ranking analysis, the eigenvector corresponding to the maximum eigenvalue is to be determined from matrix analysis).

Consistency in the pair-wise comparison matrix means that when basic data is available, all other data can be logically deduced from them. For instance, if factor A_1 is three times more important than factor A_2, and factor A_1 is six times more important than factor A_3, then $A_1=3A_2$, and $A_1=6A_3$. It should follow that $3A_2=6A_3$ or $A_2=2A_3$ and $A_3=1/2A_2$. If the numerical value of the judgment (comparison) in the (2,3) position is different from 2, then the matrix would be inconsistent.

It is very difficult to identify "*n–1*" comparisons which relate all factors or activities and of which one is absolutely certain. It turns out that the consistency of a positive reciprocal matrix is equivalent to the requirement that its maximum eigenvalue λ_{max} should be equal to the number of factors "n". Then it is possible to estimate the inconsistency — consistency index (CI) — as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{9.5}$$

This index is further used to calculate the consistency rating (I_R) as detailed in [6]:

$$I_R = \frac{CI}{RI} \tag{9.6}$$

where RI is the random average value of CI for a n-by-n matrix. Values of RI are shown in Table 9.15 [2].

Table 9.15. RI values for matrices of different order (N)

N	1	2	3	4	5	6	7
RI	0	0	0.52	0.89	1.11	1.25	1.35

A consistency rating (I_R) of 0.10 or less is considered acceptable. In case of inconsistency the process of evaluation of the judgments matrix should be repeated. We have used the software Expert Choice ® (from Expert Choice, Inc. Arlington (VA) based leading provider of enterprise portfolio analysis software and services) to produce the results for weights and the consistency rating shown in Table 9.16:

Table 9.16. Criteria weights and I_R provided by Expert Choice ®

Criteria	Weight (w_i)
FF	0.302
FD	0.110
FS	0.230
FC	0.358
IR =	0.02

8. *Determine the final equipment criticality hierarchy.*

Table 9.17. Final hierarchy provided by Expert Choice

	Asset relative value × criteria weight				
Asset	$\frac{FF_i}{\sum_i FF_i} \times w_{FF}$ (1)	$\frac{FD_i}{\sum_i FD_i} \times w_{FD}$ (2)	$\frac{FS_i}{\sum_i FS_i} \times w_{FS}$ (3)	$\frac{FC_i}{\sum_i FC_i} \times w_{FC}$ (4)	Final Asset Hierarchy = (1)+(2)+(3)+(4)
(RA1)	0.0833 × 0.302	0.06060 × 0.11	0.20408 × 0.23	0.20 × 0.358	0.1504
(RG1)	0.0833 × 0.302	0.18181 × 0.11	0.12244 × 0.23	0.14 × 0.358	0.1234
(SP1)	0.1250 × 0.302	0.06060 × 0.11	0.04081 × 0.23	0.08 × 0.358	0.0824
(TR1)	0.2500 × 0.302	0.06060 × 0.11	0.18367 × 0.23	0.16 × 0.358	0.1817
(GC1)	0.0833 × 0.302	0.06060 × 0.11	0.10204 × 0.23	0.12 × 0.358	0.0983
(TH1)	0.0416 × 0.302	0.24242 × 0.11	0.04081 × 0.23	0.06 × 0.358	0.0701
(PV1)	0.2083 × 0.302	0.15151 × 0.11	0.12244 × 0.23	0.08 × 0.358	0.1364
(BO1)	0.1250 × 0.302	0.18181 × 0.11	0.18367 × 0.23	0.16 × 0.358	0.1572

Table 9.18. Final assets criticality ranking

Assets	Final hierarchy	Ranking
(TR1)	0.182	1
(BO1)	0.157	2
(RA1)	0.150	3
(PV1)	0.136	4
(RG1)	0.123	5
(GC1)	0.098	6
(SP1)	0.082	7
(TH1)	0.070	8

Calculations are carried out as in Table 9.17 and results are presented in Table 9.18

9.5 Maintenance Strategy Definition

As mentioned above, once there is a certain ranking of assets priority, we have to set up the strategy to follow with each category of assets. Of course, this strategy will be adjusted over time, and will consist of a course of action to address specific issues for the emerging critical items under the new business conditions.

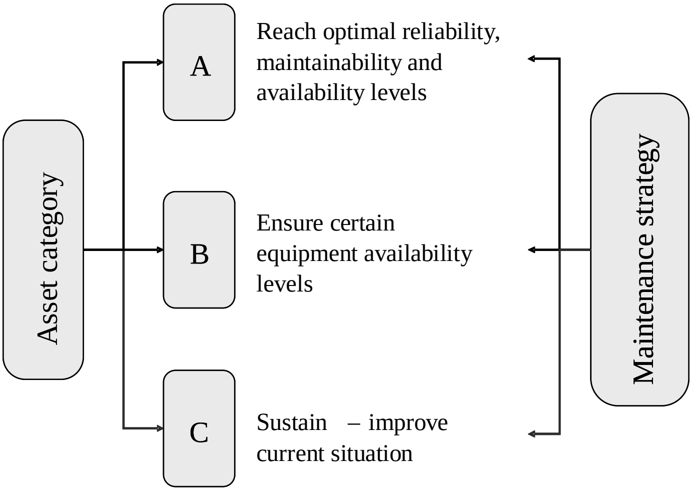

Figure 9.5. Example of maintenance strategy definition for different category assets

Let us try to exemplify this process of strategy definition by assuming that we have the assets classified according to three categories of criticality: A, B and C. This was the case for our example in Figure 9.1. But this could also correspond to the critical, semi-critical and non-critical categories that we also considered in previous example in Figure 9.2. In Figure 9.5 we define a maintenance strategy for each type of asset, which we then detail in Figures 9.6 — 9.8.

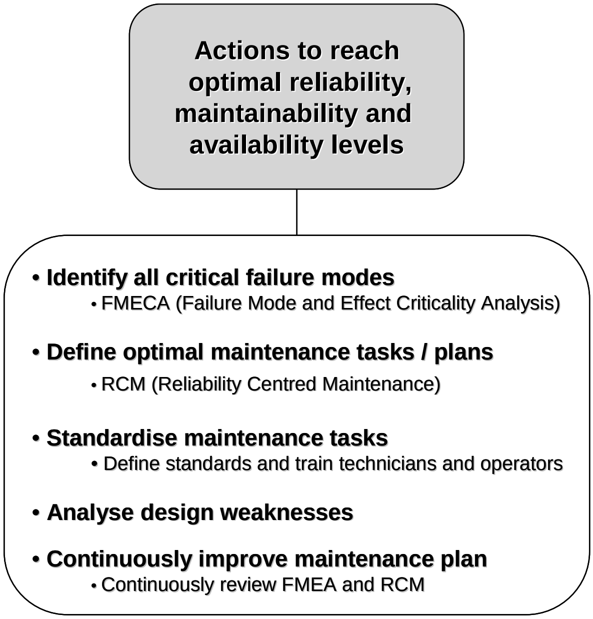

Figure 9.6. Example of detailed maintenance actions for category A assets

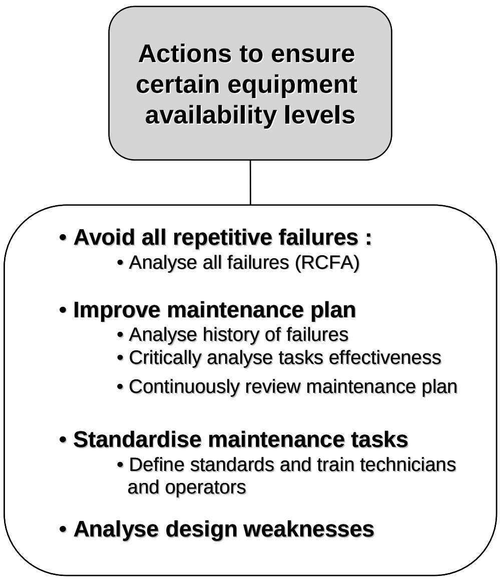

Figure 9.7. Example of detailed maintenance actions for category B assets

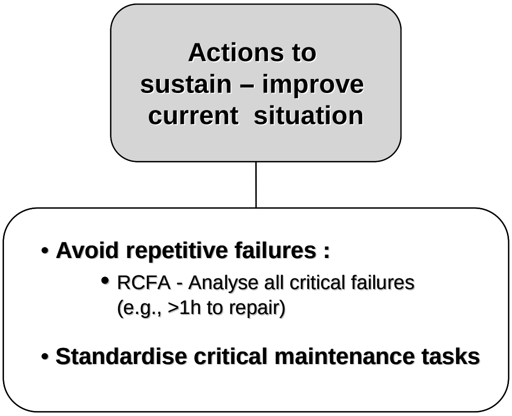

Figure 9.8. Example of detailed maintenance actions for category C assets

Note that the three last figures include a clear statement of maintenance strategic actions that will be carried out on each specific type of equipment or asset.

9.6 References

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10

Root Cause Failure Analysis (RCFA) for High Impact Weak Points

10.1 RCFA When and Why

The root cause of a failure can be defined as the most basic failure cause that can be reasonably identified and that management has control to fix [1].

Root Cause Failure Analysis (RCFA) is one of the basic reliability-enhancements methods that, when carried out using formal problem-solving techniques, and performed in a structured group with a facilitator, can be used very effectively [2]. This method consists of a series of actions taken to find out why a particular failure or problem exists and to correct those causes.

It is curious to note that, in general, RCFA is applied for important failures and accidents analysis, for high visibility events that require immediate action at the request of authority and when resources, time, and money are not an issue due to the level of management that is requesting the analyses to be carried out. While RCFA will be carried out under these circumstances, note that we are now proposing a different and more conventional use of this methodology.

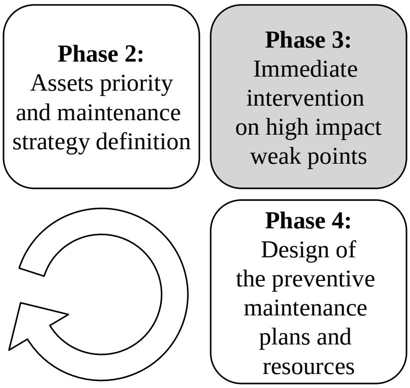

Figure 10.1. Phase 3 – immediate intervention on high impact weak points

When are we proposing to use this method? Studying Figure 10.1 and the current phase of our maintenance management model. At this point our assets have already been prioritized; we have characterised a certain maintenance strategy to follow for each assets priority category, and we are about to develop the corresponding maintenance actions associated each category of assets (for instance, we are about to begin an RCM program development).

At this point, implementing RFCA can be of major interest; we are trying to carry out a short-cut to reach immediate high impact reliability enhancements, but at the same time other significant benefits can be achieved.

Why is this activity really worth undertaking? The experience of many maintenance consultants and practitioners in general leads to a clear answer to this question. In most industrial environments it is common to find hidden deficiencies in management systems allowing human errors to remain unchecked, producing rare or strange assets behaviour regarding reliability (strange failures and rare mode of failures frequencies), corrupting reliability data and resulting, moreover, in ineffective preventive maintenance plan definitions.

By properly carrying out this phase, if the weak point analysis and the corresponding corrective actions are effective, we will not only obtain fast and relevant payback in terms of assets reliability enhancement, we will also ensure a very effective definition of our subsequent maintenance plan activities and we will improve the overall efficiency of the maintenance department.

10.2 RCFA Techniques in Literature

The majority of root causes analysis methodologies reviewed were essentially checklists of potential root cause factors to stimulate thought. These ‘checklists’ are presented in a number of forms (see for instance [3 — 5]) :

- As trees incorporating fault tree logic;
- As simple trees without fault tree logic;
- As lists with cross referencing systems ;
- As simple lists.

The analyst must work systematically through the ‘checklist’ and, first, judge whether the causal factors presented were applicable to the failure and, second, for those that are found to be applicable, whether they were necessary and sufficient to be one of the contributory causes of the failure.

In the book entitled ‘Guidelines for Investigating Chemical Process Incidents’ [6], a variety of root causes analysis methods are described for application in the process industry. These are categorised into four groups, namely:

1. *Deductive*. This approach involves reasoning from the general to the specific (*e.g*. Fault Tree Analysis or Causal Tree Method);
2. *Inductive*. This approach involves reasoning from individual cases to general conclusions, providing an overview approach (*e.g*. Cause-Effect Logic Diagram or HAZOP Analysis);

3. *Morphological.* This method is based upon the structure of the system being studied. Morphological approaches focus upon the potentially hazardous elements, concentrating primarily upon the factors having the most significant influence on safety (*e.g.* Accident Evolution and Barrier Technique and Work Safety Analysis);
4. *Non-systems Oriented Techniques.* Concepts and techniques that are not as comprehensive as systems oriented techniques mentioned above (*e.g.* Change Analysis [7], Human Error Probability Study [8]).

10.3 Failure Cause Characterization

Causes of failure can be classified as physical, human or latent:

- *The physical cause* is the reason why the asset failed, the technical explanation of why things broke or failed;
- *The human cause* includes the human errors (omission or commission) resulting in physical roots;
- *The latent cause* includes the deficiencies in the management systems that allow the human errors to continue unchecked (flaws in the systems and procedures). Latent failure causes will be of our main concern at this step of the process.

10.4 Failure Root Cause Analysis Method and Process

The root cause failure analysis method that is proposed here should include the following basic steps:

1. Select the RCFA team;
2. Identify the problems;
3. Determine the significance (impact) of the problems and estimate the expected effort of subsequent steps of your analysis for each problem. Plot results in the priority matrix, defined as in Figure 10.2. Start the analysis for those problems with highest significance and less expected effort to be solved;
4. Identify the physical cause of the problem. Formulate hypotheses, *i.e.* the technical explanations on why things failed according to the physical evidence that was found;
5. Determine, for each one of the validated hypotheses, the physical, human and latent root causes of the problem. Use or follow a RCFA logic tree as in Figure 10.3;
6. Propose recommendations, corrective actions, that can minimize, eliminate or mitigate the consequences of the failure events. Solutions should be sustained with any cost -benefit analysis;

7. Determine wether corrective actions have been effective in resolving problems. Corrective actions should be tracked to ensure that they have been properly implemented and are functioning as intended. The recurrence of the same or similar events must be identified and analysed. If an occurrence re-occurs, the original occurrence should be re-evaluated to determine why corrective actions were not effective.

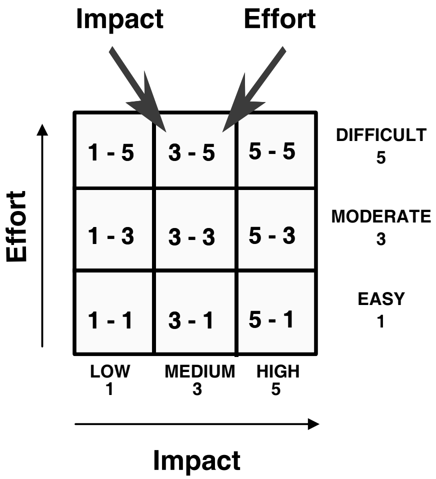

Figure 10.2. The problem priority matrix

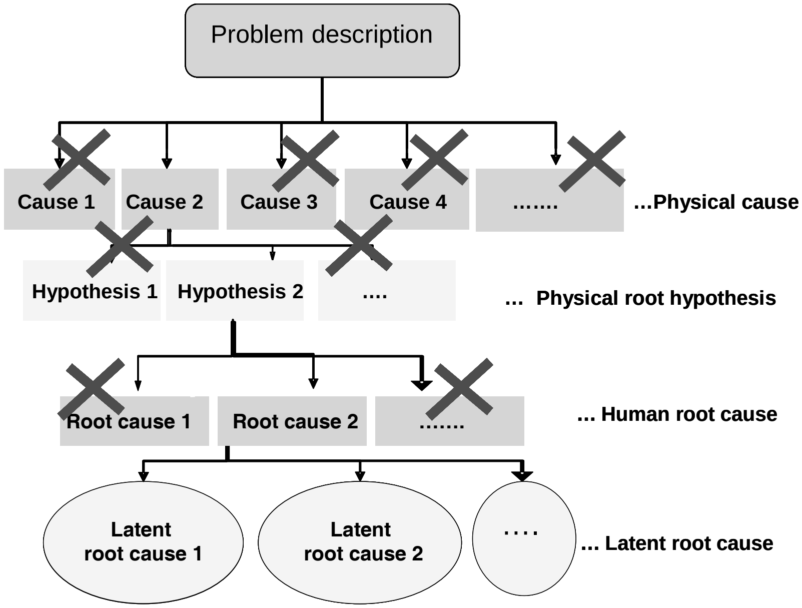

Figure 10.3. The RCFA logic tree

10.5 Case Study

Conveyors may sometimes become critical equipment. Wet and dirty conditions, besides non-existent, incorrect or inefficient maintenance, may cause for instance worn out drives and bearings. Conveyors are often neglected even when they are easy to maintain and repair. For instance, maintenance problems on pulp and paper industry conveyors can often be traced to system problems that are correctable. These problems need not be addressed by repeated repairs of the same symptom. Instead, they can be corrected at source. In addition, some problems within the mechanical system are very simple to correct if the source of the problem is found. The case that we present in Figure 10.4 addresses the issue of chronic problems with conveyor rollers. After the RCFA team started to address the issue, six possible physical causes of the roller problems were found. Among these causes, only one of them — stuck bearings — was found to show clear physical evidence.

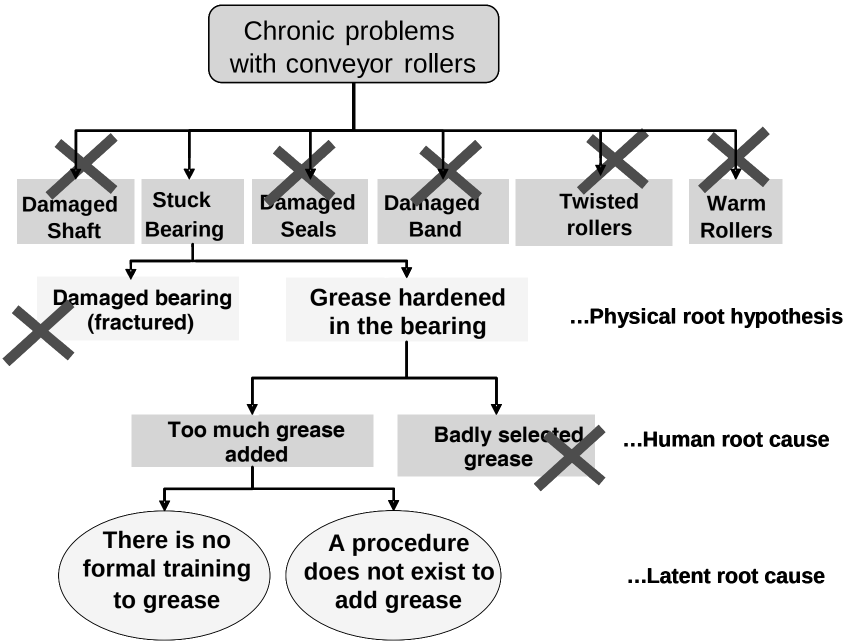

Figure 10.4. The RCFA logic tree, conveyors rollers problem analysis

Hypotheses regarding the possible cause of the stuck bearing problems were formulated. The team found that the hypothesis of "hardened grease in the bearing" was the correct physical root cause of the problem and that the human root cause for that was simply that "too much grease was added to the rollers when greased". In this example, the latent cause was related to the non-existence of formal training to grease and with the need for a written procedure to make sure the workers would carry out the work properly.

10.6 References

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11

A Method to Design the Maintenance Plan

11.1 An Introduction to RCM History

Reliability Centred Maintenance (RCM) originated during the late 1960s, as a joint effort of the North American government and the aeronautical industry [1]. The idea was to establish a logical process to design appropriate maintenance activities, with optimal frequency, to support new larger capacity and more complex aircraft as well as the size of airplane fleets. The purpose was to establish appropriate maintenance procedures allowing a reduction in maintenance stops, a decrease in the maintenance costs and an increase in flight security. As a result of this effort the document *"MSG-1: Maintenance Evaluation and Program Development"* was published, which formalised and established a new criteria for a maintenance program development.

The publication of the MSG-1 document changed the existing concept of maintenance policies design. Orientation changed from the evaluation of *team functions* to the analysis of *system functions.* Later, the MSG-2 document was published to generalize, throughout the aircraft industry, the use of the procedures development included in MSG-1. In this second document a simple but powerful tool named *logical decision tree* was integrated. A logical decision tree is a diagram that provides a sequence of questions about the series of possible events and their consequences, structured in a logical and hierarchical manner. Each question in the decision tree may only be answered with a YES or NO. The answer to each should lead to an action or to the next question in the sequence. This tree is similar to a logical road map. Each possible fault in the system is characterised by the application of the logical tree questions, leading the evaluator to the logical analysis ending upon obtaining a YES answer. At each NO answer, the evaluator continues with the next question of the sequence. If you reach the end of the tree, then the logical conclusion is that no action is necessary for the fault under evaluation. The MSG-2 document became a norm in the aircraft industry for the design and execution of maintenance, and contained the steps of what today is understood as reliability centred maintenance.

The success of RCM in the aircraft industry has had no precedents. In the 16-year period after its introduction, commercial airlines had no increase in unit maintenance costs, even though the size and complexity of the aircraft, as well as the labour costs increased during the same period. Likewise, during the same period, the safety records of the airlines improved considerably.

The benefit obtained by the aircraft industry was no secret and soon the RCM was adapted and introduced according to the needs of other industries, such as power generation, manufacturing, food processing, mining, military, *etc*. In all these industries successful results were observed in terms of availability increase and, at the same time, on maintenance costs savings. Some details of this method are still under development to adapt it to the changing needs of a wide variety of industries, although the basic principles are still maintained.

11.2 RCM Concept

RCM serves as a guide to identify maintenance activities with their respective frequencies in the most important elements of an operative context. This is not a mathematical formula; its success is based on the functional analysis of a certain operational context undertaken by a review team. The effort developed by the review team allows the generation of a flexible maintenance management system, adapted to the needs of real maintenance in the organization. Keeping in mind, personal security, environment, operations and benefit/cost reason [2].

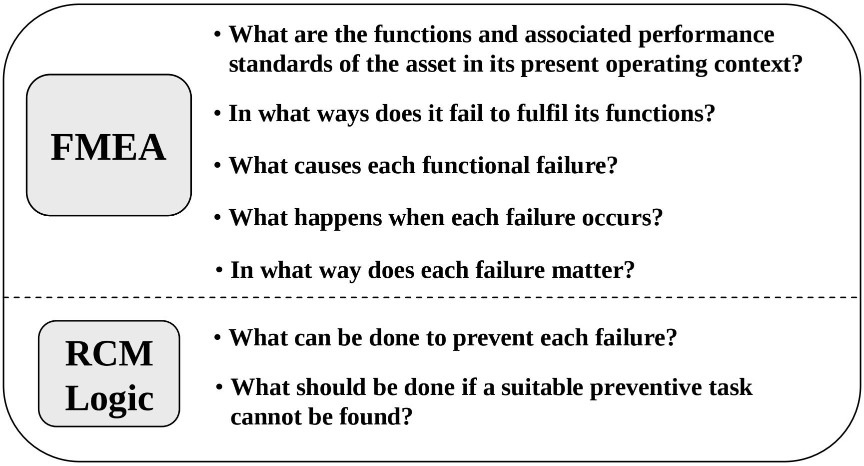

Figure 11.1. Seven key questions of RCM

As we said in Part 1 of this book, 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. RCM specifically allows: a) detection of failures early enough to ensure minimum interruptions to system's operation, b) elimination of 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 happen without any decrease in the system's safety. RCM methodology allows the identification of real maintenance needs starting from the analysis of the questions given in Figure 11.1.

11.3 RCM Implementation

11.3.1 The Process and the Review Team

Hereafter we present the proposed scheme for implementation of RCM. The success of this process will depend basically on the selection of the proper *RCM review team*. This team will have the responsibility of answering the seven basic questions of the RCM, according to the scheme in Figure 11.2.

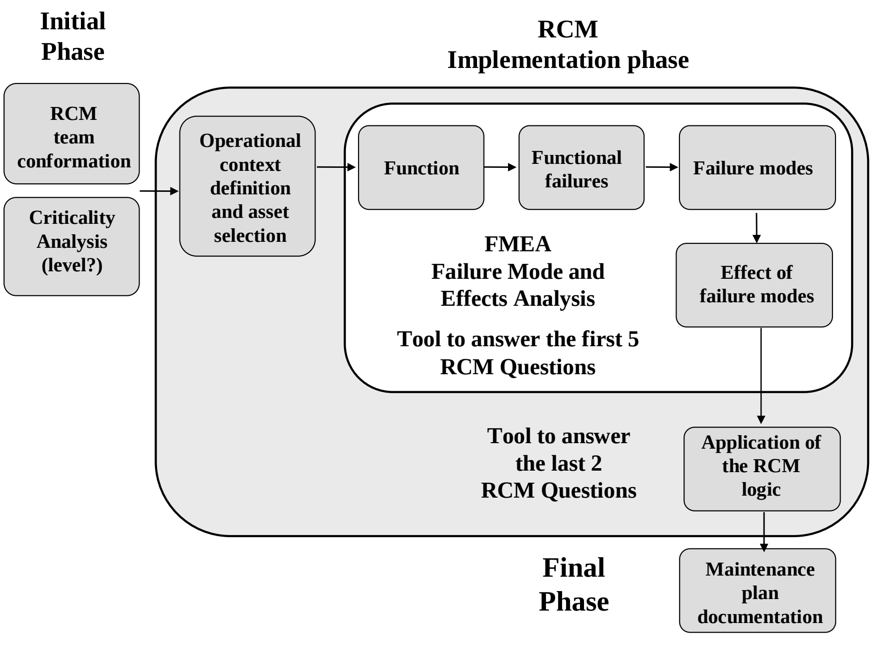

Figure 11.2. RCM implementation process

People with different functions in the organization (see Figure 11.3) will form the RCM review team. This team will work jointly for a certain period of time in a positive atmosphere, to analyse common problems with the different departments and with a common goal. The review team should have the following features:

- *Alignment.* Each member is involved with the team agreement. This demands that they all share the same mission and vision. They will make the best use of potential disagreements and conflicts in order to integrate each team member’s contribution, to reach effective solutions;

- *Commitment.* This feature means that members of the team assume the team commitment as their own. Leadership, management and coaching will be abilities of all the members;
- *Understanding*. This requires the ability to understand each others points of view, “get into the others shoes”, but without losing the perspective of operations reality;
- *Confidence.* Trust that all team members shall undertake their responsibilities in an optimal manner.

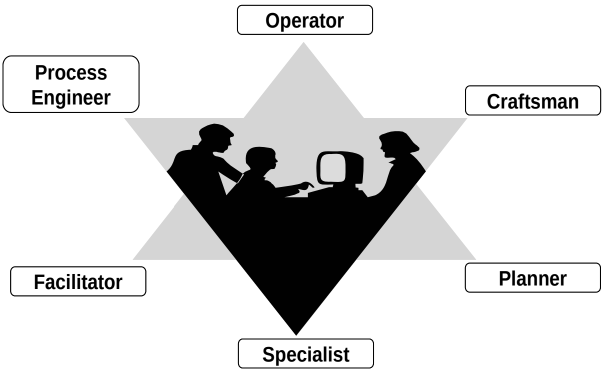

Figure 11.3. The RCM review team

The facilitator plays an important role in this team; his/her basic function consists in guiding and leading the implementation of the RCM process. In other words, the facilitator is in charge of ensuring that the implantation of the RCM process is done in an orderly and effective manner. The activities that the instructor should undertake are:

- Guide the review team during the failure modes and effects analysis (FMEA) and the selection of maintenance activities;
- Help to select the decision level to be used in the failure mode and effects analysis;
- Help to identify the critical assets that should be analysed under this methodology;
- Ensure that the work meetings are led in a professional manner;
- Ensure real consensus;
- Motivate the team;
- Ensure that all required information is in place when needed;
- Ensure that results are correctly recorded.

In order to fulfil his/her function, the profile and convenient knowledge areas for the facilitator are:

- Wide analysis capacity;
- High development of personality features (leadership, credibility, security and confidence);
- Abilities to lead work meetings (in communication);
- Basic theory of RCM;
- Technique to undertake Failure Modes and Effects Analysis (FMEA);
- Evaluation and selection technique of maintenance activities (Logical Decision Tree);
- Statistic analysis techniques (for reliability, availability and maintenance);
- Risk assessment techniques;
- Computer tools.

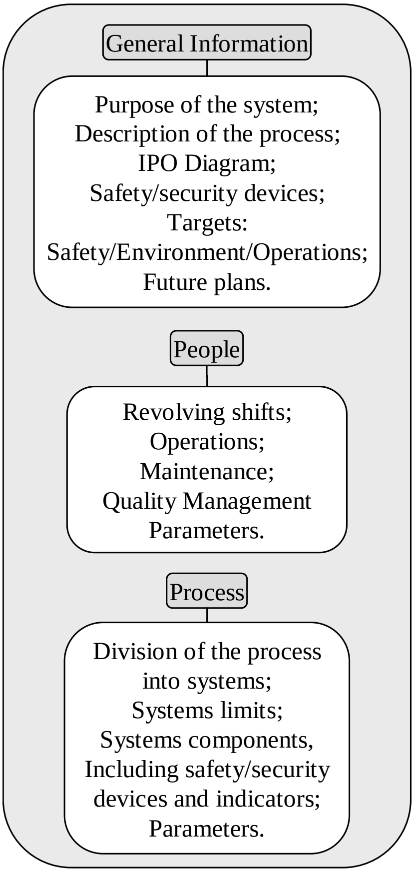

Figure 11.4. Operational context definition

11.3.2 System Selection and Definition of the Operational Context

The selection of the assets, systems or equipment where RCM will be applied can be carried out using techniques explained in the previous chapters. The correct definition of the operational context will be a requirement to do this phase properly. Operational context definition will require certain information to be gathered. This information can be grouped as in Figure 11.4.

A graphical tool that eases the visualization of the overall operational context is the IPO (Input—Process—Output) diagram, which can be synthesized and represented as in Figure 11.5.

In Figure 11.5, insumes are raw materials or resources to be transformed or converted. For instance: gas, crude, wood, *etc*. Services are other resources used, which are necessary for the transformation of the raw materials. For instance: electricity, water, steam, *etc*. Controls are a special type of input and output; they protect both the personnel as well as the process. This is done through special control equipment and its basic objective is to prevent any possible fault that may occur in the process starting from the specific control variables.

The process will be divided into systems that will have a certain function (or group of functions). Maintenance efforts will be then concentrated on each one of the systems functions.

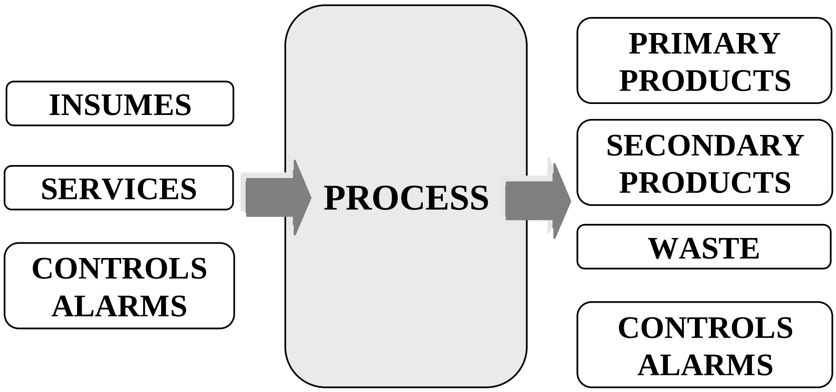

Figure 11.5. Input Process Output diagram (IPO)

11.4 Failure Mode and Effect Analysis (FMEA)

11.4.1 Introduction to the Methodology

FMEA is recognized as the most fundamental tool that is used in RCM. Due to its practical and qualitative approach, it is also the most widely understood and applied form of reliability and risk analysis found throughout industry. Given a specific process, FMEA deals with the identification of its failure modes, failure causes and frequencies (reliability), and the effects that might result if any specific failure occurs during the process operation (risk). Traditionally, FMEA has been a design tool, used extensively in the recognition and understanding of inherent design weaknesses. Based on the information provided by FMEA, design and management personnel are better informed about the way to determine what can be done in order to avoid or mitigate failure modes. This information also provides basic input to reliability models that can be used to predict and measure product reliability performance against specified targets and requirements.

How is a FMEA performed? First, it is essential to have a fairly good understanding of the equipment design and operation from the beginning. The FMEA process is followed in an orderly fashion that qualitatively considers the ways in which individual parts or assemblies in the equipment might fail [3]. These are the failure modes that we wish to list and they are physical states in which the equipment could be found. For example, a switch could be in a state where it can be either open or closed. The failure modes thus describe desired functions of the device, which have been lost. Alternatively, when sufficient knowledge is available, failure modes may be described in more specific terminology, such as jammed or broken actuating spring. Clearly, the more precise failure mode description, the more perception we have to enable us to decide how it may be eliminated, mitigated, or fixed.

Each failure mode is then evaluated for its effect. This is usually done by considering its local effect on the device with which it is directly involved both at the next higher level of assembly (*i.e.*, subsystem) and at the top level of assembly or product level (say, system or plant). It is usually more convenient to define two or three levels of assembly when evaluating failure effect in order to understand the consequence of the failure mode if it ever occurs. In this way, the analyst gets a bottom up view of the devices and failure modes that are important for the functional objectives of the overall system or product. Frequently, FMEA includes additional information for each failure mode. This additional information could include failure symptoms, failure detection and isolation steps, failure mechanism data, failure rate data on failure mode (not always available with the required accuracy) and the recommended corrective/mitigation action.

The FMEA process is divided into the following four steps [3]:

1. Description of functions;
2. Description of functional failures;
3. Failure modes (failure rate data) definition;
4. Description of failure mode effects.

11.4.2 Describing Functions

Each item or equipment usually has more than one function. They can be divided into five categories:

- *Primary Functions.* These are functions required to fulfil the intended purpose of the item. Simply stated, they are the reasons for the item to appear in the process;
- *Auxiliary Functions.* These are functions that support the primary function. Containing fluid is a typical example of an auxiliary function for a compressor. In many cases, the auxiliary functions are *more crucial* to safety than the primary functions;
- *Protective and Control Functions.* These are functions intended to control a process and protect people, equipment, or the environment;
- *Information Functions.* These are related to alarms, and the monitoring of several conditions;
- *Interface Functions.* These are functions that apply to the interface between two items. The interface may be active or passive. For example, a passive interface is present if an item is used as the support base for another item (oil cooler is supported by the base plate of the compressor which in turn is lubricated with the oil cooled by the heat exchanger).

An example of definition of functions for heat exchangers is shown in Table 11.1.

Table 11.1. FMEA example: functions description

FMEA Item: heat exchanger without change of phase	
Function type	Function description
Primary	- Provide correct heat exchange at a desired rate.
Auxiliary	- Contain cooling and heating fluids - Prevent mixing of cooling and heating fluid
Protective and control	- Prevent damage to heat exchanger and downstream equipment - Control the process
Information	- Condition monitoring
Interface	- Heat exchanger supports (oil cooler)

11.4.3 Defining Functional Failures

A functional failure is defined as the inability of the equipment to keep a desired standard of performance (function). Functional failures vary in degree of magnitude; for example, a pump may have no output or may have its output restricted. Consequently, functional failures have been divided into three categories of severity, which are defined as follows:

- *Catastrophic failure*. A failure that is both sudden and causes termination of one or more fundamental functions. It requires immediate corrective action in order to return the item to a satisfactory condition;
- *Degraded failure*. A failure which is gradual, partial or both. Such failure does not cease the fundamental functions, but compromises one or several functions. The function may be compromised by any combination of reduced, increased, or erratic outputs. Such type of failure may develop into a catastrophic failure;
- *Incipient failure.* An imperfection in the state or condition of an item or equipment. A degraded or catastrophic failure can be expected if corrective action is not taken.

An example of definition of functional failures for heat exchangers is shown in Table 11.2.

Table 11.2. FMEA example: functional failures

FMEA Item: Heat exchanger without change of phase		
Function	Function description	Functional failure
Primary	- Provide correct heat exchange at a desired rate	Unable to provide any heat /catastrophic
		Provide reduced/excessive heat exchange /degraded
Auxiliary	- Contain cooling and heating fluids	Unable to contain cooling and heating fluids / catastrophic
		Contain partially cooling and heating fluid /degraded
	- Prevent mixing of cooling and heating fluids	Unable to prevent mixing of fluids / catastrophic
		Partial mixing of fluids / incipient
Protective and control	- Control the process	Unable to control the process / catastrophic
	- Prevent damage to heat exchanger and downstream equipment	Unable to prevent damage to heat exchanger equipment / catastrophic
Information	- Condition monitoring	
Interface	- None	

11.4.4 Definition of the Failure Modes

A failure mode is defined, in RCM as the cause of the functional failure. Only failure modes with a high occurrence possibility are recorded. It is not recommended to list every single failure possibility. Reasonably likely failure modes include the following:

Table 11.3. FMEA example: failure mode

FMEA Item: Heat exchanger (HE) without change of phase				
Function	Function Description	Functional failure	Failure mode	MTTF months
Primary	- Provide correct heat exchange at a desired rate	Unable to provide any heat /catastrophic	Complete stoppage of fluid	--
			External rupture	--
		Provide reduce/excessive heat exchange /degraded	Partial reduction in fluid flow	--
			Partial external rupture	48
			Plugged	--
Auxiliary	- Contain cooling and heating fluids	Unable to contain cooling and heating fluids / catastrophic	External rupture	48
		Contain partially cooling and heating fluid /degraded	Partial external rupture	--
	- Prevent mixing of cooling and heating fluids	Unable to prevent mixing of fluids / catastrophic	Internal rupture	28
		Mixing partial of fluids / incipient	Partial internal rupture	18
Protective and control	- Control the process	Unable to control the process / catastrophic	Control system fail	6
	- Prevent damage to HE and downstream equipment	Unable to prevent damage to heat exchanger equipment / catastrophic	Support structure fails	72
Information	- Condition monitoring			
Interface	- None			

- Failures which have occurred before on the same or similar assets;
- Failures modes which are already the subject of preventive maintenance routines, and which would occur if no preventive maintenance is done;
- Any other failure modes that have not yet occurred, but nevertheless have a real possibility of occurrence.

Additionally, we need to estimate the mean time to failure (MTTF) for each failure mode. The MTTF is expressed as the expected mean time to failure expected of a given failure mode. In this case, the ideal situation is to have valid historical data for the equipment in the operational context. In most cases, plant-specific data is unavailable or may have a low reliability level to allow its use without corroborating it. The uncertainties of data selection can be reduced by learning as much possible about data sets, taxonomy, equipment boundaries, used equipment type, equipment design and construction, process medium, plant operation, maintenance programs, and failure modes. OREDA [4] and PERD [5], are examples of data sets that provide details of taxonomy, data origin, treatment, and limitations. An example of definition of failure modes and MTTF data for heat exchangers is shown in Table 11.3.

11.4.5 The Description of the Failure Modes Effects

The failure effects describe what would happen if the failure mode occurs, and are related to issues such as downtime, effects on product quality, evidence that the failure has occurred, and threats to safety and environment. The description of these effects should include all the information needed to support the evaluation of the consequences of the failure. When describing the effects of a failure, the following issues should be recorded:

- Evidence (if any) that the failure has occurred;
- Threats (if any) to safety or environment;
- Effects (if any) in production or operations;
- Physical damages (if any) caused by the failure;
- Repairs needed to correct the effects of the failure.

The impact that a failure mode has on the organization depends on the operating context of the asset, the performance standards, which apply to each function and the physical effects of each failure mode. This combination of context, standards and effects means that every failure has a specific set of consequences connected to it.

An example of failure mode effects definition for heat exchangers is shown in Table 11.4.

A complete example of failure modes and effects analysis for a coke furnace is shown in Figure 11.6 and Table 11.5.

Table 11.4. FMEA example: failure effects

FMEA Item: Heat exchanger without change of phase				
Function type and description	Functional failure	Failure mode	MTTF months	Effects of failure modes
Primary: - Provide correct heat exchange at a desired rate	Unable to provide any heat /catastrophic	Complete stoppage of fluid	--	Total loss of heat exchange /this failure has operational consequences
		External rupture	--	Total loss of heat exchange/this failure could have safety and environmental consequences
	Provide reduce/excessive heat exchange /degraded	Partial reduction in fluid flow	--	Partial loss of heat/ operational consequences
		Partial external rupture	48	Partial loss of heat/ operational consequences
		Plugged	--	Partial loss of heat / operational consequences
Auxiliary: - Contain cooling and heating fluids	Unable to contain cooling and heating fluids / catastrophic	External rupture	48	Major loss of process fluid to atmosphere /this failure could have safety and environmental consequences
	Contain partially cooling and heating fluid /degraded	Partial external rupture	--	Partial loss of process fluid to atmosphere/ safety and environmental consequences
Auxiliary: - Prevent mixing of cooling and heating fluids	Unable to prevent mixing of fluids / catastrophic	Internal rupture	28	Major leakage between media/operational consequences
	Mixing partial of fluids / incipient	Partial internal rupture	18	Leakage between media/ operational consequences

FMEA

Item: Process Systems / Coke Furnace

Description: Carbon steel vessels , vertically mounted stack

Application: Heating of Vacuum Residue from a blend of Zuata crudes

Operational Mode: Continuous

Internal environment : Coke Furnace is designed to be fired by fuel gas . A Fuel Gas K.O. drum, is provided to prevent any condensate from reaching the main fuel gas burners .

External environment : Generally outdoor

System Boundary:

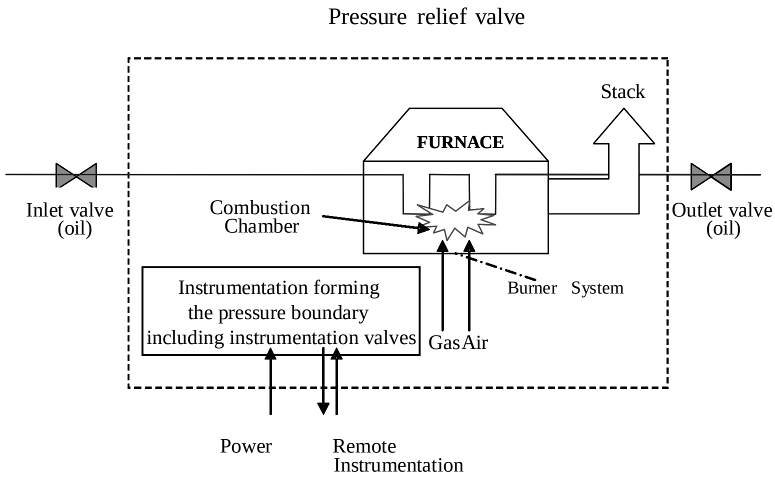

Figure 11.6. FMEA example: coke furnace / operational context

Table 11.5. FMEA - item: process system / coke furnace

Class of function	Function description	Functional failure	Failure mode	MTTF	Effects of failure modes
Primary	- Provide heat at a desired rate	Unable to provide any heat / catastrophic	Electrical system failure	40-48 months	Total loss of heating/this failure has operational consequences
			Complete stoppage of products for the combustion	This failure has not been reported	Total loss of heating/this failure has operational consequences
		Provide reduce heat /degraded	Partial reduction in fluid flow	This failure has not been reported	Partial loss of heating/ operational consequences
			Partial reduction in products for the combustion	This failure has not been reported	Partial loss of heating/ operational consequences
			Damage in radiant section caused by high temperature sulfurization	This failure has not been reported	This corrosion mechanism is manifested as a general uniform thinning and that could produce rupture in tubes and loss of heating / operational and safety consequences
			Damage in radiant section caused by sulfide stress corrosion cracking	This failure has not been reported MTTF expected > 10 years	Phenomenon is identified as the cracking of a material under the combined effects of stress and corrosion by H_2S. The combination of corrosive attack plus stress results in crack propagation. No prior warning or any physical change in size or appearance of the material, and could produce rupture in tubes / operational and safety consequences

Table 11.5. FMEA - item: process system / coke furnace (continued)

Class of function	Function description	Functional failure	Failure mode	MTTF	Effects of failure modes
			Damage in radiant section caused by carburization	This failure has not been reported MTTF expected >10 years	This phenomenon can result in a significant loss of fracture toughness in the furnace tubes
			Damage in radiant section caused by sulfidation	This failure has not been reported	This mechanism is manifested as a uniform thinning or localized pitting or thinning and could produce rupture in tubes and loss of heating / operational and safety consequences
			Damage in furnace housing by creep/stress	Not reported MTTF expected 10-15 years	This mechanism could produce rupture in furnace well / This failure could have safety and environmental consequences
			Partial failure in burner system	6-9 months	Partial loss of heating/ operational consequences
			Partial plugging (furnace tube)	6-9 months	Fluid flow is impeded due to a partial obstruction in the pipe (coke build up) / operational consequences
Auxiliary	- Conduct fluid from coker furnace to coker drum (transfer piping)	Conduct partially fluid/ degraded	Plugged (transfer piping)	Failure has not been reported MTTF expected 10-15 years	Fluid flow is impeded due to an obstruction in the pipe (coke build up) / operational consequences
			Partial rupture in transfer piping caused by high temp. Sulfurization	This failure has not been reported MTTF expected 10-15 years	This corrosion mechanism is manifested as a general uniform thinning and could produce rupture in tubes and loss of heating / operational and safety consequences

Table 11.5. FMEA - item: process system / coke furnace (continued)

Class of function	Function description	Functional failure	Failure mode	MTTF	Effects of failure modes
	- Conduct blast-furnace gas to atmosphere	Unable to conduct / degraded	Stack system fails	This failure has not been reported MTTF expected 10-15 years	Partial loss of combustion process – decreasing efficiency / operational consequences
			Stack damper fails	72 months	Partial loss of combustion process – decreasing efficiency / operational consequences
Protective and control	- Control the process	Loss of control the process / degraded	Control system fail (three way valves)	6-9 months	Failures could result from a change in the process/ operational consequences. Tendency is to improve: present value: 1 failure per year
	- Prevent damage to furnace and downstream equipment	Unable to prevent damage to furnace and downstream equipment / catastrophic	Structure of support fail	This failure has not been reported	Failures could result in damage at any point or elsewhere in the furnace/safety and operational consequences
Information	- Provide correct information about the conditions of process (temperature, pressure, *etc.*)	Unable to provide correct information (temperature, pressure, flow)	Condition monitoring system Fail	10 months	Decrease or loss of monitoring function that could result in a failure to perform a primary, auxiliary or protective function
Interface	None				

11.5 RCM and the Hidden Failure Modes

11.5.1 RCM and the Hidden Failures

Equipment, in most cases, has more than one function. When one of these functions fails and someone may notice the failure or the fault state of the equipment, failures are said to be evident. However, in some occasions, no one knows that the equipment is in fault state unless another failure takes place. The first failure, the one that remained unnoticed until another took place, was not evident on its own. These are know as hidden failures.

To be able to understand this, suppose you have two pumps in a given operational context. Pump C (reserve pump) is not available (fault state), this fact shall not be evident under normal circumstances, since pump B is working under normal operation. In other words, the fault/failure of pump C shall not have any direct impact on its own unless or until pump B also fails.

Pump C failure will not be evident under normal operating conditions unless other failures do occur. Notice that failures in pump C will only have some consequence if another failure – in this case in pump B - also takes place. When pump C is in fault state, the failure in pump B is known as a multiple failure. Regarding this point, the review team must know that all sole hidden failures will not have any direct consequences; however, they shall have an indirect consequence increasing the risk level of multiple faults/failures. “The only consequence of a hidden failure is the consequent increase of a multiple failure”.

For this type of failure consequences, maintenance activities helping to prevent, or at least reduce, the consequences of multiple failures should be selected; this means that the review team should focus its effort to prevent hidden failures in the analysis, and by doing so, diminishing the possible consequences of multiple failures.

11.5.2 Hidden Failures and Their Maintenance

The appearance of hidden failures, on their own, are not evident, in the normal operation process; therefore in order to identify or recognize hidden faults, the RCM review team should answer the following question:

If the functional failure is caused by a failure mode on its own,
is it evident under normal operation conditions?

If the answer to the question is NO, the failure mode is a hidden failure (not evident), and if the answer is YES, the mode is evident. When equipment fulfils the protection function (which is hidden), it works basically in the following manner:

- Alerting the operators of abnormal conditions;
- Stopping the equipment at the time the fault takes place;
- Eliminating or easing abnormal consequences that may take place immediately after the appearance of the failure (consequences that would cause greater harm, in case no protection equipment existed).;
- Preventing the development of dangerous situations.

In general, the typical study of the hidden functions include the following equipment: medical emergency equipment, most of the detection equipment, fire protection and prevention equipment, overload and over-voltage protection equipment, the components of redundant structures, systems for emergency stop and most of the emergency power generators.

11.5.3 Maintenance Actions to Prevent Multiple Failures Caused by Hidden Failure Modes

One of the ways to aid in the reduction of the possible effects of a multiple failure is to try to reduce the possibility of occurrence of hidden faults, periodically checking if a hidden function is working correctly. These revisions/checks are known as hidden fault investigation.

All hidden fault investigations are basically a set of inspections of the hidden functions, over regular periods of time, with the idea of detecting if these hidden functions are under normal operating conditions or at fault state.

The introduction of hidden faults investigation tasks is basically orientated towards protection equipment and to systems components such as electrical circuits or control instruments. Checking must be under real operation or simulated operation conditions. Function checks should be able to reduce the possibility of occurrence of any multiple failure to an acceptable level and should be done at comfortable time periods. The hidden fault revision task will be effective only if we ensure to reach the desired availability for such hidden function.

However, there are situations where we may experience problems; carrying out these checks for instance:

- When a hidden function of equipment may not be checked without destroying the equipment itself (such as the case of the protection fuses or rupture disks);
- When it is impossible to access hidden functions (a problem related to the design);
- Where it is really difficult to simulate real operation conditions of the active with hidden functions.

When a hidden fault revision task is not technically feasible, there are possible actions to be undertaken:

- If the hidden fault mode may generate a multiple failure, and that affects safety or the environment, redesign is compulsory;
- If the hidden fault mode generates a multiple failure that does not affect safety or the environment, it is advisable not to undergo any programmed maintained activity, and it is possible to think of redesigning, if the consequences are overtly costly.

11.6 Selection of Maintenance Activities Within RCM

11.6.1 The Determination of the Consequences of a Failure Mode

Once the FMEA has been done, the RCM team should select the maintenance activity targeted to each previously identified failure mode, starting at the RCM low decision tree (RCM that leads the selection of the most adequate maintenance actions to prevent the appearance of a failure mode or decrease its possible effects). After the selection of the maintenance action following the RCM logic, we also have to specify its frequency of execution.

The first step for the selection of maintenance actions requires the identification of the failure modes consequences, proceeding as in Figure 11.7.

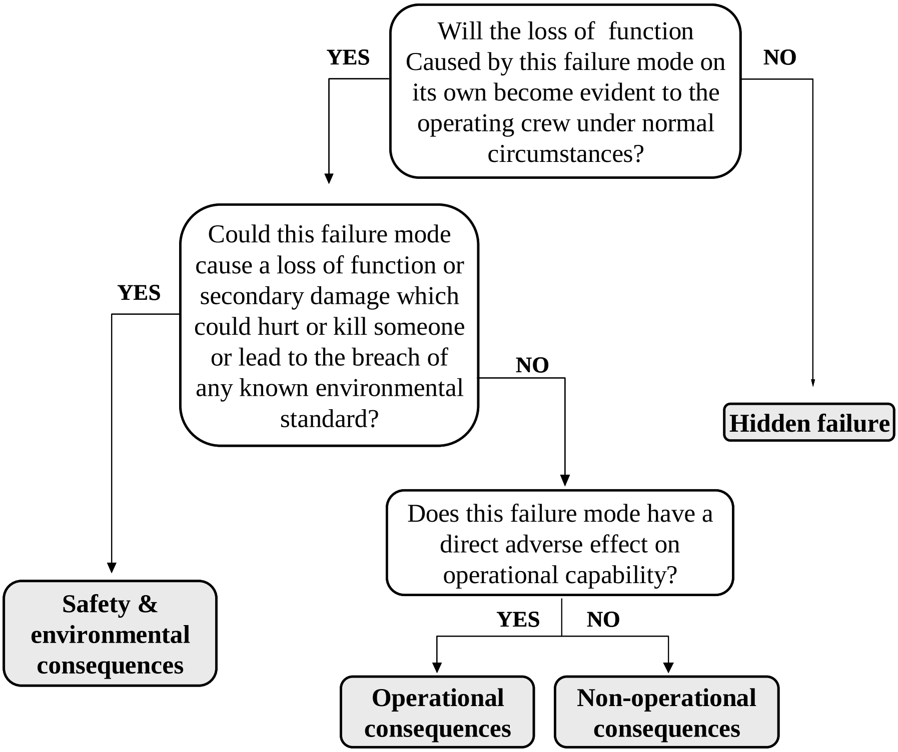

Figure 11.7. Consequences of failure modes

Once the consequences of failure mode are identified, the RCM team should identify the type of maintenance action by using the RCM logic (see Figure 11.8).

RCM classifies maintenance activities to be undertaken within two large groups, preventive and corrective activities; the latter are undertaken only in such cases where no other effective preventive action is possible. Each group of activities has its corresponding maintenance tasks, which are mentioned hereafter.

11.6.2 Preventive Activities

11.6.2.1 Condition Based Maintenance Actions

Many preventive maintenance activities can be based on the equipment condition. This is due to the fact that the equipment conditions do not change instantaneously when the failure takes place (function loss), but they normally follow a certain continuous deterioration process during a period of time. A potential failure can then be defined as an identifiable physical equipment condition that indicates that a functional failure is about to happen, or is happening, during the process. The moment in time when it is possible to detect the occurrence of a functional failure, or that a failure is about to occur, is known as the potential failure time. Common examples of potential failures are:

- Vibration readings indicating imminent bearings failure;
- Existing cracks in metals indicating imminent failure due to fatigue;
- Oil particles in any gearbox, indicating imminent faults due to excessive teeth wearout;
- Hot spots indicating deterioration/wearing of the isolating material in a boiler, *etc*.

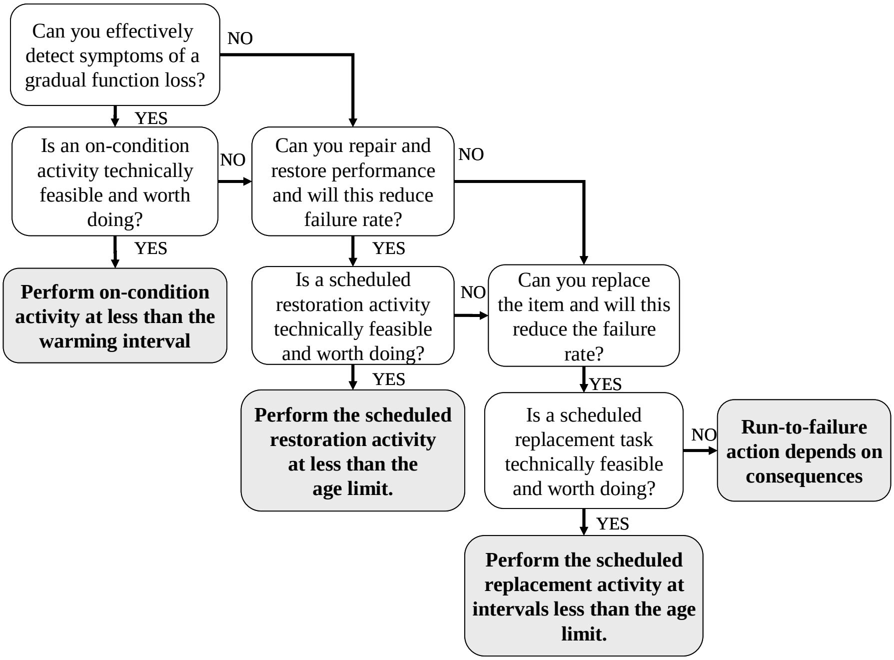

Figure 11.8. RCM logic

The behaviour over time of the equipment condition is illustrated in Figure 11.9. This figure shows how a certain equipment condition that starts to deteriorate (beginning point “I”; often this point may not be detected); then this condition reaches a point when the failure may be detected (potential failure point “P”); finally, if the failure is not detected nor corrected the equipment condition gets to a point where the functional failure takes place (point “F”, where the equipment does not fulfil the function any longer).

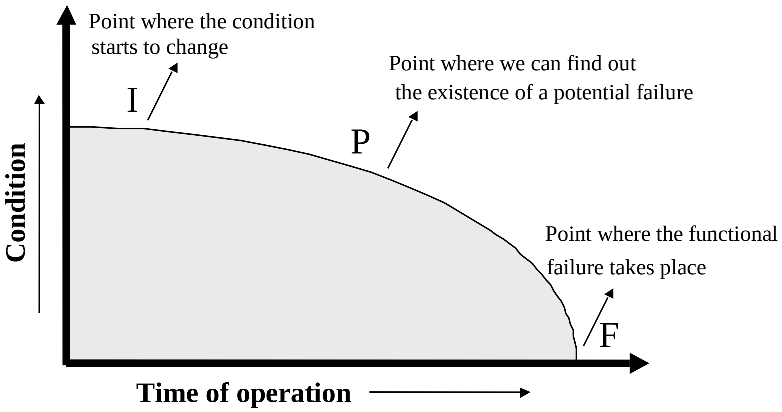

Figure 11.9. Behaviour curve of potential faults

11.6.2.2 Scheduled Restoration Actions

These are periodical activities carried out to restore a part of an item (system, equipment, part) to its original condition. Of course the time interval between two consecutive scheduled actions will be shorter than the operative life limit of the item part to be restored. During this type of preventive maintenance action, items are taken out of service, unarmed, put aside and inspected in a general manner, corrected and replaced if necessary, in order to prevent the appearance of possible failure modes. In case of large equipment or systems, these scheduled restoration tasks are generally known as “overhauls” and they are common in equipment such as compressors, turbines, broiler, furnaces, engines, *etc*. Restoration includes different actions such as: adjustment, inspection, improvement, cleaning, restoration and even replacement.

11.6.2.3 Scheduled Replacement Actions

This type of preventive action is oriented to change a used part of an item with a new one. Again the time interval between two consecutive replacement actions will be shorter than the operative life limit of the item part to be replaced. Normally, we replace —discard— simple items and restore complex ones.

11.6.2.4 Revisions Searching for Hidden Faults
The hidden fault modes are not evident under normal operation conditions. In order to reduce the possible existence of hidden faults we have to check, periodically, whether hidden functions are working correctly. These checks are known as revision tasks for hidden faults.

11.6.3 Corrective Activities

When preventive activities are not technically feasible, or they are ineffective, for a certain failure mode, corrective activities shall be those that apply. Possible corrective actions can be as below.

11.6.3.1 Redesign
In the case that one may not find preventive actions reducing consequences of a failure mode to an acceptable level, a re-design will be necessary.

11.6.3.2 Non-programmed Maintenance Activities
In the case that there are no preventive activities available less costly than the possible failure mode effects, the decision to wait for a failure or act in a corrective manner may be taken.

11.7 Concluding Remarks

RCM methodology provides an important decision-making tool to quantify risk and reliability in terms of the severity of the consequences and the frequency of occurrence (mean time to failure – MTTF). The severity of the consequences will be evaluated by considering the environment in which the failure mode occurs. To evaluate MTTF of the failure mode, the analyst must have an understanding of failure mode rates data, their origin and limitations. By using the results of an FMEA, analysts are better equipped to answer questions such as: "Which of several candidate systems poses the least risk?" "Are risk reduction modifications necessary?" and, "Which modifications would be most effective in reducing risk or increasing reliability?"

For a system, particularly when the effects of failure are serious (safety and environment, reputation, high warranty costs, *etc*.) the analysis should take into account all failures modes of all systems. The RCM should be started as soon as the initial design information is available. It should be performed iteratively as the design evolves, so that the analysis can be used to influence the design and to provide documentation of the eventually complete design. Design options should be separately analysed, so that reliability and risk implications can be considered when deciding the right option to choose.

RCMs can be used effectively for several purposes, besides identifying safety or reliability failure modes and effects. The organizations can use RCMs for:

- Preparation of diagnostic routines such as flowcharts or fault-finding tables. FMEA provides a convenient listing of failure modes, which produce particular failure effects, or symptoms, and their relative likelihood of occurrence;
- Preparation of preventive maintenance requirements. The effects and mean time to failures can be considered in relation to the need for scheduled inspection, servicing or replacement;
- Retention as formal records of the safety and reliability analysis, to be used as evidence if required in reports to customers or in product safety litigation.

Finally, it is important to coordinate these activities, so that the most effective use can be made of RMCs in all of them, and to ensure that RCMs are available at the right time and to the right people.

11.8 References

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12

Models to Deal with Maintenance Capacity Planning

12.1 Models for Maintenance Resources Management

Carrying out maintenance activities requires the utilization of different types of resources. Spare parts and materials, skilled manpower, tools, instruments of diverse type and even money, are examples of maintenance resources.

The management of these resources simultaneously, their planning so that the correct quantity of every resource is available in the time and form that is needed, turns most cases into an arduous task for which many organizations are not prepared. As a consequence, some of these organizations will incur a series of costs derived from the excessive possession of certain resources that are not necessary, whereas at the same time, the lack of other essential ones will lead to serious losses in their operations and a definitive decrease in the quality of service that they offer to their clients. Therefore, the activity of maintenance resources management can be considered as a critical activity for the maintenance function in an organization.

In the following sections of this chapter we review different techniques and methods, of major application, for the management of maintenance resources. It is not the intention to offer an exhaustive revision of all the existing methods, but to provide concise principles of those major applications found in literature and in the real life experience.

12.2 Maintenance Staff Planning and Scheduling

At the present time, an elevated number of maintenance tasks require highly qualified personnel. To carry out many of these tasks requires the presence of specialists with different skills (*i.e.* welders, instrumentalists, mechanics, *etc*.). It is also common that the maintenance tasks are carried out by groups of technicians or maintenance teams, with a suitable mixture of the necessary skills that are required according to the production environment.

Under these circumstances, there will be occasions where the assignment of the maintenance tasks will not be as efficient as it could be, since obviously not all the specialists would be needed in equal quantities of time. A solution might be to schedule the individual activity of every technician, instead of the collective activities, but in certain environments this is not possible due to the existence of laws, or specific regulations regarding safety, that prevent the accomplishment of certain works by only one person (this happens, for example, in the maintenance of fleets for mineral extraction). Another solution might be to promote the polyvalency of the maintenance workers, which has its limitations commonly related to the technological level of the equipment to be maintained.

After raising the dilemma that we face in this section, let us see a more detailed classification of the problems to deal with, and then comment on each of the existing tools, in common use, for their resolution.

The problems to deal with can be classified as follows:

1. Determination of the maintenance workload. Classified by skills;
2. Determination of the ideal number of maintenance workers, and skills, in our organization;
2. Determination of the maintenance teams schedules. This is equivalent to the resolution of the following problem: What is the quantity of normal hours, extra hours, and hours to be contracted with external companies, that will be necessary?

Obviously, in order to be able to solve these problems, we will have to balance properly cost and availability of each one of the resources at any time.

When problems 1 and 2 of the previous list are put together, they describe the maintenance capacity planning problem as considered by classical production and maintenance literature. The main concern of this problem is related to the determination of the labour force to address the corrective maintenance work that may arise in a plant, generally assuming that the preventive maintenance was previously reasonably planned once the plant master production schedule was known. If the size of the maintenance team devoted to equipment repair is small, new machines that break down must wait for service and the cost associated with downtime will grow with the delay. Of course we can reduce the chance that this will happen by increasing the size of the team, but this solution also costs money and will increase the amount of the time that the team will be idle, waiting for breakdowns to occur. The problem is therefore one of striking a balance between the downtime cost of the equipment and the idle time cost of the maintenance staff. There are two common approaches to deal with this problem:

- *Analytical models.* At this point, queue theory models are the most commonly used models. These models determine the maintenance staff using the criteria of minimizing the total cost of the unavailability of the productive equipment, together with minimizing the cost of the manpower [1]. The utilization of these models requires the knowledge of the rate of failures (the so-called rate of arrival in the queue theory models), and the distribution of the time to repair, or corrective maintenance time. Other analytical models to deal with this problem such as Linear Programming models can also be used [2], although many authors of these models recognize that it is very complex to treat the general maintenance capacity planning problem in a single optimization model including all aspects of the problem [2];

- *Monte Carlo Simulation models*. A more general approach than the previously mentioned analytical models can be based on stochastic simulation [3]. The idea of this method is the generation of certain random and discrete events in a computer model in order to create a realistic scenario of the system. Then, the simulation will be carried out in the computer, and estimates will be made for the desired measures of performance [4]. The simulation will be then treated as a series of real experiments, and statistical inference will be then used to estimate confidence intervals for the desired performance metrics.

  Examples of the utilization of these techniques can be found in Baker *et al.* [5]; they determine the ideal number of maintenance workmen for a plant with a finite number of identical equipment, using discrete probability distributions obtained with field data —for the times to repair and times to failures— and using FIFO maintenance service criteria for the machines with breakdowns. Also Barnett and Blundell [6] use this type of simulation to optimize the number of maintenance teams and the size of those teams assuming that demand for different types of skills are generated (electrical, mechanical and static equipment). In this case, the optimality criteria was also to minimize the cost of manpower and the total cost of repair.

Problem 3 of the above-mentioned list has been normally classified according to its time horizon. For instance Duffuaa [2] classifies the maintenance scheduling problems in three different groups:

- Short term. Daily routing scheduling;
- Medium term. Scheduling maintenance activities in shut down or a large job and;
- Long term. Scheduling preventive maintenance for a large number of production units.

Models to deal with the maintenance scheduling problems will be reviewed in Chapter 14.

12.2.1 Queuing Theory Models for Birth-and-death Processes

In this section we review the basic principles of queuing theory in order to use these principles later, for the resolution of the maintenance capacity planning problem. We will first introduce the reader to the Homogeneous Poisson Processes (HPP), then we will present the birth-and-death processes (B&DP) as a particular case of the HPP for which, under some assumptions, we can calculate their steady state. The determination of the steady state of the B&DP, besides the application of certain laws that will be introduced, will allow us to estimate a complete set of process performance measures with important practical implications.

Queuing processes can be modelled as continuous time stochastic processes with a discrete number of states. The process changes when new customers enter the system or leave it [7]. If we assume that the times between two consecutive arrivals are independent random variables with equal distribution functions, we say that the arrival process is a "renewal process". When the distribution function is exponential, the process is said to be an homogeneous Poisson process (HPP).

In a Poisson process:

1. The process has no memory. The number of occurrences in $[t_o,t_o+t]$ is independent of the previous history of the phenomena;
2. The probability of n arrivals in a certain time interval depends on the length of the time interval, but not on the initial time of the interval;
3. The probability that an element arrives in dt has the order of dt and it is proportional to the interval length (see Equation 12.1).

$$p_1(t)=\lambda dt \tag{12.1}$$

where λ is the average number of arrivals per unit time (arrival rate). With *dt* suficiently small we have

$$p_1(t)+ p_o(t)=1 \tag{12.2}$$

$$p_n(t) = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \tag{12.3}$$

Poisson processes, because of their definition, have properties that are interesting to us, for instance:

- Reproductive property. If we mix *n* independent Poisson processes, the result is another Poisson process which has an arrival rate equal to the sum of the rates of the processes considered;
- Divisible character. That is to say, if the arrivals are ruled by a Poisson process of rate λ and every arrival is directed to a certain subsystem *i* with probability p_i, with $i=1, \ldots, n$, then each of the subsystems is a Poisson process with arrival rates $\lambda p_1, \lambda p_2, \ldots \lambda p_n$;
- If a phenomenon of arrivals is obtained from a great number of renovation independent processes, the above-mentioned process it is approximately a Poisson process, at least in intervals of time of short duration in comparison with the times between arrivals of the individual processes.

Then, assume that we have an HPP. Suppose a system's situation can be defined by a discrete set of states $E_0, E_1, \ldots, E_n$. Consider that, in *dt*, only transitions among contiguous states are possible. Suppose that each of the states is defined as follows:

E_k: state in which k elements exist in the system (see Figure 12.1)

Then, assume that we have the following state transition probabilities:

$$p(E_k \rightarrow E_{k-1}) = \mu_k dt \quad (12.4)$$

$$p(E_k \rightarrow E_{k+1}) = \lambda_k dt \quad (12.5)$$

$$p(E_k \rightarrow E_k) = 1 - (\mu_k + \lambda_k) dt \quad (12.6)$$

where λ_k and μ_k are the arrrival rate and service rate, respectively, when the system is in E_k.

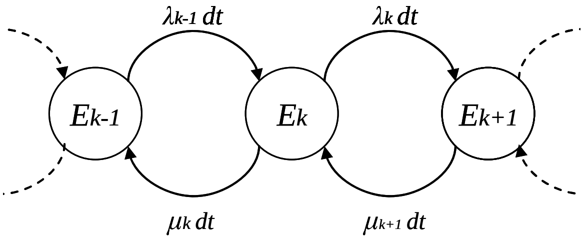

Figure 12.1. State transitions diagram

Then, the probabilities that the system has to be in every state can be calculated from the following system of differential equations (Equations 12.7—12.9):

$$\frac{dp_0(t)}{dt} = -\lambda_0 p_0(t) + \mu_1 p_1(t) \quad (12.7)$$

$$\frac{dp_k(t)}{dt} = \lambda_{k-1} p_{k-1}(t) + \mu_{k+1} p_{k+1}(t) - (\lambda_k p_k(t) + \mu_k p_k(t)), \text{ with } 0<k\leq n-1 \quad (12.8)$$

$$\frac{dp_n(t)}{dt} = \lambda_{n-1} p_{n-1}(t) - \mu_n p_n(t) \quad (12.9)$$

If we assume, as we do by definition, that the process is ergodic and homogeneous, there exists a stationary distribution of the state probabilities (Markov chain) that can be calculated by equalizing previous derivatives to zero:

$$\lambda_0 p_0(t) = \mu_1 p_1(t) \quad (12.10)$$

$$\lambda_{k-1} p_{k-1}(t) + \mu_{k+1} p_{k+1}(t) = \lambda_k p_k(t) + \mu_k p_k(t) \text{ , with } 0<k\leq n-1 \quad (12.11)$$

$$\lambda_{n-1} p_{n-1}(t) = \mu_n p_n(t) \tag{12.12}$$

with the following additional condition:

$$\sum_{i=0}^{i=n} p_i = 1 \tag{12.13}$$

Hence we get

$$p_k = \frac{\lambda_0 \lambda_1 \ldots \lambda_{k-1}}{\mu_1 \mu_2 \ldots \mu_k} p_0 \quad \text{, with } 0<k\leq n \tag{12.14}$$

$$\sum_{i=0}^{i=n} p_i = 1 \tag{12.15}$$

and thus we can obtain p_o, as follows:

$$p_0 = \left[1 + \frac{\lambda_0}{\mu_1} + \frac{\lambda_0 \lambda_1}{\mu_1 \mu_2} + \ldots + \frac{\lambda_0 \lambda_1 \ldots \lambda_{k-1}}{\mu_1 \mu_2 \ldots \mu_k} + \ldots \right]^{-1} \tag{12.16}$$

Let us now consider a particular case of the HPP called *birth and death process* (B&DP). In these processes we assume that:

- Arrrival rates and service rates are equal regardless the state of the system. *i.e.* $\lambda_k = \lambda$ and $\mu_k = \mu$, $\forall\, k$;
- The arrival time and the service time are distributed exponentially (we will use the notation E/E/1, due to Kendall. The form of this notation is X/Y/S, where X is the distribution of the time between arrivals, Y is the service time distribution and S is the number of servers. X and Y will be E — exponential — or M — Markovian — for the exponential distribution, G — generic — for a generic distribution and D for a constant).

For the birth-and-death processes Equation (12.16) turns out to be

$$p_n = \left(\frac{\lambda}{\mu} \right)^n p_0 = \rho^n p_0 \, , \quad \text{with } \rho = \frac{\lambda}{\mu} \quad (\rho\text{: utilization factor}) \tag{12.17}$$

At the same time, if we use Equation (12.15) we get

$$\sum_{i=0}^{i=\infty} p_i = p_0 \sum_{i=0}^{i=\infty} \rho^i = 1 \tag{12.18}$$

If $\rho<1$, the following geometric series in Equation (12.18) converges to

$$\sum_{i=0}^{i=\infty} \rho^i = \frac{1}{1-\rho} \tag{12.19}$$

Then, if we substitute Equation (12.19) in Equation (12.18) we find the steady state solution of the B&DP as follows:.

$$p_0 \frac{1}{1-\rho} = 1 \quad \Rightarrow \quad p_0 = 1-\rho, \text{ and } p_n = (1-\rho)\rho^n \tag{12.20}$$

Note that if $\rho \geq 1$ then $\lambda \geq \mu$ and the queue would increase over time.

Once we have the probabilities for the steady state, we can calculate the expected number of customers for the E/E/1 problem, waiting to be served in the queue — at steady state. Let N be the number of customers in the queue, including the one in service. Hence, the expected number of customers $E[N]$ is given by (see Figure 12.2)

$$E[N] = \sum_{i=0}^{i=\infty} i \cdot p_i = p_0 \sum_{i=0}^{i=\infty} i \cdot \rho^i = (1-\rho)\sum_{i=0}^{i=\infty} i \cdot \rho^i = \frac{\rho}{1-\rho} \tag{12.21}$$

The above proof is based on the sum of the following modified geometric series:

$$\sum_{i=0}^{i=\infty} i \cdot \rho^i = \rho \frac{\partial}{\partial \rho} \sum_{i=0}^{i=\infty} \rho^i = \rho \frac{\partial}{\partial \rho} \frac{1}{1-\rho} = \frac{\rho}{(1-\rho)^2} \tag{12.22}$$

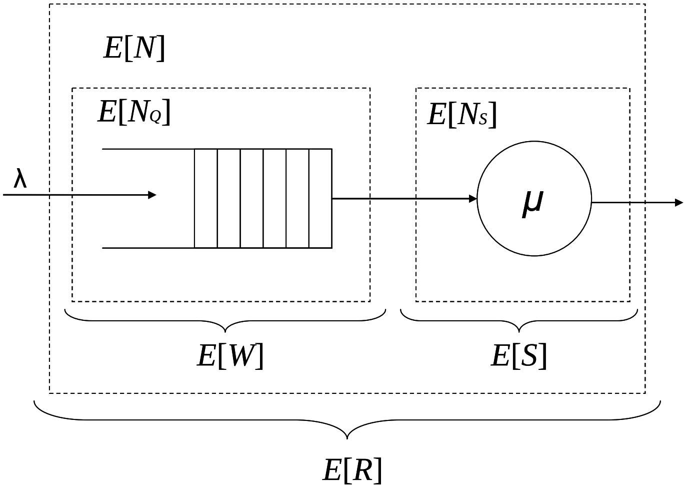

Figure 12.2. Notation used in this section and queue representation

At the MIT, the title of *Institute Professor* is given to a small number of members of the faculty with extraordinary records of achievement. A MIT Institute Professor, John D.C. Little, provided a mathematical proof — known as Little's Law — for a relationship that links the expected response time of the queue — expected time spent in the system — $E[R]$ and the expected number of customers $E[N]$. This relationship is proven [8] to be as follows:

$$E[N] = \lambda \cdot E[R] \tag{12.23}$$

Hence

$$E[R] = \lambda^{-1} E[N] = \frac{1}{\lambda}\frac{1}{1-\rho} = \frac{1/\mu}{1-\rho} \tag{12.24}$$

From Equation (12.24) the expected response time $E[R]$ can be interpreted as the ratio between the mean service time ($1/\mu$) and the probability of the server to be idle ($1-\rho$). But let us continue obtaining performance measures of the E/E/1 problem. Let us define the waiting time $W=R-S$ as the time a customer waits in the queue before service, where R is the response time and S the service time. Then the expected waiting time $E[W]$ is given by

$$E[W] = E[R] - E[S] = \frac{1}{\mu(1-\rho)} - \frac{1}{\mu} = \frac{\rho}{\mu \cdot (1-\rho)} \tag{12.25}$$

Note how, if we know the expected waiting time in the line, we can again use the Little's Law to calculate the expected number of customers in the line (only the ones waiting to be served), as follows:

$$E[N_Q] = \lambda \cdot E[W] = \frac{\rho^2}{(1-\rho)} \tag{12.26}$$

and the expected number of customers in service is

$$E[N_S] = E[N] - E[N_Q] = \rho \tag{12.27}$$

That must be coincident with the result obtained by applying Little's Law to the server only:

$$E[N_S] = \lambda \cdot E[S] = \frac{\lambda}{\mu} = \rho \tag{12.28}$$

12.2.1.1 Case Study

Earthmoving Ltd is a mining company that, for the exploitation of a new quarry of large proportions, has recently acquired a great number of identical dumper trucks, each of which uses the same model of diesel engine. The zone of the quarry is isolated, and companies offering technical services for the mentioned engines are not located near by. The maintenance of the engines has become a problem that Earthmoving has to face. The company has also decided to carry out a study of the future maintenance needs in order to evaluate the personnel requirement for the accomplishment of the project. The company has decided to hire a pair of technicians initially and would like to know:

1. Their expected utilization of the maintenance technicians;
2. The average number of dumpers unavailable because they are waiting to be repaired;
3. The average downtime of a dumper that waits to be repaired.

Time between failures and time to repair failures was researched and it was found that both times were exponentially distributed. The average time between failures was found to be one failure every 10 h of engine operation (λ=1/10), and the mean time to repair was 8 h (μ=1/8). Then, the utilization factor is

$$\rho = \frac{\lambda}{\mu} = \frac{1/10}{1/8} = \frac{8}{10} = 0.8$$

That means that 20% of the time the pair of technicians will be idle.

The average number of dumpers unavailable, waiting to be repaired, can be calculated using Equation (12.26):

$$E[N_Q] = \frac{\rho^2}{(1-\rho)} = \frac{(8/10)^2}{(1-8/10)} = 3.2 \text{ dumpers}$$

The average downtime of a dumper waiting to be repaired can also be calculated using Equation (12.25):

$$E[W] = \frac{\rho}{\mu\cdot(1-\rho)} = \frac{8/10}{1/8\,(1-8/10)} = 32 \text{ h}$$

Let us now suppose that the same company tries to determine the best number of engine mechanics to minimize the total costs of dumper maintenance and unavailability.

Assume that the cost of an hour of the engine mechanic is 30 €/h and that the cost of unavailability of the dumper is 40 €/h

The company would proceed with the following calculations.

❖ *Total cost of two mechanics:*

Manpower cost per hour = 2 mechanics x 30 €/h	= 60.0 €/h
Unavailability cost per hour = 3.2 dumpers x 40 €/h dumper	= 128.0 €/h
Total cost per hour	= 188.0 €/h

❖ *Total cost of four mechanics:*

$$\rho = \frac{\lambda}{M\mu} = \frac{\lambda}{\mu'} = \frac{1/10}{2\ 1/8} = \frac{8}{20} = 0.4$$

$$E[N_Q] = \frac{\rho^2}{(1-\rho)} = \frac{(8/20)^2}{(1-8/20)} = 0.27 \text{ dumpers}$$

Notice that increasing the number of pairs of mechanics (*M*) from one pair to two, duplicates the repair speed and maintenance capacity, but diminished the maintenance crew utilization proportionally.

Manpower cost per hour = 4 mechanics x 30 €/h	= 120.0 €/h
Unavailability cost per hour = 0.27 dumpers x 40 €/h dumper	= 10.8 €/h
Total cost per hour	= 138.8 €/h

❖ *Total cost of six mechanics:*

$$\rho = \frac{\lambda}{M\mu} = \frac{\lambda}{\mu'} = \frac{1/10}{3\ 1/8} = \frac{8}{30} = 0.27$$

$$E[N_Q] = \frac{\rho^2}{(1-\rho)} = \frac{(8/30)^2}{(1-8/30)} = 0.1 \text{ dumpers}$$

Manpower cost per hour = 6 mechanics x 30 €/h	= 180.0 €/h
Unavailability cost per hour = 0.1 dumpers x 40 €/h dumper	= 4.0 €/h
Total cost per hour	= 184.0 €/h

❖ *Summary of results*

Designing a four mechanics maintenance team, in two pairs of mechanics, minimizes the total cost of the company, as can be appreciated in Figure 12.3, where results are presented with mechanics pairs varying from 1 to 4. In Figure 12.4 the results obtained for the maintenance crew utilization *vs* the queue length are presented. Notice that when new pair of mechanics are added the decrease in the queue length is not linear.

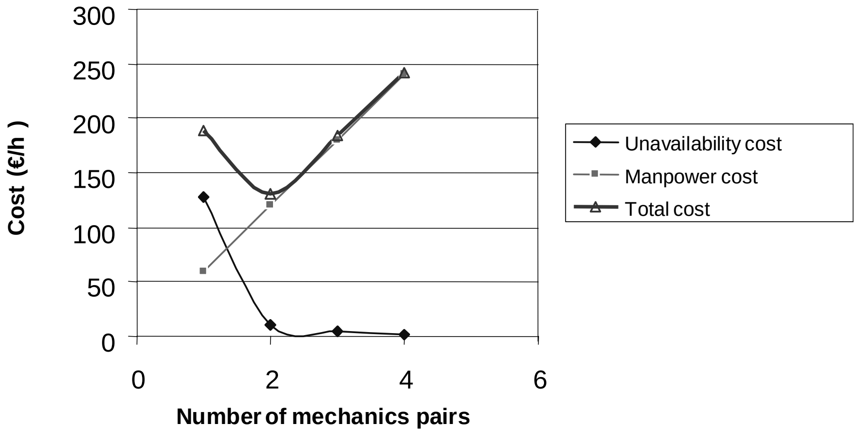

Figure 12.3. Total fleet cost as a function of the number of mechanics pairs

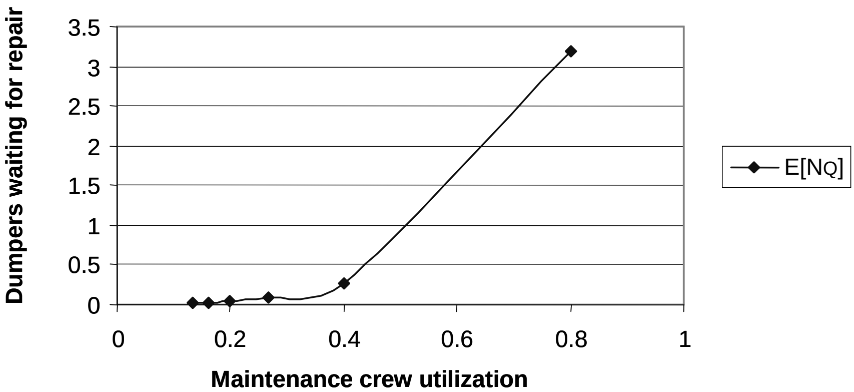

Figure 12.4. Maintenance crew utilization *vs* number of dumpers unavailable in the queue

12.2.2 Monte Carlo Simulation Models

In this section we will first explain the interest in using Monte Carlo stochastic modelling for maintenance capacity planning, where we discuss the pros and cons of this approach. Then, and with the intention of illustrating the modelling process, we will present an application of this methodology to the resolution of the problem that was discussed in the previous section.

As was previously mentioned in Section 12.2, the idea of this method is the generation of certain random and discrete events in a computer model in order to create a realistic lifetime scenario of the system. Therefore the simulation of the system's life process will be carried out in the computer, and estimates will be made for the desired measures of performance [4].

The events can be simulated either with variable time increments — *discrete event simulation* — or with fixed time increments, at equidistant points of time — *continuous time simulation* (the reader is referred to Pidd [9] for a discussion regarding both simulation practices).

The Monte Carlo simulation method allows us to consider various relevant aspects of systems operation which cannot be easily captured by analytical models such as K-out-of-N, redundancies, stand-by nodes, aging, preventive maintenance, deteriorating repairs, repair teams or component repair priorities. By doing so, we can avoid restrictive modelling assumptions that had to be introduced to fit the models to the numerical methods available for their solution, at the cost of drifting away from the actual system operation and at the risk of obtaining sometimes dangerous misleading results [10].

The weak point of the Monte Carlo method is the computing time [11], especially when the search space for the control variables of the problem to test increases.

12.2.2.1 Case Study

The dumpers fleet maintenance capacity planning problem in Section 12.2.1.1 will now be solved using continuous time stochastic simulation techniques. This simulation will evaluate the system state every constant time interval (Δt), the new system state will be recorded and statistics collected. We will consider chronological issues by simulating the number of dumpers to be maintained at any time. Then the time is incremented another Δt, and so on. As a simulation tool we will use VENSIM [12], which has special features to facilitate Monte Carlo type of simulation experiments, and to provide confidence interval estimations.

Notation of the model will be as follows:

- System status information related variables:

$N(Q)_t$: Dumpers waiting to be repaired at t;
$N(S)_t$: Dumpers being repaired at t;
NAR_t : Arrival (1 yes, 0 no) of a new dumper to be repaired in period t;
STR_t : A dumper starts to be repaired (1 yes, 0 no) in period t;
FNR_t : A dumper repair is finished (1 yes, 0 no) in period t;
RN_t : Random number, within the interval (0, 1), generated in t;
EUC_t : Total equipment unavailability cost per unit time in t;
MPC_t : Total manpower cost per unit time in t;
TC_t : Total cost per unit time in t;

- Model parameters:

λ : Failure rate of the entire fleet of dumpers;
μ : Service rate of team with a pair of technicians;

M : Number of teams in the maintenance crew;
uc : Unavailability hourly cost;
mc : Manpower hourly cost.

The process first requires modelling the number of dumpers waiting to be repaired $N(Q)_t$:

$N(Q)_t = N(Q)_{t-1} + NAR_t - STR_t$, with the following initial condition: (12.29)

$$N(Q)_0 = 0 \tag{12.30}$$

Then we model the number of dumpers being repaired — $N(S)_t$:

$N(S)_t = N(S)_{t-1} + STR_t - FNR_t$, with the initial condition (12.31)

$$N(S)_0 = 0 \tag{12.32}$$

A new dumper will need repair when the following condition is fulfilled:

$$NAR_t = \begin{cases} 1 & , if\ \lambda \geq RN_t \\ 0 & ,otherwise \end{cases} \tag{12.33}$$

A dumper starts to be repaired when the following condition is fulfilled:

$$STR_t = \begin{cases} 1 & , if\ N(Q)_t \geq o\ and\ N(S)_t = 0 \\ 0 & , otherwise \end{cases} \tag{12.34}$$

A dumper repair will be finished according to the following equation:

$$FNR_t = STR_{t-1/\mu'}, \qquad \text{with } \mu' = M \cdot \mu \tag{12.35}$$

Finally, cost equations can be defined as follows:

$$EUC_t = uc \cdot N(Q)_t \tag{12.36}$$

$$MPC_t = mc \cdot 2 \cdot M \tag{12.37}$$

$$TC_t = EUC_t + MPC_t \tag{12.38}$$

Note that MPC_t is considered constant for each siulation in this model.

Previous equations can be represented graphically, building a stock and flow diagram with VENSIM software, as shown in Figure 12.5. In this diagram, $N(Q)_t$ and $N(S)_t$ are modelled as stock variables; NAR_t, STR_t and FNR_t are flow variables, changing the conditions of the stocks; RN_t, EUC_t, MPC_t and TC_t are considered auxiliary variables; finally, the remaining variables in the diagram are understood as parameters of the simulation model.

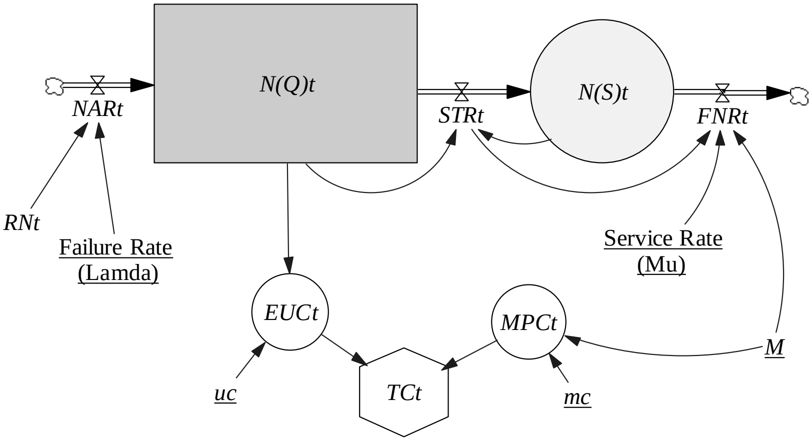

Figure 12.5. Stock and flow diagram of the dumpers maintenance problem

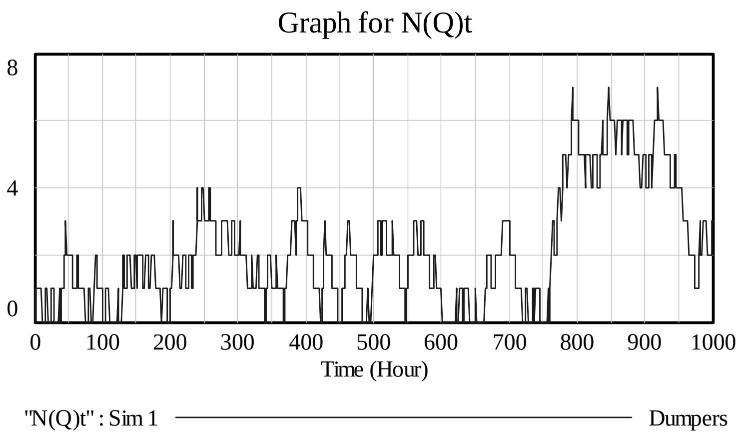

Figure 12.6. Sample simulation results for *N(Q)t*

Figure 12.6 shows the behaviour of the queue of dumpers waiting to be repaired over time. Note that for this particular example of data, the queue never reached a number higher than eight dumpers to be repaired. In Figure 12.7 we can see the convergence of the mean value of that variable over time for a simulation horizon of 50,000 h, and for three different seeds for the random numbers generation.

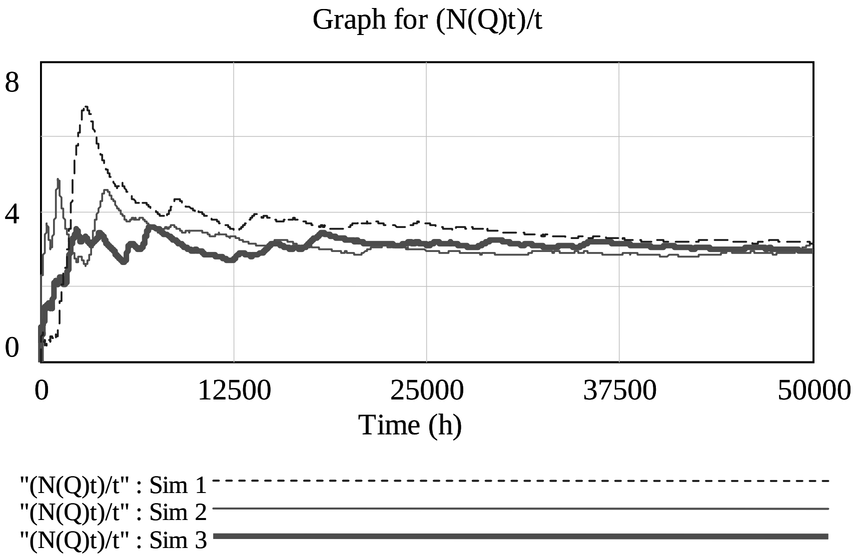

Figure 12.7. Convergence of the *N(Q)t* average value over time

Numerical values for the variables after 50,000 h, and, for the *M=1* case, are presented in Table 12.1, where we can see wich were the maximum and minimum values for the variables considered during the simulation horizon, as well as their mean and median values during that time.

Table 12.1. Sample of statistics provided by the software for the M=1 case

Variable	Min	Max	Mean	Median
N(Q)t	0.00	16.00	3.11	2.00
N(S)t	0.00	1.00	0.79	1.00
EUCt	0.00	640.00	124.21	80.00
MPCt	60.00	60.00	60.00	60.00
TCt	60.00	700.00	184.21	140.00

The comparison of the results obtained through Monte Carlo simulation *vs* those calculated previously using the Queue Theory analytical models are presented in Figure 12.8. We can appreciate that those results are basically idential and lead to the same final decision concerning the number of mechanics teams to have (*M=2*).

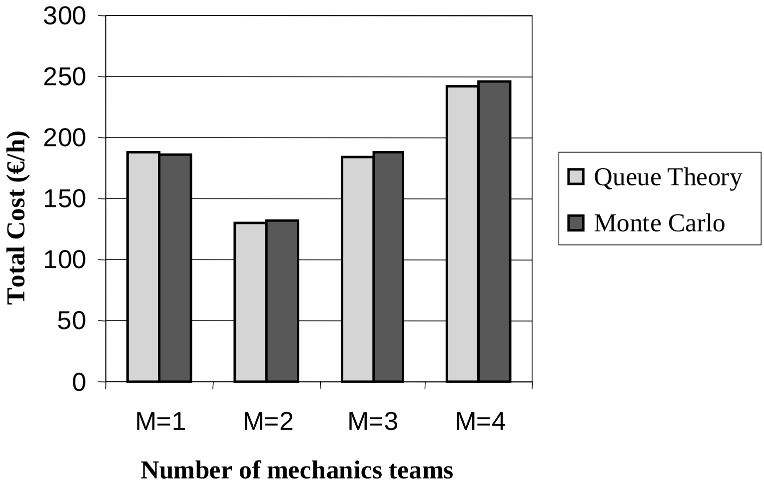

Figure 12.8. Comparison of results obtained with the two different approach

12.3 Maintenance Materials Requirements Planning

Keeping spare parts and other maintenance materials in inventory requires an important financial effort for many organizations. By holding this inventory companies ensure a certain level of equipment availability and reduce risk, but that effort has a cost that is often difficult to estimate. The components of maintenance inventory driven cost can be classified as follows:

- Inventory holding costs:
  - Capital cost of money tied up in inventory. Although there are always important components with an elevated acquisition cost, this cost is not high for many other parts and components for which multiple small disseminated warehouses traditionally appear in the factories;
  - Physical cost of having the inventory (warehouse space costs, storage taxes, insurance, information systems, rework, breakage, spoilage);
- Component price devaluation costs. Many components may drop in price during their life cycle, and the penalties for holding excess parts when a price drop occurrs could be important to consider;
- Component obsolescence costs. End-of-life write-offs. Many parts that are held in stock could be useless for the maintenance department after certain equipment/asset removal or replacement;
- Inventory ordering cost. Cost associated with an order released to the maintenance parts/materials suppliers. In the case of scheduled maintenance parts, many materials may be purchased in small quantities,

with high frequency, according to the preventive work orders schedule. In case of corrective maintenance, last-minute purchases done by the corrective work reponsible person are common;

- Stock-out costs. Risk increase associated to the lack of maintenance inventory when needed (lost production, accidents, environmental risk, *etc*.). Normally, the production time that is lost when a stock-out happens is very difficult to recover afterwards.

Investments in maintenance materials, as any other investment in a company, can be justified according to the return they may produce on said investment. In order to do an analysis [13] we may use the Return On Net Assets (RONA) ratio (Figure12.9) and translate to that formula the influence of the previously mentioned elements of the maintenance inventory-driven cost.

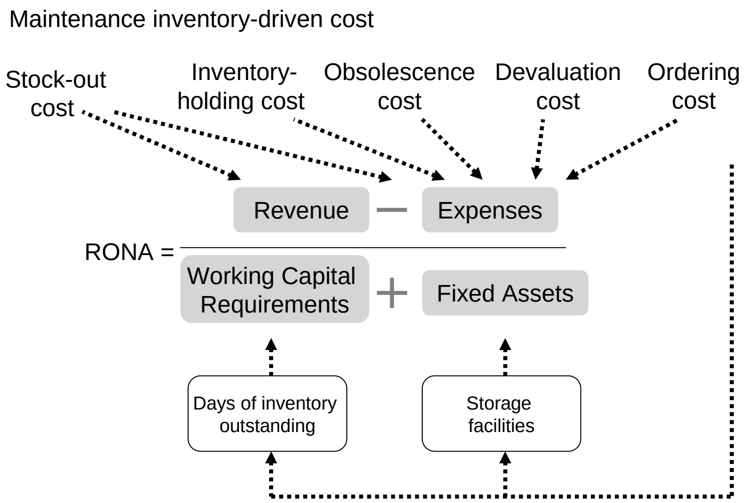

Figure 12.9. Maintenance inventory impact on Return On Net Assets (RONA)

Note that a very important aspect at this point is the correct assessment of the stock-out cost of maintenance inventory. This cost is closely related to the criticality of the equipment and failure mode we keep the inventory for. The maintenance logistic system should ensure high standard service levels for those components considered critical, but let us now see how to translate these ideas to the calculation of suitable stock levels.

Spare parts (maintenance material) problems have been traditionally approached in three ways [1]:

1. Using statistical inventory models;
2. Using selective control procedures along with some heuristics;
3. Using the material requirements planning/manufacturing resources planning (MRP/MRPII) technique.

12.3.1 Statistical Inventory Models

These models add stochastic considerations to an initial, more simple, deterministic model which defines the optimal quantity to order that minimizes the total variable costs required to order and hold inventory. This model is known as the Economic Order Quantity (EOQ) model (by Wilson [14]). The EOQ original model considers the following assumptions:

- The component demand is known;
- The lead time (supplier delivery time) is known and fixed;
- The receipt of the order occurs in a single instant;
- Stockouts or shortage do not occur.

Notation of the model is as follows:

Q = Order quantity;
Co = Cost per order event;
D = Demand of the product (per unit time);
P = Purchase cost per unit;
Ch = Holding cost per unit per month.

The single item EOQ formula can be seen as the minimum point of the following cost function: Total cost = purchase cost + order cost + holding cost, which corresponds to

$$TC(Q) = PD + \frac{D \cdot Co}{Q} + \frac{Ch \cdot Q}{2} \tag{12.39}$$

Taking derivatives both sides of the equation and setting equal to zero:

$$\frac{dTC(Q)}{dQ} = \frac{d}{dQ}\left(\frac{D \cdot Co}{Q} + \frac{Ch \cdot Q}{2}\right) = 0 \tag{12.40}$$

$$-\frac{D \cdot Co}{Q^2} + \frac{Ch}{2} = 0 \tag{12.41}$$

Then solving for Q,

$$Q^2 = \frac{2D \cdot Co}{Ch} \tag{12.42}$$

$$Q^* = \sqrt{\frac{2D \cdot Co}{Ch}} \tag{12.43}$$

Then Q^* is the optimal component order quantity with the above-mentioned assumptions, *i.e.* we are considering only purchase cost (with no discount policy), inventory holding cost and ordering cost. Note that this can be of minor importance if, by the stochastic nature of our process, stock-outs are produced and critical components of our system cannot be maintained due to lack of the correspondig spare parts and materials. Therefore, the problem of “what to order?” may become less important than the “when to order?” problem — finding the correct reordering point. It is important to make sure that we keep enough critical components in stock so that their demand to perform maintenance activities during the lead time is fulfilled (Figure 12.10).

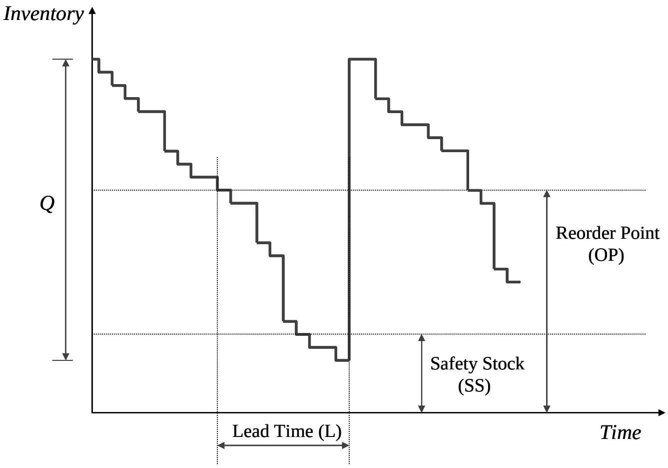

Figure 12.10. Component demand during lead time

With regards to the reordering point, we have to find the amount of inventory below which order will be released to suppliers. In order to do so it is important to fix properly the safety stock to keep to ensure no inventory shortages.

The safety stock level can be calculated assuming [15] that inventory availability is measured in terms of the no-stockout probability per order cycle (see Figure 12.11). In this case, safety stock can be modelled as a function of the management-specified customer service level and the standard deviation of the spare part demand during lead time [16]. At the same time, this standard deviation of lead time demand is based on the mean and variance of demand and of lead time, assuming that the demand and lead time distributions are independent of one another:

$$SS = Z\sigma = Z\sqrt{L\sigma_D^2 + \sigma_L^2 \overline{D}^2} \tag{12.44}$$

where Z is a safety factor based on target customer service level (to choose appropriate values of Z, the reader is referred to Aucamp and Barringer [17]), L is the lead time, σ is the standard deviation of demand during the lead time, $\overline{D}$ is the average demand per time unit and σ_D and σ_L are the standard deviation of demand and lead time, respectively. Equation (12.44) needs an explanation. Note that during the lead time (L time units) a total of L components demands are received; therefore the total variability of those L demands will be the first addend of the square root. The second addend of the square root is the variability of the lead time, but expressed in component units not in time units (that is why we multiply σ_L by the average demand $\overline{D}$).

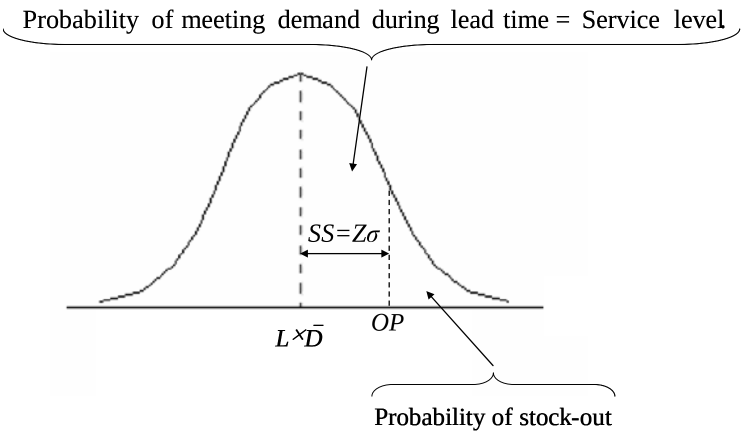

Figure 12.11. Service level calculation

12.3.1.1 Case Study

Let us propose the case in which an urban transportation company wants to design the diesel engine drive belts stock so that 95% of the time that it receives a demand for drive belts for the diesel equipment of the buses it could be satisfied (level of service 95%). Suppose that average demand is ten straps a week with standard deviation of two straps per week, and that the average procurement time of the strap is four weeks, with a standard deviation of one week. Then the safety stock to keep would be

$$SS = Z\sigma = Z\sqrt{L\sigma_D^2 + \sigma_L^2 \overline{D}^2} = Z\sqrt{42^2 + 1^2 10^2} = Z \times 10.77$$

In Table 12.2 the values for Z in order to reach a certain service level are presented. In that table the value for Z for a 95% of service level would be 1.65; then

SS=1.65×10.77=17.77 ≈ 18 units, and the order point (OP) will be
OP = $\overline{D}$ ×L+SS=10×4+18 =58 units.

Table 12.2. Desired service level (SL%) and safety factor (Z)

SL %	Z	SL %	Z	SL %	Z
60	0.25	92	1.41	97	1.88
70	0.52	93	1.48	98	2.05
80	0.84	94	1.55	99	2.32
90	1.28	95	1.65	99.9	3.09
91	1.34	96	1.75	99.99	3.72

12.3.2 Selective Control Procedures along with Heuristics

As we have seen in the previous section, maintenance materials mathematical models are aimed at optimizing the problem of inventory investments and service levels. Besides these models, general principles of administrative efficiency have led to different types of classifications of inventory items. The most well known and perhaps the most used classification scheme is the ABC analysis according to the pareto principle. ABC analysis offers good results for the management of fairly homogeneous materials, differing from each other mainly by unit price and demand volume [18]. However, when the variety of the control characteristic increases, the one-dimensional ABC classification does not discriminate all the control requirements of different types of items.

Spare parts and maintenance materials are items with several distinctive features other than price and demand volume. This has led researchers to suggest different types of multi-dimensional classifications for spare parts inventory management. As a general rule to find the more relevant control characteristics, we have to analyse the effects of these control characteristics on the different elements in the supply system. The following are considered relevant control features [18]:

- *Criticality.* Beside the usage of the part, most of the literature classifications consider criticality as an essential feature for the analysis ([19,20], *etc*.). The criticality of a part is related to the consequences caused by its failure on the process in case the replacement is not available. Obviously these consequences may be much higher that the commercial value which makes an ABC analysis an insufficient control tool. In order to classify spare parts according to criticality, one practical approach is to relate criticality to the time in which the failure has to be corrected;
- *The specificity*. This feature relates to the fact that some parts are tailor-made for specific users; they are not standard in the market and therefore their procurement is complicated. Normally for these parts the responsibility of availability and control remains with the user himself;
- *The demand pattern.* It is common to find many spare parts with very low and irregular demand which makes their control more difficult, especially

when combined with high prices and criticality. But predictability of the spare parts is related to their failure modes behaviour patterns, and therefore we could classify spare parts in terms of predictability in at least two categories: random and wear-out.

- *The value of the part.* This is a common control characteristic to all materials. High values force the cooperation between users and suppliers to find a solution to the problem. Low values put the preassure on the replenishments arrangement for the ordering cost not to be significant.

A summary of control situations and respective strategies/policies is presented in Table 12.3, adapted from Huiskonen [18].

Table 12.3. Control situations for spare parts and suggested strategy (from Huiskonen)

		Low criticality	High criticality
Standard parts	Low value	– Order processing simplified – Outsourcing of inventory control to suppliers	– User's decentralized safety stocks and generous replenishments lot-sizes
	High value	– Stock pushed back to the supplier	– Optimized user's safety stocks (with high and smooth demand) – Time-guaranteed supplies from established service company (for lower and irregular demand) – Several users co-operative stock pools (for very low demand)
User specific	– User's own safety stock + partnership with local suppliers to shorten lead times, to increase dependability and get priorities in emergency situations – In the long run, standardization of parts when possible		

12.3.3 Using The Material Requirements Planning/Manufacturing Resources Planning (MRP/MRPII) Technique

By using MRP/MRPII we can plan and schedule maintenance resources needs according to their existing capacities. Readers can refer to Shenoy and Bhadury [1] for a detailed method application and also for the presentation of case studies. In this section we will present a vision of the global scheme of the system (see Figure 12.12) and characterise the changes required for the utilization of MRP for maintenance resources planning purposes.

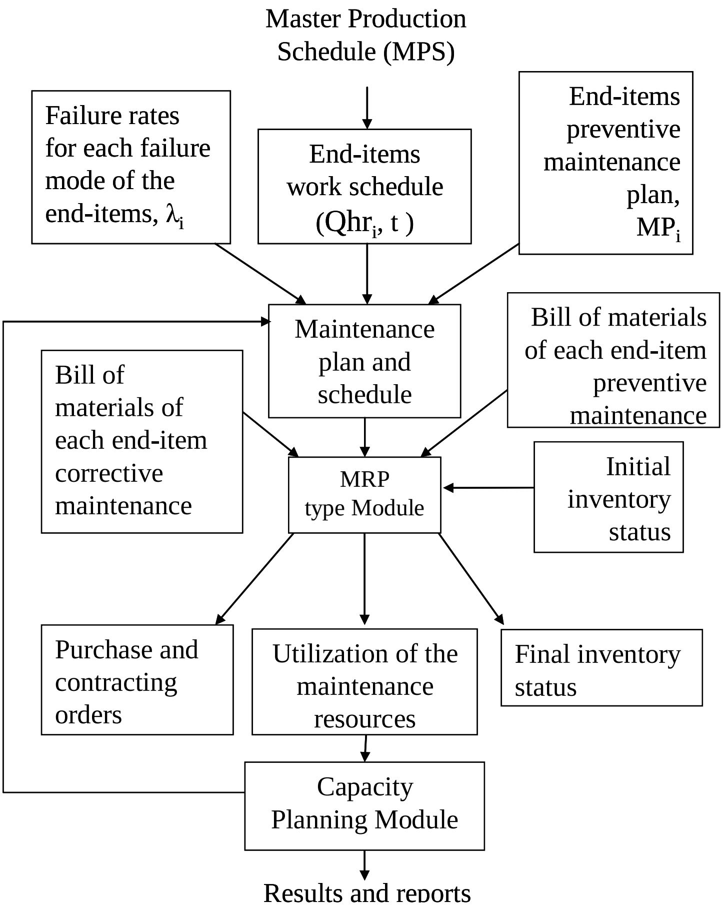

Figure 12.12. Adapting MRP/MRPII for maintenance resources management

Main modifications to accomplish are as follows [1]:

1. For all preventive maintenance activities to be carried out to end-items — where "end" refers here to the maintenance indenture level — where we will have to detail the resources they need (preventive maintenance bill of materials);
2. End-items failure modes will have to be defined and connected to those resources required for the corrective maintenance to be carried out (corrective maintenance bill of materials for failure mode). This is a main

change with respect to the original MRP systems which only considers deterministic information;
3. Preventive maintenance activities will be planned, scheduled and carried out at the scheduled time;
4. Failures of the end-items will be estimated with a certain degree of accuracy;
5. Inventory records will be modified to allow handling of maintenance manpower resources;
6. The principle will be to repair a failed item wherever possible.

12.4 A Model for Maintenance Contracts

The European Prestandard ENV 13269:2001 (Guide on preparation of maintenance contracts) was approved by CEN (European Committee for Standardization) in April 2001 [21], and three years later became European Standard EN 13269. It is a horizontal standard classified within the CEN industrial services group of standards — ICS 03.080.10 — and offers suitable guidelines for the elaboration of the maintenance contracts.

This section offers an overview of the contract structure proposed by the standard and discusses some aspects concerning the elements of this structure, their purpose and content.

12.4.1 Proposed Maintenance Contract Structure

The standard EN 13269 proposes a maintenance contract structure containing eight sections, as follows:

1. Heading;
2. Objective of the contract;
3. Useful definitions;
4. Scope of the works;
5. Additional technical considerations;
6. Commercial considerations;
7. Organizational considerations;
8. Legal considerations.

Now let us briefly discuss the suggested content of each of these points.

12.4.1.1 Heading

In this part, the necessary information for the suitable identification of the contract and of each of the parties must be included. For instance: name and address of the parties, mercantile information, identity of the people signing the contract and their position within the organization that they represent, *etc*.

12.4.1.2 Objective of the Contract

In this section the general intention of the parts will be stated, so that terms that appear in the contract can be better interpreted in case of disputes, or when drafting amendments for future contract variations. This is an important section for long duration contracts, when certain changeable conditions may make amendments necessary. It will be important in this part to avoid general purpose sentences and to make the terms very specific to cover every contractual situation.

12.4.1.3 Useful Definitions

It is suitable, in many occasions, to avoid any type of ambiguity that could appear as a consequence of the terminology that it is used in the contract. This is especially important for those relevant terms in the technical, commercial and legal considerations sections. As a general rule, it is advisable to refer, if possible, to terms which are already defined in national or international standards.

12.4.1.4 Scope of the Works

In this section, the items to be maintained, their location and the place where the maintenance task will be carried out have to be identified.

Second, this section will include a clear description of the tasks to be accomplished by the contractor (even mentioning those not included in the contract, if necessary). This description of the task content has to be extremely precise and, in accordance with the standard, it will include a series of sections dealing with the following issued (among other possible): work procedures to follow, task desired results, tools to be used, means and technologies to apply, safety requirements to follow, items conditions when maintained, workers qualification, *etc*.

Third, the periods of time in which the maintenance tasks will be carried out will have to be detailed. In this respect, it will be suitable to include the work schedule, the minimal or maximum period of time between the client calls and the contractor beginning of the works, *etc*.

In fourth place the standard indicates that any impediments that could arise for the accomplishment of the tasks must be outlined, as well as their possible consequences in terms of work schedules changes, ending dates modifications, *etc*. Mutual obligations concerning information in these cases will be detailed, as well as procedures to manage changes in the programs, and to value the costs, and each part responsibilities concerning those costs.

Finally, the procedure to follow when delays are produced must be included in this section. The rights of the parts when delays occur should be clearly stated, as well as the different degrees of delays that will be considered.

12.4.1.5 Additional Technical Considerations

These additional technical considerations refer to the verification of the works (measurable conditions that these must assemble in order to be accepted by the client), to the necessary exchange of technical information for the development of the contract, and to the strategy to follow for the supply of the required spare parts and materials. For each of these aspects, the standard suggests the elaboration of procedures to follow, and the identification of the responsibilities held by each part.

12.4.1.6 Commercial Considerations

In this section the contract has to specify the contractor financial compensation for the accomplishment of the tasks. In this respect, and according to a certain scheme of prices, there will be specified rates, taxes, insurances, travel expenses, *etc*.

Second, the selected payment formula will be described: currency, method of invoicing, description of invoiced elements, deductions for prompt payment, penalties for late payment, causes for payment retention, causes for reduced payments, date of payment, *etc*.

Third, the rights of the client and the obligations of the contractor in case of lack of contractor performance with regard to the contract must be defined. The guarantees offered by the contractor therefore have to become explicit, with their dates of beginning and ending, the manner in which they can be executed, *etc*.

In fourth place, the penalties to be paid by each part in case of breach of the contractual agreements will be declared, and also the incentives that would be paid in case of outstanding accomplishments.

In fifth place there will be a description of any type of insurance needed, for contractual or for legal reasons, indicating the part in charge of providing it as well as the procedure to follow.

Finally, included in this section, there will also be any type of financial guarantee that may be needed to safeguard the client or the contractor.

12.4.1.7 Organizational Considerations

There exist seven types of organizational considerations to be included in the contract according to the standard, that should make clear how the contract deals with the following aspects: conditions for tasks execution, risks prevention, environmental protection, safety of the property, insurance of quality, task supervision and information records to be kept.

12.4.1.8 Legal Considerations

Legal considerations are widely covered by the standard. This is the section with the most subsections (14 in total).

The section starts by requiring a definition of the property and of the initial existing relevant rights. Rights that could appear in the contract, including intellectual property (documents, information, copyright, *etc*.) should also be defined here.

Second, a series of considerations that protect and assure the suitable use of the information that is considered to be confidential will have to be included.

There is always the possibility that some major force disables the continuity of the work for the client. To foresee such a circumstance the contract will have to contain, in the third place of this section, a list of causes of “force majeure”, the procedures of mutual information, the obligations of each part, the way in which the work already done would be protected, *etc*.

In fourth place, the legal considerations of the contract will contemplate the responsibilities of the parts, for damages caused during the accomplishment of the contract. It will be necessary to detail the indemnifications to third parties for wounds, death, damages to the property, *etc*.

In fifth place, the standard advises a definition for whom, where, and how the disputes that could take place in the contract will be solved — the possible admitted arbitration procedures and, in the last case, the competent courts.

Sixt, the reasons and procedures for the completion or rescission of the contract will be defined. In seventh place, this section will contain the set of enumerated documents — with their rank of priority — implying rights or obligations for the parts.

In eighth place, formalisms that could be relevant at the moment of variations, supplements and alterations of the contract will be described. This would include the formats for using, or the persons or charges authorized, to realize such variations, *etc*.

In ninth place, the standard demands that the contract allows the client control regarding possible use of subcontractors, and therefore, the part (or total) of the contracted tasks that can be subcontracted, and the procedure to follow when subcontracting, must be indicated.

In tenth place, laws that apply should be specified. This will have special importance in cases of international contracts. Also the language of application assumes importance. The contract can be written in different languages, but the one to be used for disputes resolution will have to be specified.

Finally, the last three legal considerations are related to the times for the validity of the contract and the renovation periods, with the procedures of notification, and with the contract date of signing.

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13

Models to Deal with Maintenance Activities Planning

13.1 Markov Processes Models

In this section we briefly review the basic features of Markov processes models in order to use these models later for the resolution of the maintenance activities planning problem. We will first introduce the Markovian homogeneous and ergodic processes and their mathematical formulation. Then, in the following section, we will see the required conditions in order to use these quantitative models for the resolution of different maintenance planning optimization problems.

In 1907, the Russian mathematician A.A. Markov (1856—1922) introduced a special type of stochastic process for which future probabilistic behaviour is uniquely determined by present process condition. That is why we say that these processes have no memory. This Markovian attribute of a process considerably simplifies many problems since the knowledge about the process current conditions decouples the future from the past. The behaviour of an important number of physical systems falls under this category of processes.

A Markov stochastic process, with a discrete space of states and a discrete time space, is also known as a Markov chain. In the case of a continuous time space the process is named a Markov process. Clearly there are two other possibilities: continuous space of states—discrete time, and continuous space of states —continuous time models. These last possibilities are not covered in this work.

A Markov models is defined by a set of transition probabilities

$$p_{ij} \quad , \text{ with } i,j=1,2,\ldots n \tag{13.1}$$

representing the probabily to go from the state i to the state j in one step, or specific time interval. For a system with n states, these probabilities can be gouped in a matrix called *stochastic matrix of transition probabilities*, in the following form:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix} \tag{13.2}$$

Each element in matrix P is a probability and therefore its value is within the interval $[0,1]$. Also, and given that each row contains the probability of a finite number of events, the sum of all elements of each row should be equal to unity.

In other words, P is a stochastic matrix for which each row contains a probability vector. Hence:

$$\sum_{j=1}^{j=n} p_{ij} = 1 \qquad ,\forall\ i=1...n \tag{13.3}$$

Let $S_1, S_2,..., S_n$ represent the possible states of the system and let Δt denote a given time interval. Then the probability that the systems is in S_j at the time $(t+\Delta t)$, p_{Sj}, will be given by

$$p_{Sj}(t+\Delta t)=p_{1j}p_{S1}(t)+p_{2j}p_{S2}(t)+ ...+ p_{nj}p_{Sn}(t)=\sum_{i=1}^{i=n} p_{ij}\, p_{Sj}(t) \tag{13.4}$$

Let $E(t)$ denote the state probability vector at a certain time t. This vector will have, as many components as possible system states:

$$E(t)=\{p_{S1}(t), p_{S2}(t),...,p_{Sn}(t)\} \tag{13.5}$$

with

$$E(t+\Delta t) = E(t)\times P \tag{13.6}$$

As we said previously, the representation of a stochastic process by means of a Markov model implies *lack of memory*, which means that the transition probability p_{ij} depends only on the states i and j, as well as on the transition time. This probability is totally independent of the set of states where the process was before the state i.

Within the Markov processes, we will now pay special attention to those that we can characterise in the following manner:

1. *Homogeneous processes* (or stationary). Where all p_{ij} are time independent. That means that the transition probabilities between two states are now the same as in the future;
2. *Ergodic processes*. Where besides homogeneity, the final value of the probability to be in a certain state does not depend on initial conditions of the system.

The combination of the system's lack of memory, plus its homogeneity, leads to the fact that the general behaviour of the system will not change over time (*i.e.* the system does not get old).

An aspect to take into account here is the existence of the so-called absorbing states. A state will be an absorbing state when we cannot reach another state from it. That is, when a system enters into an absorbing state and will remain in it until a new mission starts. Thus, we can say that in case the k-th state is an absorbing state, then

$$p_{kk}=1 \text{ and } p_{ki}=0, \quad \forall i, \text{ except for } i=k. \tag{13.7}$$

It can be shown that a finite state process will be ergodic when each state can be reached from another one in a finite number of steps and with a non-zero probability. In case of homogeneous and ergodic Markov chains, the system reaches a steady state or limit state that can be calculated by solving the following equations system:

$$E(t) = E(t) \times P \tag{13.8}$$

with the following additional condition:

$$\sum_{i=1}^{i=n} p_{S\,i}(t) = 1 \tag{13.9}$$

Moreover, it can be demonstrated [1] that, for ergodic processes, the stochastic transition matrix **P** is a regular matrix, *i.e.* the elements of any of its powers P^m are all positive. In this case, it can be shown that the sequence

$$P^1, P^2, P^3, \ldots\ldots, P^m, \ldots \tag{13.10}$$

tends to the matrix **T,** which has all rows the same and equal to the steady state probability vector **E**(t), also named stationary distribution of the chain.

Therefore, at the end of the day the probability that the system is in state S_j will be equal to the j-th component of **E**(t), in steady state. Notice that the effect of the initial probability distribution disappears when the number of steps of the process increases, as we should expect for ergodic processes.

13.2 Maintenance Optimization Models for Markovian Processes

In this section we present a set of optimization models that take the advantage of the mathematical formulation and properties of the Markovian homogeneous and ergodic processes previously introduced. In the original formulation of these models made by Figuera [2] the following assumptions are considered:

- The mean time to maintain/replace the equipment is very short (can be ignored) compared to the mean time between failures of the equipment;
- Equipment performance is not a function of the time since last failure;
- Equipment will be "as good as new" after maintenance (corrective and/or preventive) or replacement;
- Only one failure will be possible within the selected transition time interval.

These assumptions are feasible for many industrial circumstances where:

- The equipment under consideration could be non-repairable, remanufactured or rebuilt equipment. In these cases it is possible to shorten equipment replacement times, and repair risk and downtime can be minimized;
- Failures cannot be predicted and appear without any previous warning;
- When non-repairable, remanufactured or rebuilt equipment is used, performance and failure behavious will be "as good as new" after replacement. Curiously, and as an anecdote, many OEMs offer longer periods of equipment warranty for rebuilt equipment than to brand-new equipment;
- Finally, when modelling the Markov Chain, we can select a transition time interval shorter that the two nearest consecutive failures of the equipment, and therefore we would ensure that no more than one failure would be taking place within the selected time interval.

In the following sub-sections, we will present examples of Markov processes models for the following cases :

- Deterioration. No maintenance carried out on the equipment;
- Corrective maintenance modelling;
- Predetermined maintenance (at constant time intervals);
- Age based maintenance;
- Age and condition based maintenance.

Note that all these models will be dealing with the failure of the equipment for a given failure mode. The last three of them will deal with the problem of the optimization of the maintenance activities planning.

13.2.1 Modelling Deterioration

Assume (T_1+1) different equipment states, where T_1 is defined as the maximum number of time intervals that the equipment can operate without the reproduction of the same failure mode.

The equipment will be in S_i when gets into its i-th operating time interval without failure. Obviously, *i* will take values from 1 to T_1, but for this model we also add the state S_0, representing a state where the equipment falls when it has had a fault, remaining there since we carry out no maintenance at all. In Figure 13.1 we show the states transition diagram where we can appreciate that the fault state is an absorbing state. In that same figure non-zero transition probabilities are also shown, which are defined as follows:

$$p_{i0} = \lambda(i) \quad , \text{with } i = 1,.......T_1 \tag{13.11}$$
$$p_{i,i+1} = 1-\lambda(i) \quad , \text{with } i = 1,.......T_1 \tag{13.12}$$

where $\lambda(t)$ is the failure rate for the selected mode of failure.

Notice that $p_{T1,0}=1$ — *i.e.* the equipment will always fail in S_{T1} if it reaches S_{T1}— and that $p_{0,0}=1$ — *i.e.* the equipment with a fault will remain with the fault—. With these considerations, the transition matrix of the Markov Chain will be as in Equation (13.13)

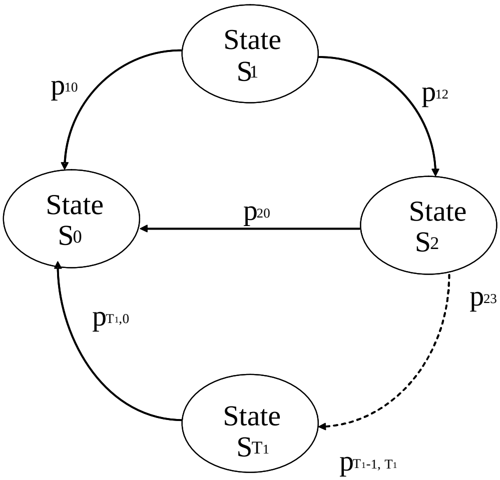


Figure 13.1. Transition diagram for the deterioration case

The transition matrix in (13.13) defines an absorbent Markov Chain with only one absorbent state S_0, and T_1 transition states. We can evaluate [3] the expected number of times that an absorbent Markov Chain will visit a certain state before falling into an absorbent state. However, and by the definition of our process, we know that the equipment will only be in each state once (assuming, of course, that the system is “as new” when starting the mission).

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ p_{10} & 0 & p_{12} & 0 & \cdots & 0 \\ p_{20} & 0 & 0 & p_{23} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ p_{T1-1,0} & 0 & 0 & 0 & \cdots & p_{T1-1,T1} \\ 1 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \tag{13.13}$$

Let us now see a case study where we apply this model to formalize the deterioration process of a set of industrial assets.

13.2.1.1 Case Study

A refinery plant where a pumping system needs to be designed to ensure its continuous operation between maintenance activities that are scheduled every two months is considered. Such a system should include a total number of N similar pumping units, and 10 of these units will be required to be in good operating conditions for the pumping system to fulfil its function. According to the previous history of the pumps selected for this mission, they present a particular failure mode which seems to be critical for the two month period of time considered in this project. That failure mode presents a failure pattern according to Table 13.1.

Table 13.1. Failure rate and reliability for the pumping units

Period (months)	$\lambda(t)$	R(t)
1	.3	.7
2	.1	.63
3	.1	.567
4	.1	.5103
5	1	0

What is the total number of pumping units (N) that we have to include in the pumping system to ensure that it fulfils its function? To answer this, let us formalize the problem as explained above. The transition matrix would be

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0.3 & 0 & 0.7 & 0 & 0 & 0 \\ 0.1 & 0 & 0 & 0.9 & 0 & 0 \\ 0.1 & 0 & 0 & 0 & 0.9 & 0 \\ 0.1 & 0 & 0 & 0 & 0 & 0.9 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Note that, in this particular case, the state vector E(t) would have six components:

$$E(t)=\{N_o(t),N_1(t),N_2(t),N_3(t),N_4(t),N_5(t),N_6(t)\}$$

where $N_o(t)$ is the set of elements that are in the fault state at time t. Then the system evolution over time would then be as follows:

$$E(0) = N\ \{ 0, 1, 0, 0, 0, 0\}$$
$$E(1) = N\ \{ 0.3, 0, 0.7, 0, 0, 0, 0\}$$
$$E(2) = N\ \{0.37, 0, 0, 0.63, 0, 0, 0\}$$

And then the problem would be solved if the condition $N\times0.63\geq10$ is fulfilled, and therefore $N \geq (10/0.63)$; Hence $N \geq 15.9$**.** That can be compared with reliability values for t=2.

13.2.2 Modelling Corrective Maintenance

Five different states are now considered (since T_1=5). The system will be in state S_i when it reaches its i-th interval of operation without failure. Now *i* takes values from 1 and T_1. Let us assume that when the system fails, an immediate repair is carried out, and the system is again as good as new — goes again to state S_1 — or is placed in its first interval of operation without failure; see Figure 13.2.

Now there is no absorbent state in the process, and each state can be reached from anywhere else after a certain finite number of transitions. Therefore, this is an ergodic process with the following transition matrix:

$$\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} & 0 & 0 & \cdots & 0 \\ p_{21} & 0 & p_{23} & 0 & \cdots & 0 \\ p_{31} & 0 & 0 & p_{34} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & 0 \\ p_{T1-1,1} & 0 & 0 & 0 & \cdots & p_{T1-1,T1} \\ 1 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \tag{13.14}$$

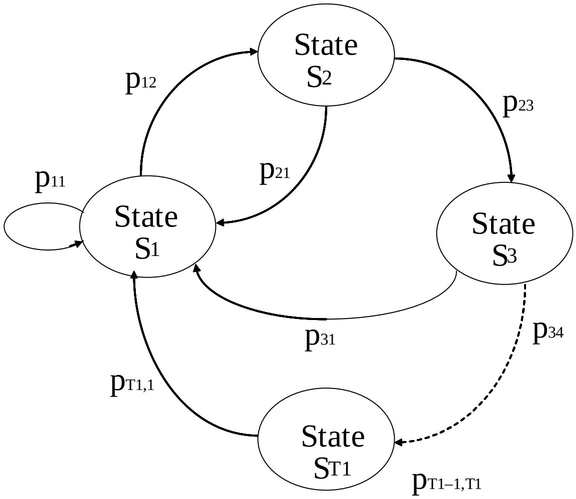


Figure 13.2. Transition diagram for the corrective maintenance case

Then we will be able to find the vector of limit state transition probabilities, also named "stationary distribution", of the Markov chain in Equation (13.15).

$$E^{*}(t) = \{ p_{S1}^{*}(t), p_{S2}^{*}(t), \ldots\ldots\ldots , p_{ST1}^{*}(t)\} \tag{13.15}$$

This will be done by finding the values of $pS_i(t)$ solving the following equations system:

$$E(t)=E(t)\times\mathbf{P} \tag{13.16}$$

with the following additional condition:

$$\sum_{i=1}^{i=T_1} p_{Si}(t) = 1 \tag{13.17}$$

Once the vector in Equation (13.15) is known, we can easily determine the expected cost per period of the corrective maintenance policy under steady/limit state operating conditions. In order to do so, we need to know the average cost of a corrective maintenance operation for the considered failure mode — C_C — and multiply it by the expected number of corrective activities per each transition time interval once the system reaches the steady state conditions:

$$\text{Expected maintenance cost per period} = p_{S1}^{*}(t)\, C_C \tag{13.18}$$

where $p_{S1}^{*}(t)$ is the first component of the state vector under steady state conditions, which represents the number of repairs carried out per unit transition time.

The problem could also be solved using another property of the process and a different equation formulation. The property that we refer to is related to the input-output rate to/from each state under steady state conditions. Note that equations determining state probabilities under steady state conditions could also be formalized as "balance or input/output equations" per state, as follows:

For $S_1(t)$,

$$p_{S1}(t)p_{11} + \sum_{i=2}^{i=T_1}\left(p_{Si}(t)p_{i1}\right) = p_{S1}(t)(p_{11} + p_{12}) \tag{13.19}$$

For Si(t), with i=2,...,T_{1-1}

$$p_{Si}(t)\left(p_{i,1} + p_{i,i+1}\right) = p_{Si-1}(t)p_{i-1,i} \tag{13.20}$$

For $S_{T1}(t)$,

$$p_{ST_1}(t)p_{T1,1} = p_{ST_{1-1}}(t)p_{T1-1,T1} \tag{13.21}$$

As a result, we have T_1 lineal equations that, with the additional condition:

$$\sum_{i=1}^{i=T_1} p_{Si}(t) = 1 \tag{13.22}$$

are sufficient to determine the values of the state probabilities under steady state conditions.

13.2.2.1 Case Study

Let us now see an application of this model to the example we had in Part 2 — Chapter 3 — of this work, related to failures in the diesel system straps. In Table 13.2 we show time periods where failures where found and cost of each failure is presented between brackets.

Table 13.2. Failure histogram in diesel system straps

Test period	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	-	Fault (100)	-	Fault (150)	-
2	-	-	Fault (120)	Fault (140)	-
3	-	-	-	-	Fault (200)
4	Fault (60)	Fault (110)	-	Fault (230)	Fault (80)
5	-	-	Fault (80)	-	-
6	-	-	Fault (160)	-	-
7	Fault (70)	-	Fault (190)	-	-
8	-	Fault (130)	-	Fault (120)	Fault (120)
9	-	-	-	.	-
10	Fault (100)	Fault (140)	-	.	-

In that same chapter we saw how to estimate the failure rate for the mode of failure of this study (Table 13.3).

Table 13.3. Straps reliability and failure rate estimation

Strap life period	R(t)	λ(t)
1	12/18	1/3
2	9/18	1 /4
3	4/18	5/9
4	0	1

Thus we arrive at the following transition matrix:

$$\mathbf{P} = \begin{bmatrix} 1/3 & 2/3 & 0 & 0 \\ 1/4 & 0 & 3/4 & 0 \\ 5/9 & 0 & 0 & 4/9 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

Then we can find the Markov Chaín stationary distribution, or limit state vector

$$\mathbf{E}^{*}(t)=\{N_1^{*}(t),N_2^{*}(t),N_3^{*}(t),N_4^{*}(t)\}$$

if we find the values of $N_i(t)$, solving the equations system

$$\mathbf{E}(t)=\mathbf{E}(t)\times\mathbf{P}$$

with the additional condition

$$\sum_{i=1}^{i=4} \mathrm{N}_i(t) = 5$$

If we solve these equations we obtain

$$\mathbf{E}^*(t)=\{90/43,60/43,30/43,50/43\}$$

The average cost — C_C — of a corrective maintenance operation can be calculated as follows:

C_C =(100+150+120+140+200+60+110+230+80+80+160+
+190+130+120+120+100+140)/18= 121.6 monetary units

Then, the expected cost per period of the corrective maintenance policy can be calculated as follows:

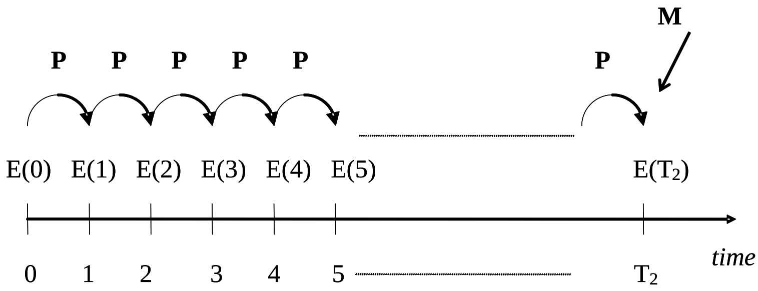
$C_C N_1(t)$=121,6×(90/43)=254.5 monetary units/period

13.2.3 Modelling Predetermined Maintenance

Let us now assume that maintenance is done after the failure (*corrective maintenance*) or after a certain constant time interval T_2 (*preventive maintenance cycle*). The evolution of the system can be described as in Figure 13.3, and formulated using a new matrix named maintenance matrix (**M**) that will be described as follows:

$$\mathbf{M}=\begin{bmatrix} 1 & 0 & 0 & 0 & \cdots & 0 \\ 1 & 0 & 0 & 0 & \cdots & 0 \\ 1 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & 0 & \cdots & 0 \\ 1 & 0 & 0 & 0 & \cdots & 0 \end{bmatrix} \tag{13.23}$$

Regardless of the maintenance policy, failures will take place according to a given distribution function. Corrective activities will be carried out immediately and instantaneously (we disregard repair time) after the failure. Preventive activities will be carried out after a certain number of periods — cycle time T_2 — and also instantaneously (we also disregard preventive maintenance time).



where:

P= State transition matrix
E(t) = State probability vector
T_2= PM cycle time
M= Maintenance matrix

Figure 13.3. Predetermined preventive maintenance policy

Maintenance activities, preventive and corrective, will initialize the equipment, that means that after maintenance activities the equipment will be as good as new. Therefore note that after T_2 periods of time, the equipment will always be as good as new, if we follow this policy (this is formalized by setting to “1” all elements of the first row in the maintenance matrix **M,** and setting the rest of the matrix elements to “0” in Equation (13.23)).

The process described can be formalized then as follows:

$$\mathbf{E}(i+1)=\mathbf{E}(i)\times\mathbf{P}, \quad \text{with } i=0,1,\ldots,T_2-1 \tag{13.24}$$

$$\mathbf{E}(0)=\mathbf{E}(T_2)\times\mathbf{M}, \quad \text{with } \mathbf{E}(0)=\{1,0,0,\ldots,0\} \tag{13.25}$$

Note that with this maintenance preventive policy the equipment can never reach steady state conditions. This policy will produce the repetition of a sequence of certain state vectors for a cycle of T_2 time periods. In these circumstances we can estimate corrective (CM) and preventive (PM) maintenance expected costs per time period as follows:

$$\text{CM expected cost per period} = \frac{C_C * \sum_{i=1}^{i=T_2} p_{S1}(i)}{T_2} \tag{13.26}$$

$$\text{PM expected cost per period} = \frac{Cp}{T_2} \tag{13.27}$$

The total expected cost per time period (TEC) would then be:

$$\text{TEC per períod}=\frac{1}{T_2}\left(C_C * \sum_{i=1}^{i=T_2} p_{S1}(i)+Cp\right) \tag{13.28}$$

This model is built to determine the optimal preventive maintenance cylce T_2 — with $T_2 \in [1, \infty)$ — that minimizes the total expected cost per time period.

13.2.3.1 Case Study

Let us formalize this model for the refinery plant pumping units of the example in Section 13.2.1.1. Consider that every two months we have access to the pumping systems and that the maintenance policy to follow is to repair units that we find with a fault and carry out preventive maintenance to the remaining working units. The transition matrix for this case was presented in Section 13.2.1.1. The maintenance matrix to formalize the mathematical model for this case would be

$$\mathbf{M}=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

For this particular case the state vector at the end of the second period was

$$E(2) = N\ \{0.37, 0, 0, 0.63, 0, 0, 0\}$$

The expected cost per time period of this maintenance policy would be as follows:

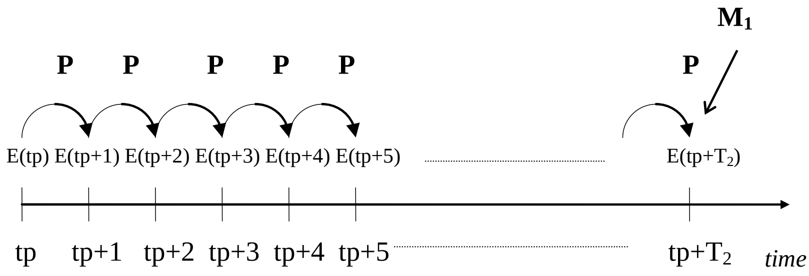
$$\text{CM expected cost per period} = \frac{C_C \sum_{i=1}^{i=T_2} p_{S1}(i)}{T_2} = \frac{(0.37 C_c N)}{2}$$

$$\text{PM expected cost per period} = \frac{C_p}{T_2} = \frac{(0.63 C_p N)}{2}$$

$$\text{Total maintenance expected cost per period} = \frac{N}{2}\left(0.37 C_c + 0.63 C_p\right)$$

13.2.4 Modelling Predetermined Age Based Maintenance

Assume that preventive maintenance is now carried out after a certain number of time periods, but only to those units that have been operating more that T_3 time periods. T_3 is therefore the minimum number of time operating intervals over which preventive maintenance will be carried out on the equipment. Figure 13.4 now replaces Figure 13.3 and some differences in the policy formalization are now discussed.



where

tp= Time when the limit cycle starts;
P= State transition matrix;
E(t)= State probability vector;
T_2= PM cycle time;
$\mathbf{M_1}$= Maintenance matrix.

Figure 13.4. System cycle in steady state with corrective and preventive maintenance

The maintenance matrix for this new case, $\mathbf{M_1}$ in Equation (13.29), is different from the previous case one. Since the new maintenance policy takes into account the age of the equipment to carry out the preventive maintenance, the matrix will be now is diagonal until row number T_3, after that, the matrix would resemble the previous case one, *i.e.* the first column elements will be equal to one and the rest of the elements will be equal to zero.

This new maintenance matrix $\mathbf{M}_1$ does not totally reset the state vector every T_2 time intervals. Now, the time since the last failure of the equipment, besides the value of T_2 selected in the maintenance policy, is considered. As a result of this, it can be shown that the system does not reach a permanent steady state or limit state, but a limit cycle or permanent cycle that is repeated. During this cycle of time periods, the state vector takes certain values that are repeated periodically over time. Figure 13.4 illustrates this point.

$$\mathbf{M_1}= \begin{array}{c} \begin{array}{cccccccc} & & & & T_3 & T_3+1 & & \end{array} \\ \left[\begin{array}{ccccc|ccc} 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 & 0 & \cdots & 0 \\ 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \hline 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \end{array}\right] \end{array} \qquad (13.29)$$

The determination of the expected maintenance cost per period is only possible if we calculate each state vector of the limit cycle. In order to do so we have to proceed as follows:

$$\mathbf{E}(t_p+1)=\mathbf{E}(t)\times\mathbf{P} \qquad (13.30)$$

$$\mathbf{E}(t_p+2)=\mathbf{E}(tp+1)\times\mathbf{P}=\mathbf{E}(t_p)\times\mathbf{P}^2 \qquad (13.31)$$

....

$$\mathbf{E}(t_p+T_2)=\mathbf{E}(t_p+T_2-1)\times\mathbf{P}=\mathbf{E}(t_p)\times\mathbf{P}^{T_2} \qquad (13.32)$$

When we come to the limit cycle, the following condition should be valid:

$$\mathbf{E}(t_p)\times \mathbf{P}^{T_2}\times\mathbf{M_1}=\mathbf{E}(t_p) \qquad (13.33)$$

and therefore we can obtain the state vector for the period of time of the limit cycle (t_p), solving the following system of equations:

$$\mathbf{E}(t_p)[\mathbf{P}^{T_2}\times\mathbf{M_1}-\mathbf{I}] = \varnothing \text{ , where } \varnothing \text{ is the null matrix.} \qquad (13.34)$$

The following condition is also fulfilled:

$$\sum_{i=1}^{i=T_1} pS_i(tp)=1 \qquad (13.35)$$

Let E(tp) be the solution to the previous system of equations. Then we just have to apply Equations (13.30) — (13.32) to obtain the state probability vector for the remaining time periods of the limit cycle.

The calculation of the limit cycle state probability vectors could be done departing from a different point in time of the cycle. For instance, through the following equations system:

$$\mathbf{E}\,(t_p+T_2)\,[\mathbf{M_1}\times \mathbf{P}^{T_2}-\mathbf{I}] = \varnothing \tag{13.36}$$

with the additional condition

$$\sum_{i=1}^{i=T_1} p\,S_i\,(tp+T_2)=1 \tag{13.37}$$

$E(t_p+T_2)$ can be obtained, and from that state vector, we can generate the remaining elements of the limit cycle. From the moment that we know all the state probabilities vectors which form the limit cycle, it is possible to evaluate the expected maintenance cost of the current maintenance policy as follows:

$$\text{CM expected cost per period} = C_C \frac{\sum_{i=tp+1}^{i=tp+T_2} p_{S1}(i)}{T_2} \tag{13.38}$$

$$\text{PM expected cost per period} = Cp \frac{[P_{S1}(tp) - P_{S1}(tp+T_2)]}{T_2}, \tag{13.39}$$

Note that the PM expected cost can also be calculated as follows:

$$\text{PM expected cost per period} = Cp \frac{\sum_{i=T_3+1}^{i=T_1} p_{Si}\,(tp+T_2)}{T_2} \tag{13.40}$$

The total expected cost per time period (TEC) would then be:

$$\text{TEC per period} = \frac{1}{T_2}\left(C_C \sum_{i=1}^{i=T_2} p_{S1}\,(i) + C_2\left(p_{S1}(tp) - p_{S1}(tp+T_2)\right)\right) \tag{13.41}$$

The problem will be solved if we choose the values of T_2 and T_3 minimizing this expression.

13.2.4.1 Case Study

Consider the case of the straps in the diesel system introduced in Section 13.2.2. Suppose that the person who is responsible for the maintenance of the fleet decided to start a study for maintenance cost improvement. Assume that the result of the study of each diesel system was that straps should be checked every time period and those working for more than two time periods without failure would be replaced. What is the cost of a strap preventive replacement so that this age based policy is better than the corrective one? Let us try to solve this question modelling the optimal policy that was suggested by the study (see Figure 13.5).

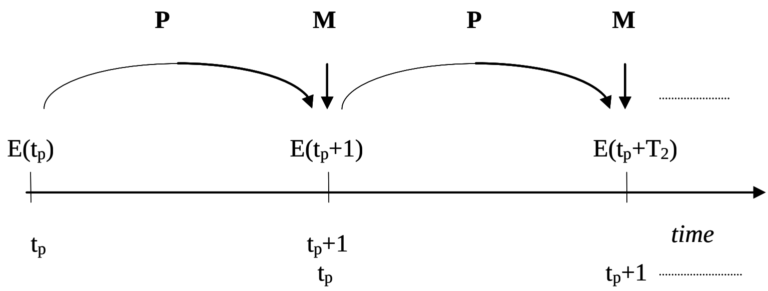


Figure 13.5. Limit cycle for straps with age based preventive maintenance

The matrix of transition probabilities is the same as in as in Section 13.2.2.1, but the maintenance matrix is now defined as follows:

$$\mathbf{M} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

The limit cycle for the straps is defined as follows:

$E(t_p+1) = E(tp)\times P$

$E(t_p) = E(tp+1)\times M$, and hence

$E(tp) = E(tp)\times P\times M$,

and therefore the systems of equations to solve in order to get to the first state vector of the limit cycle at tp will be

$E(tp)[\ P\times M - I]=\varnothing$, where $\varnothing$ is the zero matrix

$$\sum_{i=1}^{i=4} \mathrm{N}_i\,(tp) = 5$$

The solution of this system of equations is

$$E(t_p)=[3, 2, 0, 0]$$

and the second vector of the limit cycle will be

$$E(t_p+1) =[3, 2, 0, 0]\times P=[3/2,2,3/2,0]$$

According to this, when the diesels achieve the limit cycle, the expected number of preventive replacements per cycle will be

$$N_3(tp+1)+N_4(tp+1)=3/2+0=3/2$$

That could also have been calculated as follows:

$$N_1(tp)–N_1(tp+1)=3–3/2=3/2$$

The number of corrective activities per cycle will be

$$N_1(tp+1)=3/2$$

Then, the total expected cost per time period (TEC) will be

$$\text{TEC per períod}=C_C 3/2+C_p 3/2$$

In Section 13.2.2.1 we calculated the expected cost of the corrective maintenance policy of the straps. It was found that this cost was

$$C_C N_1(t)= C_C\times(90/43)$$

Therefore, the condition that this new age based maintenance policy has to fulfil to be better than the previous corrective policy can be expressed as follows:

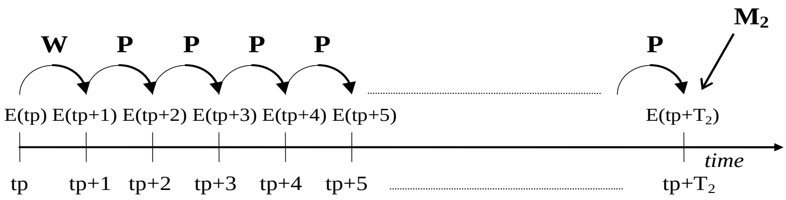
$$C_C 3/2+C_p 3/2 <C_C 90/43, \text{ and then}$$

$$C_P<2/3(90/48–3/2)\times Cc=5/129\times 121.6=4.7 \text{ monetary units.}$$

Then, if the cost of a preventive replacement is lesser that 4.7 m.u., the second maintenance policy (age based policy) is more convenient than the corrective one.

13.2.5 Modelling Predetermined Age and Inspection Based Maintenance

This policy will try to increase the effectiveness of maintenance through periodical inspection activities that will determine the opportunity of the preventive maintenance (replacement or service). Inspections will allow us to foresee equipment failures in the near term. Obviously, this new maintenance policy will be more or less convenient depending on the accuracy of the inspections and on their cost.



where tp= Time when the limit cycle starts;
P= State transition matrix;
E(t)= State probability vector;
T_2= PM cycle time;
$\mathbf{M_2}$= Maintenance matrix;
W= Update matrix.

Figure 13.6. Limit cycle for age and inspection based policy

We will assume that the inspection unit cost will be constant and equal to C_i. Every T_2 periods of time, the system age will be checked, in case the system has been working without failure for longer than T_3 time periods, the system will be inspected. The inspection results will determine whether the system will fail or not within the next time period. In the case that the inspection concludes that the system will fail we will maintain it (replacement or service). Figure 13.6 now describes how we model the condition of the system over time.

For this maintenance policy formalization we will use a different maintenance matrix (M_2). This matrix takes into account the effect that the inspection has on the system. This effect will only be noticed if the system has been working more that T_3 time intervals without failure:

$$\mathbf{M_2}= \begin{array}{c} \begin{array}{cccccccc} & & & T_3 & T_3+1 & & & \end{array} \\ \left[\begin{array}{cccc|cccc} 1 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \iddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 & \cdots & 0 & 0 \\ \hline m_{T_3+1,1} & 0 & \cdots & 0 & m_{T_3+1,T_3+1} & \cdots & 0 & 0 \\ \vdots & \vdots & \iddots & \vdots & \vdots & \ddots & \vdots & \vdots \\ m_{T_1-1,1} & 0 & \cdots & 0 & 0 & \cdots & m_{T_1-1,T_1-1} & 0 \\ 1 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \end{array}\right] \end{array} \qquad (13.42)$$

where $m_{i,1}$, for $i>T_3$, represents the probability of the system to be maintained once its inspection is done in its i-th operational interval without failure. If we carry out the decomposition of this probability according to its Bayesian properties we can obtain the following expression:

$$m_{i,1}=p_{i,1}\times(1-p_2)+p_{i,i+1}\times p_1 \tag{13.43}$$

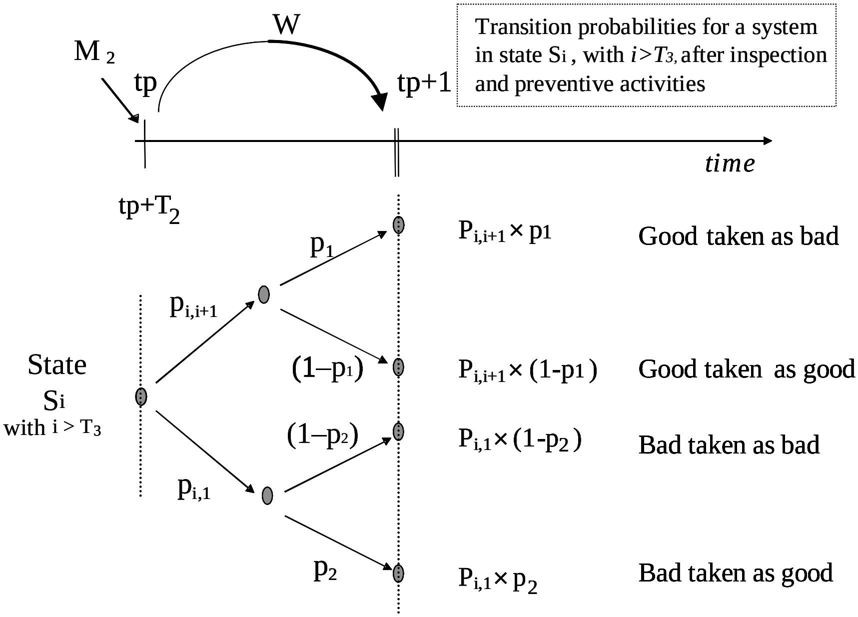


Figure 13.7. System update in the first transition after maintenance

According to this we can build Figure 13.7, where p_1 is the probability that the system "in good condition", once inspected, is taken as "in bad condition" to survive one more time interval. Similarly, p_2 is the probability that the system "in bad condition", once inspected, is taken as "in good condition" to survive one more time interval (see Figure 13.7). Following the same procedure we can calculate $m_{i,i}$, with $i>T_3$, that represents the probability that a system is not maintained and alter its inspection in its i-th operation without failure interval. The system will, in that case, remain in the same state:

$$m_{i,i}= p_{i,1}\times p_2+p_{i,i+1}\times(1-p_1)$$

Of course, after the inspection, maintenance should be more selective, since it would only be carried out on the equipment showing bad operating conditions. Therefore, system behaviour after maintenance will be better than for previous maintenance policies (in case of a perfect inspection, $p_2=p_1=0$, the system taken as "good" would not fail in the first time interval after maintenance). In general, the first transition following maintenance will not be similar to a normal system transition modelled by the matrix **P** the inspection can fail and take as “in good condition” a system that will fail in this first time interval after maintenance. In order to take into account these considerations a new matrix **W** is introduced to model the first system transition after maintenance. This matrix will have the following elements:

$$\begin{array}{rc} & \begin{array}{cccc|cccc} \phantom{p_{1,1}} & \phantom{p_{1,2}} & & T_3 & T_3+1 & \phantom{w_{T_3+1,T_3+2}} & & \phantom{w_{T_1-1,T_1}} \end{array} \\ \mathbf{W}= & \left[\begin{array}{cccc|cccc} p_{1,1} & p_{1,2} & \cdots & 0 & 0 & 0 & \cdots & 0 \\ p_{2,1} & 0 & \cdots & 0 & 0 & 0 & \iddots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & 0 & \cdots & \vdots \\ p_{T_3,1} & 0 & \cdots & 0 & p_{T_3,T_3+1} & 0 & \cdots & 0 \\ \hline w_{T_3+1,1} & 0 & \cdots & 0 & 0 & w_{T_3+1,T_3+2} & \cdots & 0 \\ \vdots & \vdots & \iddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ w_{T_1-1,1} & 0 & \cdots & 0 & 0 & 0 & \ddots & w_{T_1-1,T_1} \\ 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 \end{array}\right] \end{array} \tag{13.44}$$

where the new elements in the matrix are defined as follows:

$$W_{i,1} = \frac{p_{i,1} \times p_2}{p_{i,1} \times p_2 + p_{i,i+1} \times (1 - p_1)} \tag{13.45}$$

This element — $w_{i,1}$ — is the probability that the system fails in the first time interval after the inspection, when that inspection said that the system would survive that interval and the system was not maintained nor replaced

$$W_{i,i+1} = \frac{p_{i,i+1} \times (1 - p_1)}{p_{i,1} \times p_2 + p_{i,i+1} \times (1 - p_1)} \tag{13.46}$$

Similarly, $w_{i,1}$ is the probability that the system survives the first time interval after the inspection, when that inspection said that the system would survive the first time interval and the system was not maintained or replaced.

Again, the determination of the expected maintenance cost per period is only possible if we calculate each state vector of the limit cycle. In order to do so we have to proceed now as follows:

$$E(t_p+1)=E(t)\times W \tag{13.47}$$

$$E(t_p+2)=E(t_p+1)\times P = E(t_p)\times W\times P \tag{13.48}$$

....

$$E(t_p+T2)=E(t_p+T_2-1)\times P=E(t_p)\times W\times P^{T2-1} \tag{13.49}$$

When the system reaches the limit cycle we have:

$$E(t_p)\times W\times P^{T2-1}\times M_2=E(t_p) \tag{13.50}$$

and therefore we can obtain the first state probability vector of the limit cycle (at tp), solving the following system of equations:

$$E(t_p)[(W\times P^{T2-1}\times M_2)-I]=\varnothing \quad \text{with } \varnothing \text{ the null matrix,} \tag{13.51}$$

with the following additional condition:

$$\sum_{i=1}^{i=T_1} p_{Si}\left(tp\right)=1 \tag{13.52}$$

Since we know the state probability vectors of the limit cycle we can evaluate the expected maintenance cost of the current maintenance policy as follows:

$$\text{CM expected cost per period} = C_C \frac{\sum_{i=tp+1}^{i=tp+T_2} p_{S1}\left(i\right)}{T_2} \tag{13.53}$$

$$\text{PM expected cost per period} = C_P \frac{\left[p_{S1}(tp)-p_{S1}(tp+T2)\right]}{T_2} \tag{13.54}$$

The inspection cost, although a preventive operation, is calculated separately, as follows:

$$\text{Inspection expected cost per period} = Ci \frac{\sum_{i=T_3+1}^{i=T_1-1} p_{Si}\left(tp+T_2\right)}{T_2} \tag{13.55}$$

The total expected cost per time period (TEC) would then be:

$$\text{TEC per period} = \frac{1}{T_2}\left(C_C\sum_{i=1}^{i=T_2} p_{S1}\left(i\right)+C_P(p_{S1}(tp)-p_{S1}(tp+T_2))+Ci\sum_{i=T_3+1}^{i=T_1-1} p_{Si}\left(tp+T_2\right)\right) \tag{13.56}$$

The problem will be solved if we use the values of T_2 and T_3 minimizing this expression.

13.2.5.1 Case Study

Given the diagram in Figure 13.8 — with S_i meaning the i-th operation time interval without failure of the equipment, calculate the matrices **P, M** and **W** considering the following parameters values T_2=2, T_3=1, p_1=0,2 and p_2=0,1.

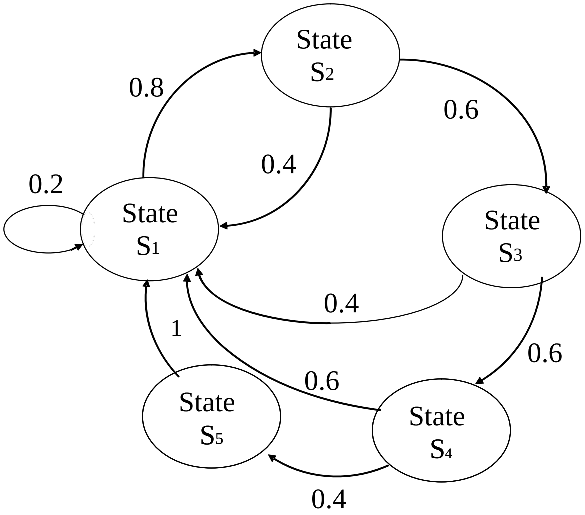


Figure 13.8. State transition diagram with transition probabilities

Parameter values mean that 20% of the time, good equipment is taken as bad by the inspection test (p_1=0,2) and 10% of the time, bad equipment is taken as good by the inspection test (p_2=0,1).

Good equipment taken as good by the test: $Gg_i=p_{i,i+1}x(1–p_1)$

Bad equipment taken as bad : $Bb_i=p_{i,1}x(1–p_2)$

Good equipment taken as bad by the test: $Gb_i=p_{i,i+1}xp_1$

Bad equipment taken as bad: $Bg_i=p_{i,1}xp_2$

Equipment probability to be maintained after the test: $m_{i,1}=Gb_i+Bb_i$

Equipment probability to continue without maintenance: $m_{i,i}$=Ggi+Bgi

Then, if we calculate the elements of the the matrices P and M, we have

$m_{2,1}=Bb_2+Gb_2 = p_{2,1}(1–p_2)+p_{2,3}p_1=0.8$

$m_{3,1}=Bb_3+Gb_3 = p_{3,1}(1–p_2)+p_{3,4}p_1=0.48$

$m_{2,1}=Bb_2+Gb_2 = p_{4,1}(1–p_2)+p_{4,5}p_1=0.62$

$m_{2,2}=Gg_2+Bg_2=p_{2,3}(1–p_1)+p_{2,1}p_2=0.52$

$m_{3,3}$=Bb_3+Bg_3=$p_{3,4}(1–p_1)+p_{3,1}p_2=0.52$

$m_{4,4}$=Gg_4+Bg_4=$p_{4,5}(1–p_1)+p_{4,1}p_2=0.38$

Then the matrix P will be:

$$P=\begin{bmatrix} 0.2 & 0.8 & 0 & 0 & 0 \\ 0.4 & 0 & 0.6 & 0 & 0 \\ 0.4 & 0 & 0 & 0.6 & 0 \\ 0.6 & 0 & 0 & 0 & 0.4 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and the matrix M is

$$M=\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0.48 & 0.52 & 0 & 0 & 0 \\ 0.48 & 0 & 0.52 & 0 & 0 \\ 0.62 & 0 & 0 & 0.38 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and the elements of matrix W for the first transition after maintenance can be obtained as follows:

$w_{2,1}=Mb_2/(Mb_2+Bb_2)=p_{2,1}p_2/0.52=0.077$

$w_{3,1}=Mb_3/(Mb_3+Bb_3)=p_{3,1}p_2/0.52=0.077$

$w_{4,1}=Mb_4/(Mb_4+Bb_4)=p_{4,1}p_2/0.38=0.16$

$w_{2,3}=Bb_2/(Mb_2+Bb2)=p_{2,3}(1–p_1)/0.52=0.92$

$w_{3,4}=Bb_3/(Mb_3+Bb3)=p_{3,4}(1–p_1)/0.52=0.92$

$w_{4,5}=Bb_4/(Mb_4+Bb4)=p_{4,5}(1–p_1)/0.38=0.84$

The matrix W will then be

$$W=\begin{bmatrix} 0.2 & 0.8 & 0 & 0 & 0 \\ 0.077 & 0. & 0.923 & 0 & 0 \\ 0.077 & 0 & 0 & 0.923 & 0 \\ 0.16 & 0 & 0 & 0 & 0.84 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

13.3 Semi-Markov Process Models for Planning

In many industrial situations, the problem of selecting a suitable maintenance policy involves repairable systems and a finite time period. Modelling this problem normally requires the representation of various corrective and/or preventive actions that could take place at different moments, driving the equipment to different states with different hazard rates. One approach to pattern the system under finite periods of time has been the use of semi-Markovian probabilistic models. As we will see later, these models allow the maintenance policy optimization using dynamic programming techniques (notice that now there is no possibility of finding a steady state like that in Markov processes described in the previous section, since the system will not operate long enough time to achieve it). These models are very flexible to represent a given system, but they are also complex and therefore very difficult to handle when the number of the possible system states increases.

This section explores the trade-off between flexibility and complexity of these models, and presents a comparison in terms of model data requirements *vs* potential benefits obtained with the model.

We will use a general continuous-time model known as semi-Markov decision process (SMDP). This model format has been used ([4,5]) to pattern the impact of maintenance strategies in a system and for a finite number of time periods. Basicaly, the SMDP generalizes the Markov decision processes that we have seen in previous sections by [6] : a) allowing, or requiring, the decision maker to choose actions whenever the system state changes; b) modelling the system evolution in continuous time; c) allowing the time spent in a particular state to follow an arbitrary probability distribution. The scalability in terms of number of possible states of the system, and number of maintenance actions, is an important reason why these are excellent models for the purpose of this section. Capabilities to represent additional problems will be added to an initial model, and new data requirements which appear will be studied.

13.3.1 Formulation of the SMDP Model

The notation that we will use is the following:

- ϕ_t : a random process with a finite set of states;
- E_i : state of the process (i=1,2,…,n);
- Im : state the system enters at time t_m;

- t_{ij}= T(i,j): one-step transition time (time between two adjacent transitions);
- $F_{ij}(t)$: distribution function of the one-step transition time ;
- P= $\{p_{ij}\}$: time homogeneous transition probabilities ;
- σ^h={σj(k); j=1,2,..,n , k=h,...,m–1}: maintenance strategy consisting in a set of MAs that the decision maker would follow, in m–h steps, starting at t_h;
- $\sigma_j(k)$: MA selected when arriving to state E_j at time t_k, with j=1,2,..,n and k=0,1,..,m–1;
- $r_{ij}(\sigma_i(k))$: cost/reward of a transition (from E_i to E_j) controlled by the strategy $\sigma_i(k)$ selected at t_k;
- $w_i(\sigma_i(k))$: expected cost of the step k+1 if the system is in state E_i at t_k, and controlled by $\sigma_i(k)$;
- $V_i(m–h,\sigma^h)$: average total accumulated cost for m–h steps of the process, departing from E_i, and for the strategy σ^h, considered since t_h;
- $V_i(m–h)$: minimum average value of the total accumulated cost of the process, assuming this process departs from E_i, at the time t_h, and for m–h steps. This minimum value will be produced by a given strategy.

Let us consider a random process ϕt with a finite set of states $\{E_1, E_2,\dots, E_n\}$. The transitions take place at random times t_1, t_2,…, t_n. Assume that the transition from the initial state Eo was at t_o=0. Let I_m denote the state the system enters at time t_m, with m=1,2,...; then

$$P\left\{Im = E_j \,/\, I_o, I_1,\dots\dots, I_{m-1} = E_i\right\} = P\left\{I_m = E_j \,/\, I_{m-1} = E_i\right\} = p_{ij} \quad (13.57)$$

The states Im form a time homogeneous Markov chain with transition probabilities P={p_{ij}}. Suppose that at time t_r the system reaches the state E_i, and that the next state to which it arrives is E_j, in tr+1. Then t_r+1–tr = {T(i,j)}. This time between two adjacent transitions is denoted one-step *transition time* (see also Gertsbakh [7], page 118). Functions Fij(t) will denote the one-step transition time distribution functions, that is:

$$F_{ij}(t) = P\{T(i,\ j) \le t\} \quad (13.58)$$

For each (i, j) there is a corresponding $F_{ij}(t)$ (in the case that p_{ij} =0 then $F_{ij}(t)$=0), so that the process can be determined as it is shown in Figure 13.9, where the system remained in state E_{io} during the time T(io,i1), and then went to state E_{i1}, *etc*.

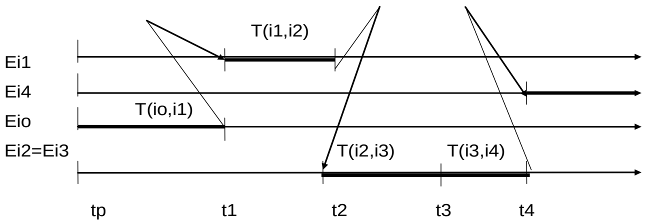


Figure 13.9. Transition process to the different states of the system

In the models to be presented in the next sections, several maintenance actions (MA) will be possible when the system is in a given state. When the system is in operation, different ages of the system to carry out the preventive maintenance are offered. When the system goes for preventive maintenance, the decision-maker may choose between different possible preventive alternatives (different in technology, instrumentation, spare parts used, *etc*.), requiring different times to be carried out. Finally, when the need for the corrective action arrives, the decision-maker can also choose between different possible repair alternatives (replacement, overhaul, repairs with differences in technology, instrumentation, spare parts used, *etc*.), also requiring different times for the repair to be carried out.

Each MA is selected immediately after the state transition. Therefore, when the m-th transition happened at random time t_m and the system went to the state E_{im}, the maintenance action chosen at time t_m will determine the stochastic mechanism of the transition to the state E_{im+1} at a certain random time t_m+1.

Let σ denote the maintenance strategy that the decision maker is following, as a rule to take decisions about the MAs to carry out in each state, and for a certain period of the equipment life time. In this section, only Markovian strategies will be considered, once it has been already demonstrated [8] that, for a number of finite time steps and maintenance actions, optimal strategy in our problem will be within that category. A Markovian strategy has the following property: “the election of the MA $\sigma_i(m)$ for the state E_i at the time t_m does not depend on the behaviour of the process ϕt until time t_m ; but only on the state E_i, on the number of steps, or on the time t_m”. Formally:

$$\sigma_i(m) = f(\phi^{t_m}, E_i, m, t_m) = f(E_i, m, t_m) \tag{13.59}$$

The optimality criteria will be to minimize the total cumulative expected cost of the system for a given number of transition steps. In order to do that, a first step is to determine the expected cost of a transition controlled by strategy $\sigma_i(k)$:

$$M\left\{ R_{ij}(T(i,j); \sigma_i(k))\right\} = r_{ij}(\sigma_i(k)) = \int_0^\infty R_{ij}(x; \sigma_i(k))\, dF_{ij}(x; \sigma_i(k)) \tag{13.60}$$

where Rij(T(i,j), σ_i(k)) is an arbitrary function which denotes the cost of the transition of the system when it goes from state E_i to state E_j, as a function of the time T(i,j), and also of the strategy selected when the system arrived to the state E_i at time t_k. The expected cost of a step could be then expressed as follows:

$$w_i(\sigma_i(k)) = \sum_{j=1}^{n} p_{ij}(\sigma_i(k)) * r_{ij}(\sigma_i(k)) \tag{13.61}$$

Once Rij(T(i,j),σ_i(k)) are additive, a recurrent relation can be established, and the dynamic programming formulation can be considered. Let V_i (m–h, σ^h) denote, if h=m–1 for t=t_{m-1}, the average total cost of the last step. Then:

$$V_i(m-(m-1), \sigma^{m-1}) = V_i(1, \sigma^{m-1}) \tag{13.62}$$

Let σ^{*m-1} denote the strategy that will produce the minimum value for previous expression in Equation (13.62), then

$$V_i(1, \sigma^{*m-1}) = V_i(1) = \min_{\sigma^{m-1}} \{V_i(1, \sigma^{m-1})\} \tag{13.63}$$

Using this notation, we can generalize according to Howard [9] the recurrent relation

$$V_i(m-h) = \min_{\sigma i(h)} \left\{ w_i(\sigma_i(h)) + \sum_{j=1}^{n} p_{ij}(\sigma_i(h)) \times V_j(m-h-1) \right\} \tag{13.64}$$

with i=1,..., n; h=0,...,m ; and $V_j(0)=0$.

The results of the algorithm will be the optimal strategy (*i.e.* optimal MA for each state and at every step, see Figure 13.10), and it is accepted according to Bellman's principle in dynamics programming [10] that the optimal strategy for the complete process is composed by the optimal strategies for each step of the process. Although dynamic programming has been used in this and other contributions [11] to solve the preventive maintenance optimization problem for multi-state systems and different possible preventive actions, the reader is also referred to recent interesting work [12] approaching the problem through other optimization techniques such as genetic algorithms.

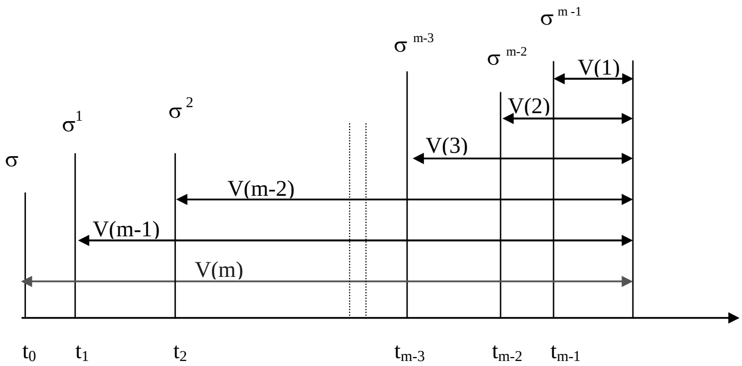
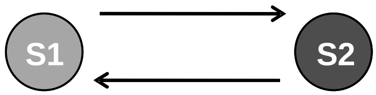


Figure 13.10. Sequence of calculations for the total accumulated cost, and its relationship with the time steps of the system (regardless of the state)

13.3.2 Modelling Corrective Maintenance

In many real situations the decision-maker in maintenance faces the following problem: the equipment can be repaired in different ways, and there is a way to a faster repair if a suitable investment is made. Since the time of the analysis is finite, "should we go ahead and spend time and money to ensure a certain degree of time to repair a failure mode in a system?". An example would be an investment in specialised tools to speed up the replacement of a component in an engine, which is scheduled to run for a specific number of months in a certain facility. For this study, the initial consideration of two possible system states (Figure 13.11) is suggested.



where

S_1: operation 100%.
S_2: corrective maintenance.

Figure 13.11. Basic corrective maintenance model

Obviously, the better the maintenance resources the faster the repair, and therefore the lesser the time the system will be in S_2.

Assuming MA to be two different corrective maintenance possibilities (A or B), data needed for the model would be:

Time related probabilistic functions:

- $F(t)$ is the distribution function of the failures of the equipment, defined in the interval $0 < t \leq T1$, where T1 in the maximum time that the equipment can operate without a failure;
- $F_A(t)$ and $F_B(t)$, are the distribution function of the time the equipment remains under corrective maintenance, when type A and B corrective maintenance, respectively, are carried out;

Costs and rewards:

- K_1 , reward per time unit the system remains in state 1 (S1 - operation);
- K_{2A} and K_{2B}, cost per time unit the system remains in state 2 (S2 - corrective), when corrective/repairs type are A or B are carried out;
- S_{12} transition cost from operation to repair state;
- S_{21} transition cost from repair state to operation;

Matrices to describe the process:

- [P] probability of transition matrix (p_{ij} is the probability to go from i to j);
- [F] transition time matrix (F_{ij} is the time in state i before system goes to j);

$$[P] = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{13.65}$$

$$[F] = \begin{bmatrix} 0 & F(t) \\ F_A(t) or F_B(t) & 0 \end{bmatrix} \tag{13.66}$$

Note that F_{21} will be $F_A(t)$ or $F_B(t)$ according to the selected MA in S_2;

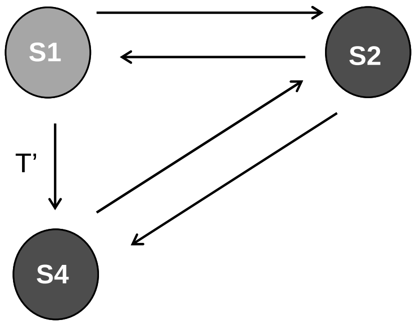
- [R] Cost and reward matrix, where $r_{ij}(\sigma i) = (R_{ij}(\sigma i) + S_{ij})$;

$$r_{ij}(\sigma j) = \begin{bmatrix} 0 & r_{12}(\sigma_1) \\ r_{21}(\sigma_2) & 0 \end{bmatrix} = \begin{bmatrix} 0 & K_1 t_{12} + S_{12} \\ R_{21}(\sigma_2) + S_{21} & 0 \end{bmatrix} \tag{13.67}$$

where $R_{21}(\sigma_2)$ will be $K_{2A}t_{21}$ or $K_{2B}t_{21}$ according to the MA selected in S_2, and $t_{ij}=T(i,j)$.

13.3.3 Modelling Imperfect Corrective Maintenance

In other real situations, there are various choices when selecting the repairs to carry out. For instance, using non-original — with less cost — spare parts is sometimes considered, or simplifying the repair procedures by reducing the number of verifications, *etc*. Lowering the requirements for a repair (changing the corrective maintenance action) usually results in different behaviour of the equipment once the repair is finished. This new situation of the equipment (S4) has to be considered for the analysis of the problem (Figure 13.12). In this particular case, it is assumed that the system would reach to such a different — less efficient — state, after a certain number of operating hours of the full efficient system (S1). An example of this would be using non-original cylinder kits, less wear resistant, for the engine repair referred to above. Now, three states are suggested.



where
S_1: operation 100%.
S_2: corrective maintenance.
S4: operation < 100%.

Figure 13.12. Imperfect corrective maintenance model

For this case, the less requirements for the repair, the higher the probability of arriving at S_4 after the repair.

New data requirements to deal with this problem are:
Time related probabilistic functions:

- T' denotes the maximum time the system can operate in S1 before going to S_4; Note that $T' \leq T_1$;
- G(t) is the distribution function of the failures of the equipment in S4, defined in the interval $0<t\leq T'_1$, where T'1 in the maximum time that the equipment can operate without a failure in S4;
- p_A, is the probability to go from state 2 to state 1, after a repair type A;
- p_B, is the probability to go from state 2 to state 1, after a repair type B;

Cost and rewards:

- K_4 is the reward per time unit is the system stays in state 4 (operation<100%);
- S_{14} transition cost from operation 100% to operation <100%;
- S_{24} transition cost from repair state to operation <100%;
- S_{42} transition cost from operation <100% to repair state.

The probability of transition and the transition time matrices would be

$$[P]=\begin{bmatrix} 0 & F(T') & 1-F(T') \\ (p_A)or(p_B) & 0 & (1-p_A)or(1-p_B) \\ 0 & 1 & 0 \end{bmatrix} \tag{13.68}$$

$$[F]=\begin{bmatrix} 0 & F_{12}(t) & F_{14}(t) \\ (F_A(t))or(F_B(t)) & 0 & (F_A(t))or(F_B(t)) \\ 0 & G(t) & 0 \end{bmatrix} \tag{13.69}$$

where:

$$F12(t) = \begin{cases} F(t)/F(T') & \text{if } t < T' \\ 1 & \text{if } t \geq T' \end{cases} \quad ; \quad F14(t) = \begin{cases} 0 & \text{if } t < T' \\ 1 & \text{if } t \geq T' \end{cases} \tag{13.70}$$

The cost and reward matrix would be as follows:

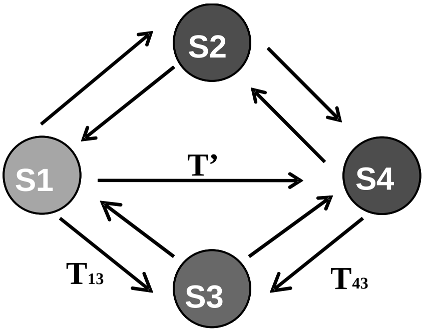
$$r_{ij}(\sigma_j)=\begin{bmatrix} 0 & r_{12}(\sigma_1) & r_{14}(\sigma_1) \\ r_{21}(\sigma_2) & 0 & r_{24}(\sigma_2) \\ 0 & r_{42}(\sigma_4) & 0 \end{bmatrix}=\begin{bmatrix} 0 & k_1t_{12}+S_{12} & k_1T'+S_{14} \\ r_{21}(\sigma_2) & 0 & R_{24}(\sigma_2)+S_{24} \\ 0 & k_4t_{42}+S_{42} & 0 \end{bmatrix} \tag{13.71}$$

where $R_{21}(\sigma_2)$ will be $K_{2A}t_{21}$ or $K_{2B}t_{21}$ according to the MA selected in S_2, and $R_{24}(\sigma_2)$ will also be $K_{2A}t_{24}$ or $K_{2B}t_{24}$ according to the MA selected, and t_{ij}=T(i,j).

13.3.4 Modelling Preventive Maintenance

The opportunity of a maintenance preventive plan is now considered. The idea is to deal with the problem faced by the decision-maker when studying the possibility of selecting a preventive maintenance option — what to do and how often — for a given timeframe. Since preventive maintenance options could also be of different cost, time to be carried out, and technical requirement levels, the same considerations already made for the repairs are taken into account here.

Also in this case, the less the requirements for preventive maintenance, the higher the probability of arriving at S4 after the maintenance. Additionally, the decision-maker will have to select the operating time (equipment age since last maintenance operation) for preventive action to be carried out (T13 for S1 and T43 for S4; see Figure 13.13).



where
S_1: operation 100%.
S_2: corrective maintenance.
S_3: preventive maintenance.
S_4: operation < 100%.

Figure 13.13. Preventive maintenance model

New data requirements:

New MAs:

- T_{13} time after which the preventive maintenance is carried out when the system is in S_1. In the model three values are offered to the decision-maker;
- T_{43} same for state 4, considering also that $T_{13} \geq T_{43}$;
- Two possible different preventive maintenance (C or D);

Time related probabilistic functions:

- $G_C(t)$ and $G_D(t)$ are the distribution functions of the time the equipment remains under preventive maintenance, when type C and D preventive maintenance, respectively, are carried out;
- p_C , is the probability to go from state 3 to 1, after a preventive type C;
- p_D , is the probability to go from state 3 to 1, after a preventive type D;

Cost and rewards:

- K_{3C} and K_{3D} cost per time unit the system remains in state 3 (preventive), when preventives type are C or D are carried out;
- S_{13} transition cost from operation 100% to preventive maintenance;
- S_{31} transition cost from preventive maintenance to operation 100%;
- S_{34} transition cost from preventive maintenance to operation <100%;
- S_{43} transition cost from operation <100% to preventive maintenance;

Matrices to describe the process:

- The probability of transition and the transition time matrices would be

$$[P]=\begin{bmatrix} 0 & p_{12} & p_{13} & p_{14} \\ (p_A)or(p_B) & 0 & 0 & (1-p_A)or(1-p_B) \\ (p_C)or(p_D) & 0 & 0 & (1-p_C)or(1-p_C) \\ 0 & G(T_{43}) & 1-G(T_{43}) & 0 \end{bmatrix} \quad (13.72)$$

where

	P_{12}	P_{13}	P_{14}
if $T_{13} \le T'$	$F(T_{13})$	$1-F(T_{13})$	0
if $T_{13} > T'$	$F(T')$	0	$1-F(T')$

$$[F]=\begin{bmatrix} 0 & F_{12} & F_{13} & F_{14} \\ (F_A(t))or(F_B(t)) & 0 & 0 & (F_A(t))or(F_B(t)) \\ (G_C(t))or(G_D(t)) & 0 & 0 & (G_C(t))or(G_D(t)) \\ 0 & G_{42}(t) & G_{43}(t) & 0 \end{bmatrix} \quad (13.73)$$

where

	F_{12}	F_{13}	F_{14}
if $T_{13} \le T'$	$F_{12}(t)$	$F_{13}(t)$	0
if $T_{13} > T'$	$F'_{12}(t)$	0	$F_{14}(t)$

with

$$F_{12}(t)=\begin{cases} F(t)/F(T_{13}), & t < T_{13} \\ 1, & t \ge T_{13} \end{cases} \qquad F_{13}(t)=\begin{cases} 0, & t < T_{13} \\ 1, & t \ge T_{13} \end{cases} \quad (13.74)$$

$$F'_{12}(t)=\begin{cases} F(t)/F(T'), & t < T_{13} \\ 1, & t \ge T_{13} \end{cases} \qquad F14(t)=\begin{cases} 0, & t < T' \\ 1, & t \ge T' \end{cases} \quad (13.75)$$

$$G_{42}(t)=\begin{cases} G(t)/F(T_{43}), & t < T_{43} \\ 1, & t \ge T_{13} \end{cases} \qquad G43(t)=\begin{cases} 0, & t < T_{43} \\ 1, & t \ge T_{43} \end{cases} \quad (13.76)$$

- Finally, the cost and reward matrix for this case would be as follows:

$$r_{ij}(\sigma_i) = \begin{bmatrix} 0 & K_1 t_{12} + S_{12} & K_1 T_{13} + S_{13} & K_1 T' + S_{14} \\ R_{21}(\sigma_2) + S_{21} & 0 & 0 & R_{24}(\sigma_2) + S_{24} \\ R_{31}(\sigma_3) + S_{31} & 0 & 0 & R_{34}(\sigma_3) + S_{34} \\ 0 & K_4 t_{42} + S_{42} & K_4 T_{43} + S_{43} & 0 \end{bmatrix} \quad (13.77)$$

where, again, $R_{21}(\sigma_2)$ will be $K_{2A}t_{21}$or $K_{2B}t_{21}$ according to the MA selected in S_2, and $R_{24}(\sigma_2)$ will be $K_{2A}t_{24}$ or $K_{2B}t_{24}$ according to the MA selected in that state. Also $R_{31}(\sigma_3)$ will be $K_{3C}t_{31}$ or $K_{3D}t_{31}$ according to the MA selected in S_3, and $R_{34}(\sigma_3)$ will be $K_{3C}t_{31}$or $K_{3D}t_{34}$ according to the MA selected in that state.

13.3.5 Case Study

The following example was developed for the mining industry [13]. The problem to deal with is the analysis of a critical failure in a dumper truck engine of an open pit mine. The failure was in the air intake system, causing a lack of air intake pressure in the air conduction from the turbo exhaust into the air box, especially when the engine was at full load, and therefore lack of power in the truck and the subsequent problems related to increasing risk and cost of day to day mining operations, and high risk of fast deterioration of the engine due to a lack of filtration in the air intake.

The failure was recorded in the CMMS of the mine and the relevant data was as follows: The failure rate was distributed as a two-parameter Weibull (2.5,1700); therefore with a MTBF = 1500 running hours of the truck, the cost of the failure in terms of personnel time to take the truck to the workshop, reorganize the mining operations, serious damage to the engine, *etc*., was evaluated in US$ 45000 per failure (S_{12}), The estimated cost to bring the truck back into operation after the repair, testing the system on the pit tracks, *etc*., was assumed to be around 100 US$ per failure (S_{21}). There were two possible repair options: Option A, removing, repairing the damaged element in the workshop, and re-installing it in the engine ($F_A(t)$ =N(68,4), K_{2A}= 100 US$/repair hour); Option B, removing the component and installing a remanufactured component in stock ($F_B(t)$ =N(30,2), K_{2B}=120 US$/repair hour). The amount of money perceived by the company responsible for the dumper truck's maintenance was 100 US$ per running hour of the truck (K_1). In Table 13.4, results for the model in Section 13.3.2 considering the previous data, are presented.

Table 13.4. Optimal strategy and reward/cost for Scenario 1 (in 1000 US$)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step10
State 1 Operation	455	416	371	335	285	255	198	178	106	109.1
State 2 Repair	402	356	321	270	241	182	165	91	93	–3.7
Optimal Repair	B	B	B	B	B	B	B	B	B	B

The model shows that repair B would be convenient while K_{2B} is under 1700 US$/h. Hence, for example, when K_{2B}=1750 US$/h (Scenario 2), the model output is as presented in Table 13.5.

Table 13.5. Optimal strategy and reward(cost) for Scenario 2 (in 1000 US$)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step10
State 1 Operation	271	255	231	217	190	178	149	139	106	109
State 2 Repair	193	167	154	126	117	84	80	41	44	–7
Optimal Repair	A	B	A	B	A	B	A	B	B	A

Let us now use the second model introduced in Section 13.3.3 and consider a third state to take into account cases when the system performs with less efficiency (S_4) than normal, as a consequence of long operating time or less requirements for the failure repair. In this example, the data observed was: Failure rate in S_4 was distributed as a two-parameter Weibull (3, 560) therefore with a MTBF of 500 running hours, S_{42}=S_{12}=1000 US$/failure, S_{41}=S_{21}=100 US$/failure, S_{14}=0, K_1=40 US$/h, K_4=35 US$/h (meaning that the truck could perform less cycles per hour because of the lower power). Finally p_A=0.5 and p_B =0.9, meaning that repair B drives the system to perfect operation (S_1) with a higher probability than repair A. The results of the model, when this data is added to previous Scenario 1, are in Table 13.6.

Now notice how the results in Table 13.7 show how repair A is optimal in all steps even for K_{2B}=1750 US$/h

Table 13.6. Optimal strategy and reward(cost) for Scenario 2 (in 1000 US$)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step10
State 1 Operation	272	244	214	206	169	142	144	89	75	83
State 2 Repair	234	204	194	160	132	131	82	62	70	–3.7
State 4 Operation <100%	193	184	150	121	120	72	52	60.0	–14	–10
Optimal Repair	B	B	B	B	B	B	B	B	B	B

Finally, we use the third model introduced in the previous section, with a new state (S_3), where the system stays while its preventive maintenance is being carried out. The idea is to analyse whether preventive maintenance is convenient or not, and to try several options for it. For instance, frequency of preventive maintenance to test in S_1 will be 600, 800 h or no preventive maintenance, and 200, 400 h or no preventive maintenance in S_4.

Table 13.7. Optimal strategy and reward/cost for Scenario 2, and 3 states (in 1000 US$)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step10
State 1 Operation	159	150	137	127	118	101	103	77	74	83
State 2 Repair	103	93	81	72	59	50	41	21	29	–7
State 4 Operation <100%	82	71	62	49	40	31	11	19	–17	–10
Optimal Repair	A	A	A	A	A	A	A	A	A	A

The new data considered now is: $G_C(t)$ =N(5,1), $G_D(t)$ =N(5,1), S_{31}=S_{34}=–25 US$/preventive operation, and S_{13}=S_{43}=0 US$/preventive operation. Moreover P_C=0.6 and P_D=0.95 (preventive C will drive the system to S_1 with lower probability than preventive D) and K_{3C}= 15 US$/h while K_{3D}= 30 US$/h The results of the model, when this data is added to previous Scenario 1, are presented in Table 13.8, and for Scenario 2 in Table 13.9 (where NO means no preventive action to be carried out).

Table 13.8. Optimal strategy and reward/cost for Scenario 1, and 4 states (in 1000 US$)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step10
State 1	376	349	308	283	242	216	172	149	92.8	83.4
State 2	340	299	273	232	206	161	139	81	72	–3.7
State 3	346	305	280	238	213	168	146	88	79	–0.1
State 4	315	291	250	224	178	157	98	91	11	12.3
Optimal Repair	B	B	B	B	B	B	B	B	B	B
Optimal Preventive	D	D	D	D	D	D	D	D	D	C
Optimal T13	NO	800	800	800	NO	800	NO	800	NO	NO
Optimal T43	200	200	200	200	200	200	200	200	200	400

Note that when carrying out preventive maintenance, the average running time of the system for the same number of steps could probably be lower, due to the fact that the system is frequently stopped to be serviced; however, the savings in cost of the failures increases the reward considerably for both scenarios.

Table 13.9. Optimal strategy and reward/cost for Scenario 2, and 4 states (in 1000 US$)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step10
State 1	357	335	293	271	229	208	162	145	91	83
State 2	300	258	236	192	173	122	110	44	40	–7
State 3	332	290	268	225	205	159	142	87	79	–0.1
State 4	301	279	236	215	169	152	97	89	11	12
Optimal Repair	A	A	A	A	A	A	A	A	A	A
Optimal Preventive	D	D	D	D	D	D	D	D	D	C
Optimal T13	NO	800	NO	800	NO	800	NO	800	NO	NO
Optimal T43	200	200	200	200	200	200	200	200	200	400

Although, it is not the purpose of this section to simulate the system but to optimize maintenance actions, it is easily understandable that simulation runs could be carried out in order to establish the average time the system is available for a certain time frame, and the average cost per hour of the maintenance according to the different optimal strategies and models considered.

In summary, the results obtained clearly show how the increase in the complexity of the models adds new analysis capabilities for the maintenance decision-maker. This trade-off between flexibility and complexity has been explored in the example of real mining operations. In this example, increasing the initial complexity of the model allows the decision maker to reach a level of better information and understanding about the system operating cost/reward, as a consequence of a more real assessment of possible system states and suitable maintenance actions. A second increase in model complexity offers a faster tool to select the best feasible strategy to face the problem of preventive maintenance planning. The reader can at the same time identify the new data requirements appearing throughout the process, and evaluate the difficulty of gathering this data in a specific industrial scenario. Nowadays, since new technologies are producing fast change in industrial environments, this chapter claims that there is a clear opportunity for the research in equipment maintenance optimization for finite time periods.

13.4 References

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14

Models to Deal with Maintenance Scheduling Issues

14.1 Introduction to the Maintenance Scheduling Process

Maintenance scheduling is a process in which different maintenance tasks or activities are assigned to resources and then placed within certain time windows in order to be accomplished. It is common to find the maintenance schedule to be developed at different levels or time horizons:

- *Master long term schedule* (from one quarter to one year). The purpose of this maintenance schedule will be to balance the required maintenance resources during the time window, to compare those resources with those available in the organization and to schedule the procurement of the necessary resources in advance. This mid-term maintenance capacity planning can be accomplished using the MRP method as explained in a previous chapter. This type of time period scheduling can also be analysed in case of maintenance activities in a shut down or a large maintenance job, and the CPM techniques also apply;
- *Weekly maintenance schedule*. This is generated departing from the long term schedule and takes into account current production schedules and relevant economical considerations. This schedule is updated weekly and normally covers a couple of weeks in time. The maintenance task sequence will be based on their priority. CPM and PERT techniques can be used to produce this schedule, as well as integer programming;
- *Daily maintenance schedule*. This is generated departing from the weekly schedule and normally one day before the maintenance tasks are released. Schedules are frequently interrupted due to urgent tasks or emergencies that may appear. Although there are priorities to release the different tasks, it is common that each maintenance supervisor has the responsibility to assign the tasks according to these priorities.

There are certain issues, especially for short term scheduling, that are required in order to produce suitable maintenance work programs [1]:

- Precise work orders properly explaining the work to be carried out, the required resources, work procedures and priority;
- Time standards for each job, based on suitable time measurements methods;
- Information regarding technicians available per skill and shift;
- Spare parts inventory status and procurement information;
- Information concerning tools and specific maintenance equipment availability;
- Production schedule information, including details regarding possible times for equipment maintenance availability, ensuring minimal impact on production schedules;
- Maintenance jobs priorities. These priorities should be properly defined together with the production department;
- Information regarding previously scheduled jobs that have been delayed for any reason.

Once we have considered all previous points, a standard daily scheduling procedure would include the steps depicted in Figure 14.1.

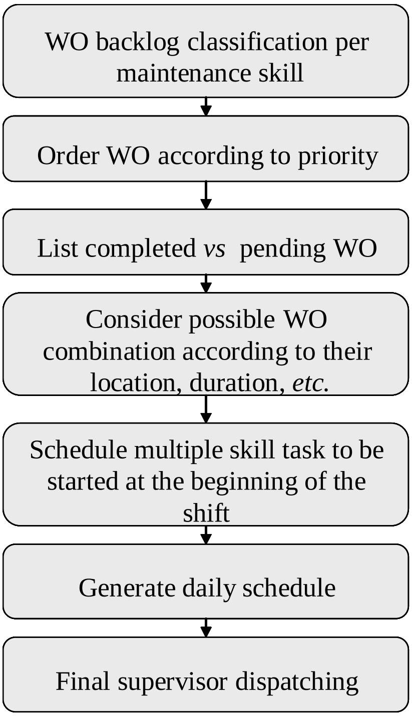


Figure 14.1. Daily scheduling process

Obviously, when the number of tasks increases, or when we are considering an important maintenance project during a plant shut down, simple heuristic rules and experience will not be enough. In these cases, it will be necessary to use quantitative methods in order to generate suitable schedules and to reach acceptable balance of resources. In the following sections of this chapter we will review those methods and will apply them to practical maintenance situations as explained in several case studies.

14.2 CPM and PERT Methods

14.2.1 History of Network Analysis

Generally speaking, CPM (Critical Path Method) and PERT (Programme Evaluation Review Technique) are effective methods of scheduling for project management.

CPM/PERT — or Network Analysis as the technique is sometimes called — developed along two parallel streams, one industrial and the other military. CPM was the discovery of M.R.Walker of E.I.Du Pont de Nemours and Co. and J.E. Kelly of Remington Rand, *circa* 1957 [2]. The first test was made in 1958, when CPM was applied to the construction of a new chemical plant. In March 1959, the method was applied to a maintenance shut-down at the Du Pont works in Louisville, Kentucky. Unproductive time was reduced from 125 to 93 h.

PERT was devised in 1958 for the POLARIS missile program by the Program Evaluation Branch of the Special Projects office of the U.S.Navy, aided by the Lockheed Missile Systems division and the Consultant firm of Booz-Allen and Hamilton. The calculations were so arranged that they could be carried out on the IBM Naval Ordinance Research Computer (NORC) at Dahlgren, Virginia.

Planning, scheduling and control are considered to be basic managerial functions, and CPM/PERT has been rightfully accorded due importance in literature on Operations Research and Quantitative Analysis.

Besides the technical benefits, PERT/CPM has provided a focus around which managers can brain-storm and put their ideas together. It is a fantastic communication tool by which thinkers and planners at one level can communicate their ideas, their doubts and fears to another level. Most important, it has become a useful tool for evaluating the performance of individuals and teams. There are many variations of CPM/PERT which have been useful in planning costs, scheduling manpower and machine time. CPM/PERT can answer the following important questions:

- How long will the entire project take to be completed?
- What are the risks involved?
- Which are the critical activities or tasks in the project which could delay the entire project if they were not completed on time?
- Is the project on schedule, behind schedule or ahead of schedule?

- If the project has to be finished earlier than planned, what is the best way to do this at the least possible cost?

14.2.2 The Critical Path Method (CPM)

CPM models the activities and events of a project as a network. CPM originally was developed as an activity on node (AON) network, but some project planners prefer to specify the activities on arcs (AOA), as in Figure 14.2.

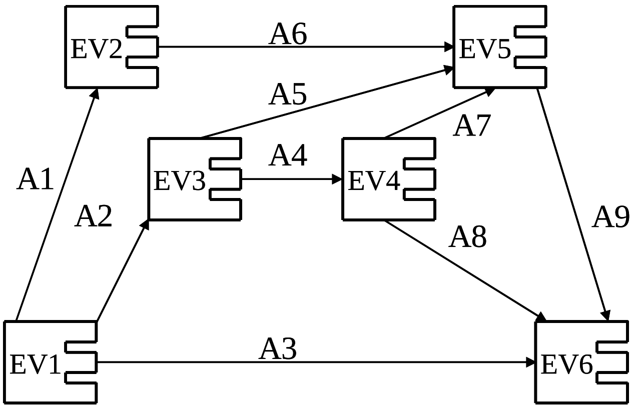


Figure 14.2. Sample CPM network (AOA)

The steps to follow for the implementation of the CPM method are as follows:

1. Specify the individual activities. From the work breakdown structure, a listing can be made of all the activities in the project. This listing can be used as the basis for adding sequence and duration information in later steps.
2. Determine the sequence of those activities. Some activities are dependent on the completion of others. A listing of the immediate predecessors of each activity is useful for constructing the CPM network diagram.
3. Draw a network diagram. Once the activities and their sequencing have been defined, the CPM diagram can be drawn.
4. Estimate the completion time for each activity. The time required to complete each activity can be estimated using past experience or the estimates of people in the know. CPM is a deterministic model that does not take into account variation in the completion time, so only one number is used for an activity's time estimate.
5. Identify the critical path (longest path through the network). The critical path is the longest-duration path through the network. The significance of the critical path is that the activities that lie on it cannot be delayed without delaying the project. Because of its impact on the entire project, critical path analysis is an important aspect of project planning. The

critical path can be identified by determining the following parameters for each activity:

D_{ij} : Duration of the activity *(i,j)*

ES_i: Earliest start time: the earliest time at which any activity departing from node *i* can start, given that its precedent activities must be completed first.

With $ES_j=max\{EF_{ij}\}$ for all *(i,j)* activities in the network

LF_i: Latest finish time: the latest time at which the activity entering in node *i* can be completed without delaying the project.

With $LF_i=min\{LS_{ij}\}$ for all *(i,j) activities in the network*

EF_{ij}: Earliest finish time, equal to the earliest start time for the activity *(i,j)* plus the time required to complete the activity.

With $EF_{ij}=ES_i+D_{ij}$ for all *(i,j) activities in the network*

LS_{ij}: Latest start time, equal to the latest finish time minus the time required to complete the activity.

With $LS_{ij}=LF_i–D_{ij}$ for all *(i,j) activities in the network*

The total slack time for an activity is the time between its earliest and latest start time, or between its earliest and latest finish time. Slack is the amount of time that an activity can be delayed past its earliest start or earliest finish without delaying the project. The critical path is the path through the project network in which none of the activities have slack, that is, the path for which any activity (i,j) fulfils

$ES_i = LF_i$
$ES_j = LF_j$
$ES_j – ES_i = LF_j – LF_i = D_{ij}$ for all activities in the path

A delay in the critical path delays the project. Similarly, to accelerate the project it is necessary to reduce the total time required for the activities in the critical path. Of course critical activities will have to be scheduled in their earliest starting time since those tasks have no slack. Non-critical activities can however offer flexibility in the scheduling and for the resources balance. Each non-critical activity has two types of slacks: the total slack (TS_{ij}) and the free slack (FS_{ij}), defined as follows:

$TS_{ij} = LF_j – ES_i – D_{ij}$
$FS_{ij} = ES_j – ES_i – D_{ij}$

Note that free slacks assume that all the activities start as soon as possible. Total slacks can be used to balance resources, diminishing maximal resources requirements.

6. Update the CPM diagram as the project progresses. As the project progresses, the actual task completion times will be known and the

network diagram can be updated to include this information. A new critical path may emerge, and structural changes may be made in the network if project requirements change.

14.2.3 The Programme Evaluation Review Technique (PERT)

CPM was developed for complex but fairly routine projects with minimal uncertainty in the project completion times. For less routine projects there is more uncertainty in the completion times, and this uncertainty limits the usefulness of the deterministic CPM model. An alternative to CPM is the PERT project planning model, which allows a range of durations to be specified for each activity.

PERT originally was an activity on arc (AOA) network, in which the activities are represented on the lines and milestones on the nodes (through time, some people began to use PERT as an activity on node network — AON —). The milestones are generally numbered so that the ending node of an activity has a higher number than the beginning node (*i.e.* j>i in the top of Figure 14.3, where in each node k also appears the earliest — t_k — and the latest — T_k — time of that event k).

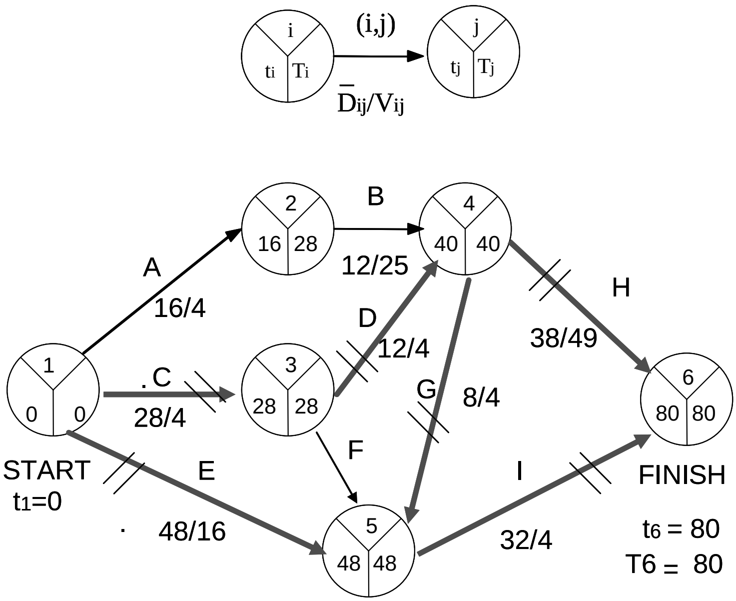


Figure 14.3. Sample PERT AOA network

PERT considers uncertainty assuming that the time estimation for the duration of each activity (i,j) has three possible values:

O_{ij}=*Optimistic time* — generally the shortest time in which the activity *(i,j)* can be completed. It is common practice to specify optimistic times to be three standard deviations from the mean so that there is approximately a 1% chance that the activity will be completed within the optimistic time.

P_{ij}=*Pessimistic time* — the longest time that an activity might require. Three standard deviations from the mean is commonly used for the pessimistic time.

M_{ij}=*Most likely time* — the completion time having the highest probability. Note that this time is different from the expected time.

PERT assumes a beta probability distribution for the time estimates. For a beta distribution, the expected time for each activity can be approximated using the following weighted average:

$$\overline{D}_{ij} = \frac{O_{ij} + P_{ij} + 4M_{ij}}{6} \tag{14.1}$$

To calculate the variance for each activity completion time, if three standard deviation times were selected for the optimistic and pessimistic times, then there are six standard deviations between them, so the variance is given by

$$V_{ij} = \left(\frac{P_{ij} - O_{ij}}{6} \right)^2 \tag{14.2}$$

Assume that all, a large number, network activities are independent. Let X_i denote the time when event in node i takes place. X_i is a random variable and is the sum of all activities within the path P from start to node i. When there is more than one path we will normally select the most uncertain path, according to its variance. Since X_i is the sume of independent random variables, the CLT states that X_i distribution is approximately normal with the following expected time and variance:

$$E(X_i) = \sum_{(i,j)\in P} \overline{D}_{ij} \tag{14.3}$$

$$Var(X_i) = \sum_{(i,j)\in P} V_{ij} \tag{14.4}$$

and, according to this, we can calculate the probability to arrive at the node i of the project within a certain time period T_i, as follows:

$$\Pr\left[X_i \le T_i\right] = \Pr\left[\frac{X_i - E(X_i)}{\sqrt{Var(X_i)}} \le \frac{T_i - E(X_i)}{\sqrt{Var(X_i)}} \right]$$

$$= \Pr\left[Z \le Z_{ii}\right] = \Phi(Z_i) \tag{14.5}$$

where Φ is the normal standard distribution. As an example, let us take the nework in Figure 14.3. The total duration time (TT) of that project would be distributed N(80,20) according to the following calculations

If we consider the critical path 1-3-4-5-6:

$$Var(X_i) = \sum_{(i,j)\in P} V_{ij} = V_{13} + V_{34} + V_{45} + V_{56} = 4 + 4 + 4 + 4 = 16$$

For the critical path 1-5-6:

$$Var(X_i) = \sum_{(i,j)\in P} V_{ij} = V_{15} + V_{56} = 16 + 4 = 20$$

Notice that we would select highest variability (20, the highest risk). For both paths:

$$E(X_i) = \sum_{(i,j)\in P} \overline{D}_{ij} = 80$$

If we know the probability distribution of the project completion time, N(80,20), we can find out, for instance, what the probability is of finishing the project before 85 days, as follows:

$$\Pr[X_6 \le 85] = \Pr\left[z \le \frac{85-80}{\sqrt{20}}\right] = \Pr[z \le 1.12] = 0.8686$$

Another question could be: what is the probability of finishing the project after 75 days?

$$\Pr[X_6 > 75] = 1 - \Pr[X_6 \le 75] = 1 - \Pr[z \le -1.12] = 1 - 0.1314 = 0.8686$$

Another example would be to find out the probability of finishing between 90 and 95 days:

$$\Pr[90 < X_6 \le 95] = \Pr[X_6 \le 95] - \Pr[X_6 \le 90] = \Pr\left[z \le \frac{15}{\sqrt{20}}\right] - \Pr\left[z \le \frac{10}{\sqrt{20}}\right] =$$

$$= \Pr[z \le 3.35] - \Pr[z \le 2.24] = 0.0121$$

or finally, what is the project duration that has 80% probability of not being exceeded?:

$$0.8 = \Pr\left[z \le 0{,}84\right]$$

Then

$$0.84 \approx \frac{X_6 - 80}{\sqrt{20}}, \ \rightarrow X_6 = 84 \text{ days}$$

PERT also has some of the following weaknesses:

- The activity time estimates are somewhat subjective and depend on judgement. In cases where there is little experience in performing an activity, the numbers may only be a guess. In other cases, if the person or group performing the activity estimates the time, there may be bias in the estimate.
- Even if the activity times are well-estimated, PERT assumes a beta distribution for these time estimates, but the actual distribution may be different. Even if the beta distribution assumption holds, PERT assumes that the probability distribution of the project completion time is the same as that of the critical path. Because other paths can become the critical path if their associated activities are delayed, PERT consistently underestimates the expected project completion time.
- The underestimation of the project completion time due to alternate paths becoming critical is perhaps the most serious of these issues. To overcome this limitation, Monte Carlo simulations can be performed on the network to eliminate this optimistic bias in the expected project completion time.

14.2.4 A Maintenance Project Case Study with CPM/PERT

Suppose that a certain large maintenance operation has to be carried out during an imporant plant shut down. The operation consists of three important maintenance tasks A, B and C that have to be accomplished within a maximum of 150 days.

Each task requires the procurement activities MPA, MPB and MPC respectively, to provide spare parts and maintenance materials of a certain type. After that, each task requires the utilization of two existing resources in the plant: equipment V and equipment W. At present, there is only one unit per each equipment. The name of the tasks, number of days required per task and equipment utilization are in Figure 14.4, where the sequence of activities per task are also provided. How should we schedule maintenance activities?

In this case study before applying the CPM/PERT method, and in order to sequence the maintenance activities meeting due dates, we have used a dispatching rule to assign resources to task (notice that by applying the method assuming infinite capacity and balancing resources later, the reader can check how we cannot meet the due date).

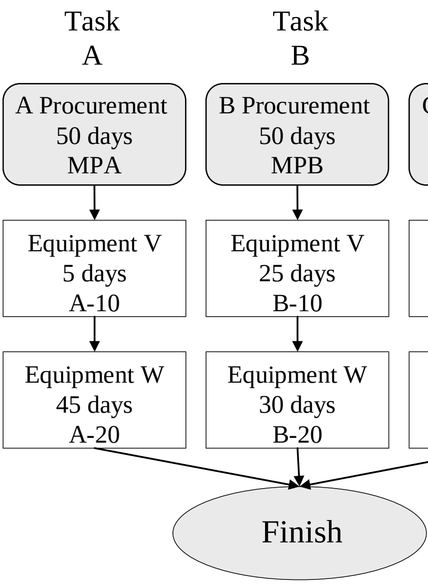


Figure 14.4. Maintenance project definition

The dispatching rule used is S.P.T. (Shortest Processing Time), once we need to minimize the project makespan. Therefore, the resulting sequence of the maintenance task is A→B→C.

Later we used WinQsb software [3] to solve the problem and obtained the graph in Figure 14.5 (AON graph), showing the critical activities in the top horizontal line of nodes. Note that each node of the graph contains information about the activity that the node represents (from top-down and from left-right): earliest start date, earliest finish date, name of the activity, latest start date, latest finish date.

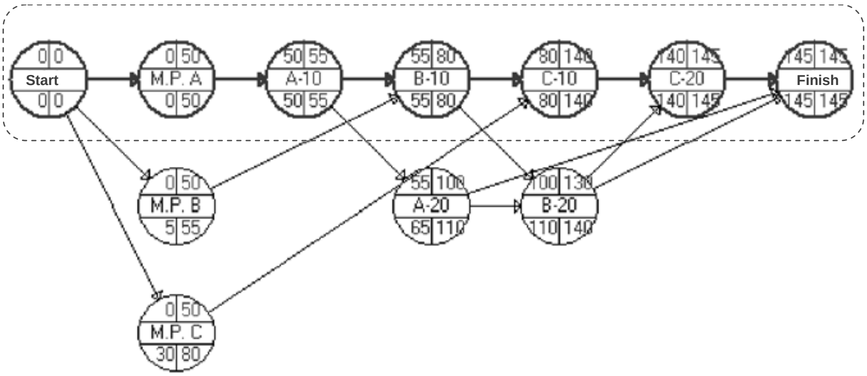


Figure 14.5. Maintenance project CPM—AON solution graph provided by WinQsb [3]

The same software also provides information about the different maintenance project activities in a table format that we have included in Table 14.1, where the critical activities are described, as well as the different slack times for all the activities. The Gantt chart of the entire project, also provided by the software tool is presented in Figure 14.6.

Table 14.1. Activities of the maintenance project

				Dates				
				Earliest		Latest		
Nº	Activity	Critical	Duration	Start	Finish	Start	Finish	Total slack
1	Start	Yes	0	0	0	0	0	0
2	MPA	Yes	50	0	50	0	50	0
3	MPB	No	50	0	50	5	55	5
4	MPC	No	50	0	50	30	80	30
5	A-10	Yes	5	50	55	50	55	0
6	B-10	Yes	25	55	80	55	80	0
7	C-10	Yes	60	80	140	80	140	0
8	A-20	No	45	55	100	65	110	10
9	B-20	No	30	100	130	110	140	10
10	C-20	Yes	5	140	145	140	145	0
11	Finish	Yes	0	145	145	145	145	0
Total project makespan=145 days								

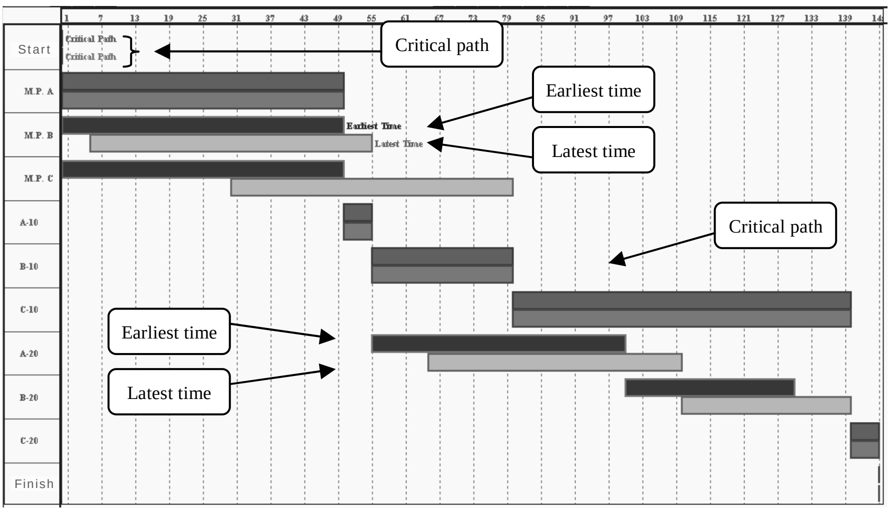


Figure 14.6. Gantt chart of the maintenance project provided by WinQsb

In Figure 14.7 we have built the AOA graph of the same project with three dummy activities {(3,4), (4,5) and (5,7)}, note that these activities (shown by dashed line) take no time (0 in the graph) but are introduced to indicate dependence. We have also remarked the critical activities in the graph (gross lines) and two of the dummy activities would be critical {(3,4) and (5,6)}.

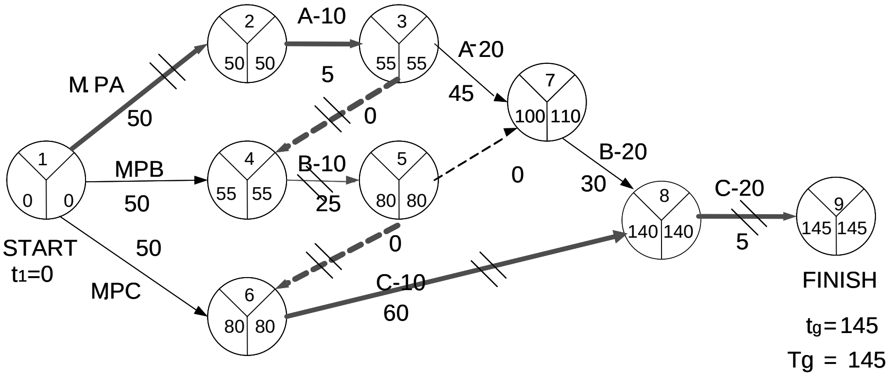


Figure 14.7. Maintenance project CPM—AOA graph

We can see in Figure 14.7 that the critical activities are MPA, A-10, B-10, C-10 and C-20. The total makespan is 145 days. If we would like to reduce the project makespan we would have several options:

- To employ more resources. We could reduce a maximum of 30 days using 3 units of resource V and 3 units of resource W. We show, in Figures 14.8—14.10, several possibilities according to the different amount of resources employed.
- Somehow reduce the duration of the critical activities. Reduction in non-critical activities would represent no reduction in the total project makespan.

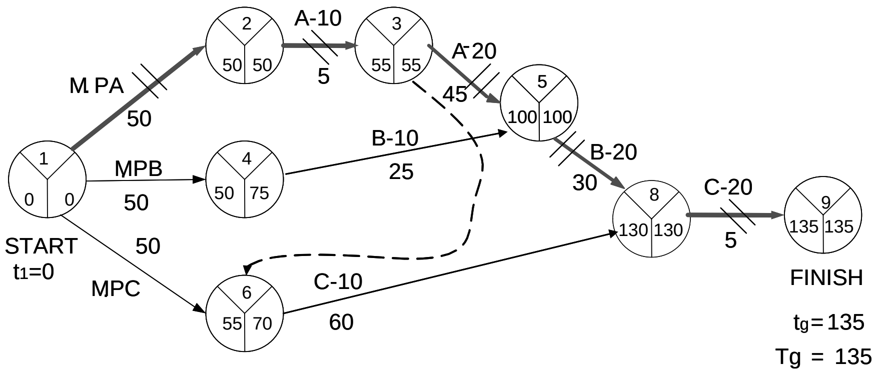


Figure 14.8. Maintenance project CPM—AOA graph with two resources V and one resource W

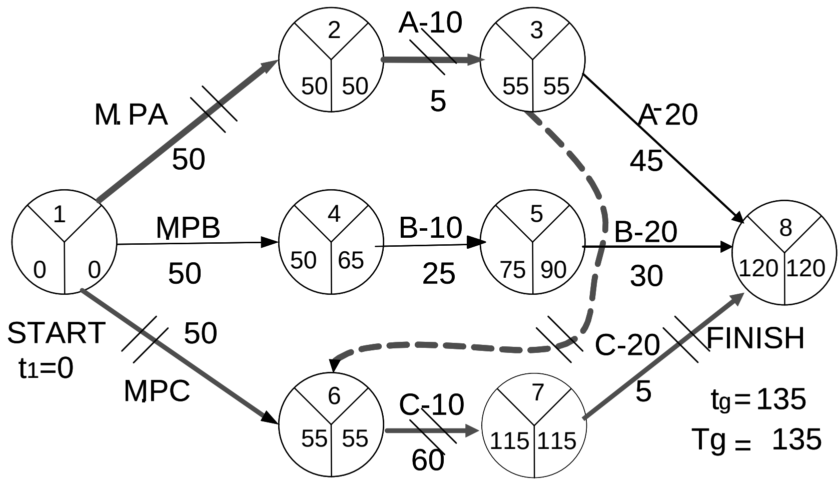


Figure 14.9. Maintenance project CPM—AOA graph with two resources V and 3 W

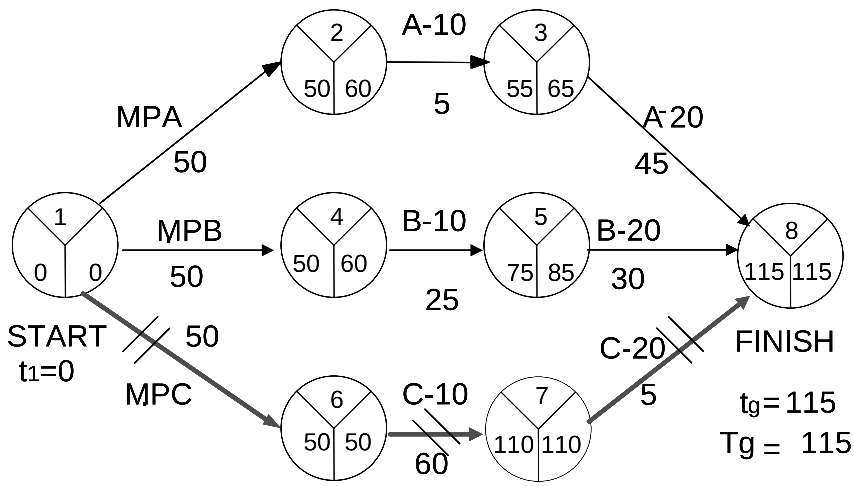


Figure 14.10. Maintenance project CPM—AOA graph with three resources V and 3 W

14.3 Maintenance Scheduling and Cost Analysis Methods

14.3.1 Problem Discussion and Case Study

Time and cost are related on maintenance projects. Maintenance managers are frequently required to make time-cost trade-offs. With the complexity of large maintenance jobs and the schedule impact of time-cost modifications, decisions on time-cost optimization are usually done on a hit or miss basis [4]. In this section we introduce a method that can be used to carry out this trade-off in an orderly manner.

In order to illustrate the methodology, let us consider a maintenance project consisting in the repair of a reactor within a chemical process plant. The project has a set of activities as presented in Table 14.2

Table 14.2. Activities of the reactor repair project

Activity	Description	Normal time (d_{ij}) (h)	Crash time (λ_{ij}) (h)	Cost slope (c_{ij}) (m.u./h)
A	Reactor shut down	6	6	∞
B	Exchanger disassembly	2	1	4
C	Reactor disassembly	3	2	5
D	Housing inspection	1	1	∞
E	Tubes renovation	9	7	3
F	Serpentines replacement	8	5	8
G	Atomizers replacement	10	9	7.5
H	Housing repair	5	4	2.5
I	Exchanger assembly	2	1	4
J	Reactor assembly	3	2	5
K	Reactor commissioning	8	8	∞

In order to shorten each of the detailed activities, the maintenance manager can consider supporting certain extra costs (to use more resources, *etc.*). In Table 14.2 we present the possible crash time duration of each activity and the cost slope (cost per unit of time saved) to take into account. Activities with cost slope equal to ∞ cannot be shortened because they have a duration that is unique.

We also know that the direct cost originated by the repair, when all activities are carried out in a normal time duration, is 100 monetary units (m.u.). Indirect costs depend on the time duration of the entire repair as indicated in Table 14.3.

Table 14.3. Indirect costs *vs* reactor total maintenance time

Indirect cost	38	40	42	46	52
Repair time	26	27	28	29	30

The dependences among activities are as follows:

- The heat exchanger and the reactor will be disassembled after the reactor shut down.
- The housing inspection and the tube renovation will be done once the heat exchanger is disassembled.
- The serpentines and the atomizers will be replaced once the reactor is disassembled.
- The housing inspection is carried out before its repair.
- The heat exchanger will be assembled after the tubes are renovated and the housing is repaired.
- Once the serpentines and the atomizers are replaced the reactor will be assembled.
- After assembling the reactor and the heat exchanger the reactor commisioning will start.

According to previous data, we can apply CPM to calculate the normal cost and duration of the project as in Figure 14.11. According to this figure the normal makespan of the project will be 30 h, the direct cost of the repair will be 100 m.u. and indirect cost 52 m.u. The total normal cost of the maintenance job in the reactor will be 152 m.u.

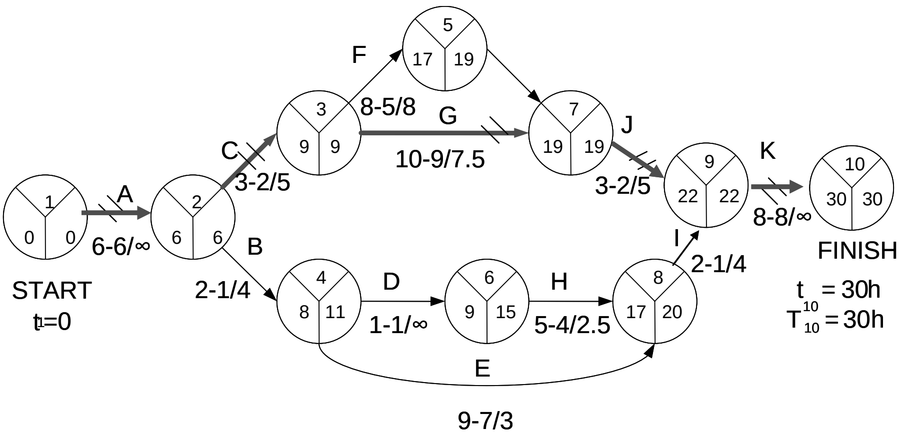


Figure 14.11. Maintenance project of the reactor repair using CPM—AOA. Normal times

14.3.2 Speeding up the Project at the Minimum Cost Increase

We can also apply CPM to calculate the duration of the project when all activities are carried out in their crash time. Obviously that would be the shortest maintenance project makespan, but probably a very expensive project schedule. The result is presented in Figure 14.12. According to this figure, the shortest makespan of the project would be 27 h, the extra direct cost of the repair, for all activities at crash time, would be

Activity	Extra cost (m.u.)
B	(2–1)x4= 4
C	(3–2)x5= 5
E	(9–7)x3=6
F	(8–5)x8=24
G	(10–9)x7.5= 7.5
H	(5–4)x2.5= 2.5
I	(2–1)x4= 4
J	(3–2)x5= 5
Total Extra Cost (∑)	57

Then, the total direct cost of the repair would be 151 m.u. (*i.e.* 100+57=157) and the indirect cost 40 m.u. The total cost of the maintenance job in the reactor, with all activities at crash time, would then be 197 m.u. It seems that we have shortened the project at a very high expense, and the cost increase for many tasks does not seem to be effective for reducing the project makespan (see task F, B, H or I).

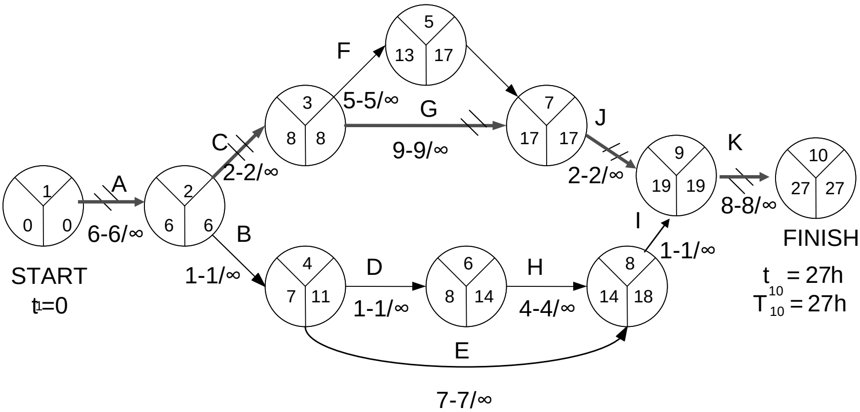


Figure 14.12. Maintenance project of the reactor repair using CPM—AOA. Crash times

We have seen that the duration of the reactor repair can vary from 30 h (activities in normal time) to 27 h (activities in crash time), while for these cases the project cost varies from 152 m.u. to 197 m.u. respectively. But can we find shorter than normal project durations at the same, or less, expense? Can we finish the project quicker and in a more economic manner? Let us now explore these possibilities.

The problem is to reduce the project makespan at the minimum cost increase. In order to do so, we will use a simple “three steps” algorithm, that we can present as follows (the reader may find more rigorous resolution methods for this problem through the Ford-Fulkerson [5] and/or the Ackoff-Sasieni algorithms, that are not covered here):

1. Depart from the normal project duration graph (Figure 14.11 in our example).
2. While there is only one critical path, determine the activity of the project that can be speeded up (in one unit of time) at the minimum cost increase. In this most simple case (only one critical path), this can be done by finding out the activity, within the critical path, with less cost slope and with a duration time longer than its crash time. When all critical path activities are at crash time, the project makespan cannot be reduced and the algorithm ends.
3. When there are more than one critical path, several trade-offs are required to determine the activity, or activities, that can be speeded up (in one unit of time) at the minimum cost increase. A first thing to do is to make sure that no critical path has all its activities at crash time, otherwise the project makespan cannot be reduced and the algorithm ends. If there is no critical path with all activities at crash time we can have several possibilities:

    a. Only common critical activities — to all critical paths — can be speeded up. We would then speed up the activity with lower cost slope in one unit of time.
    b. Parallel activities in different critical paths can also be speeded up. Then we have to find out what is the best option between the following:

        i. Reducing in one unit of time the common activity to all critical paths (at its cost slope expense); or
        ii. Reducing, in one unit of time, each one of the parallel activities of the different critical paths (at the sum of their cost slopes expense).

Let us now apply the algorithm to our example in Figure 14.11. The critical path is formed by the following set of activities: {A, C, G, J, K}, and the cost slopes of these activities are {∞, 5, 7.5, 5, ∞} respectively. Therefore activities C or J could be speeded up — they are not carried out at their crash time so far — at the same minimum cost increase for the project: 5 m.u.

Let us then consider that we speed up in 1 h, activity C in the first place. Then the new CPM graph would be like the one presented in Figure 14.13.

In this new situation the duration of the project would be 29 h, the direct cost of the repair would be 105 m.u. (*i.e.* 100+5 =105) and the indirect cost 46 m.u. The total cost of the maintenance job in the reactor for Figure 14.13 would be 151 m.u.

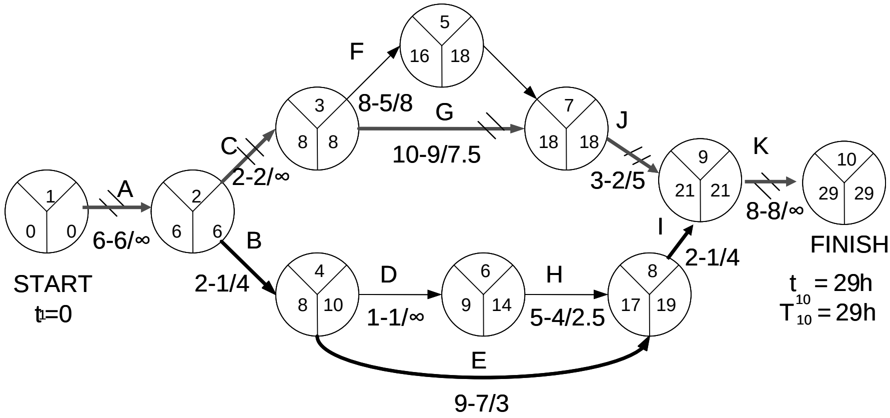


Figure 14. 13. New graph after the first iteration

After this first iteration, the project still has only one critical path, the same one as before: {A, C, G, J, K}, but now the cost slopes of the activities in this path have changed, once activity C has reached its crash time, to {∞, ∞, 7.5, 5, ∞} respectively. Therefore, we can now carry out a second iteration, speeding up activity J, as presented in Figure 14.14.

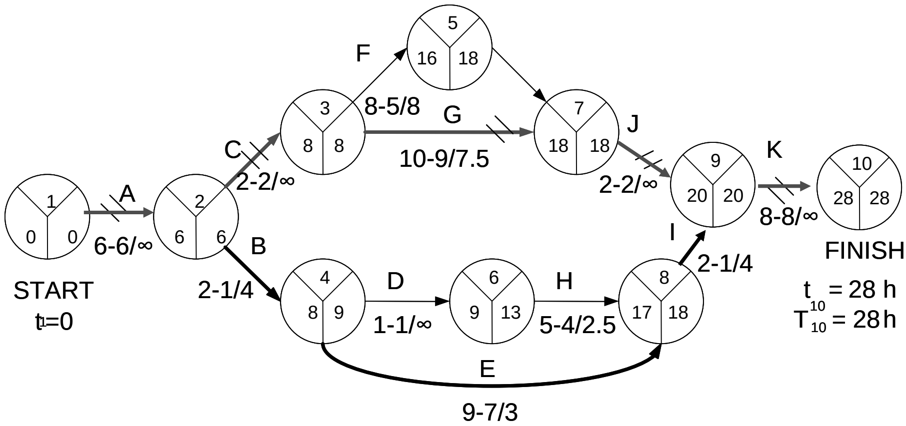


Figure 14. 14. New graph after the second iteration

In this situation, after the second iteration, the duration of the project would be 28 h, the direct cost of the repair would be 110 m.u. (*i.e.* 100+5+5 =110) and the indirect cost 42 m.u. The total cost of the maintenance job in the reactor for Figure 14.14 would be 152 m.u.

We would still remain with only one critical path in our project after this second iteration and therefore we could proceed exactly as before. The critical path is again {A, C, G, J, K}, but now the cost slopes of the activities in this path have changed again to {∞, ∞, 7.5, ∞, ∞} respectively. Therefore the only possibility is to speed up activity G 1 h at an extra direct cost of 7.5 m.u. In this situation, after the third iteration, the duration of the project would be 27 h, the direct cost of the repair would be 117.5 m.u. (*i.e.* 100+5+5+7.5 =117.5) and the indirect cost 40 m.u. The total cost of the maintenance job in the reactor for Figure 14.15 would then be 157.5 m.u.

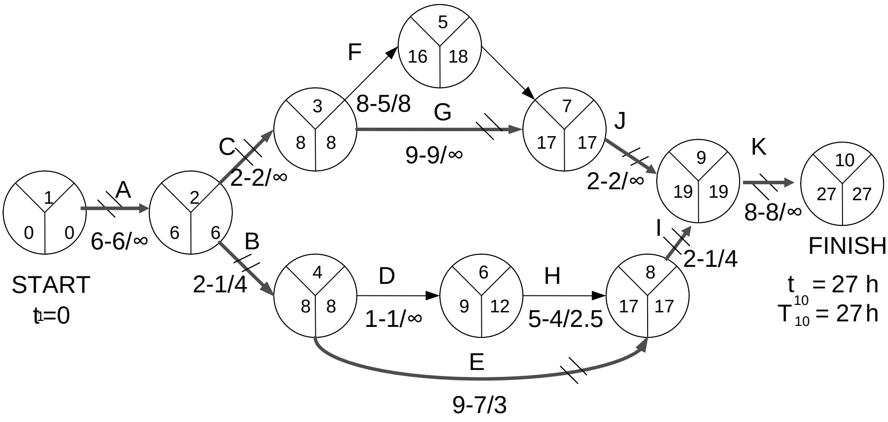
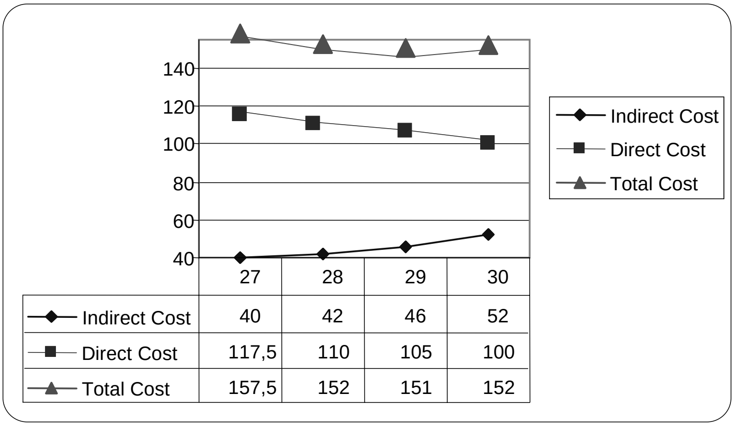


Figure 14. 15. New graph after the third and final iteration

In Figure 14.15 we can appreciate that after the third iteration we have two critical paths: {A, C, G, J, K} and {A, B, E, I, K}. We would then move to step 3 of the algorithm.



	27	28	29	30
Indirect Cost	40	42	46	52
Direct Cost	117,5	110	105	100
Total Cost	157,5	152	151	152

Figure 14.16. Reactor repair cost (Y axis in m.u.) *vs* repair time (X axis in h)

In our example, when we arrive at step 3 of the algoritm one of the critical paths — {A, C, G, J, K} — has all its activities in crash time; therefore the project duration cannot be reduced and the algorithm stops here. Results could be presented as in Figure 14.16.

According to these results, we would have to decide whether we prefer to finish the repair as soon as possible (27 h) or with the minimal cost (29 h). Note that it is not reasonable to finish it in the normal project duration time (30 h) since there exist quicker and more economic solutions. Another possibility would be to finish the project in 28 h at the same cost rather than with normal activities duration.

14.4 Using Monte Carlo Simulation Modelling for the PM Scheduling Problem

14.4.1 Introduction

In this section, we review the process of preventive maintenance shop level maintenance scheduling. We pay particular attention to the assessment of advanced maintenance scheduling policies such as those involving functional dependencies and work-in-process inventory levels. The use of Monte Carlo simulation modelling can improve preventive maintenance scheduling, allowing the assessment of alternative scheduling policies that could be implemented dynamically on the shop floor (see Figure 14.17).

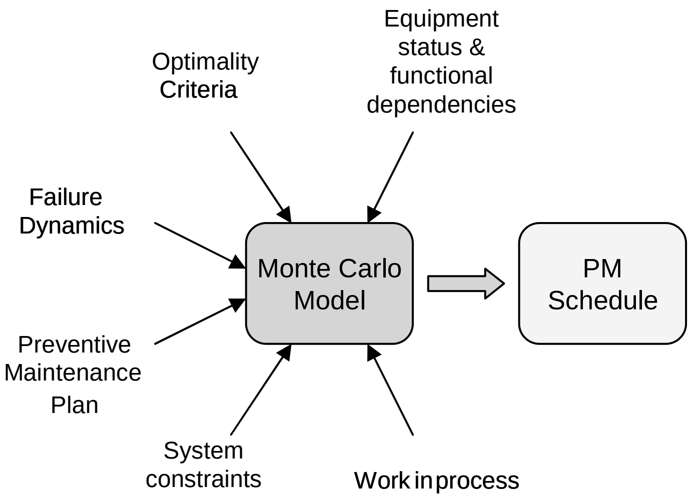


Figure 14.17. Obtaining the PM schedule

Using a simulation model, we compare and discuss the benefits of different scheduling policies on the status of current manufacturing equipment and several operating conditions of the production materials flow. To do so, we estimate measures of performance by treating simulation results as a series of realistic experiments and using statistical inference to identify reasonable confidence intervals.

Monte Carlo Simulation is the generation of certain random and discrete events in a computer model to create a realistic time frame scenario of the system. The simulation is carried out in the computer and estimates are made for the desired measures of performance [6]. The simulation is actually a series of realistic experiments where statistical inference is used to estimate confidence intervals for the performance metrics. In general, the events can be simulated either with variable time increments (*discrete event simulation*) or with fixed time increments, at equidistant points of time (*continuous time simulation*)[13].

In this section, we will use the continuous time simulation technique which evaluates the system's state at the end of every constant time interval (Δt), records the new system's state and collects the statistics of interest. Then the time is incremented another Δt, and so on. As a simulation tool, we use the VENSIM simulation environment (Ventana Systems ®), which has special features to assist in easy Monte Carlo type simulation experiments, and to provide confidence interval estimations. This method allows us to consider various relevant aspects of systems operation (such as K-out-of-N, redundancies, functional dependencies or component repair priorities) which can hardly be captured by analytical models [8].

14.4.2 Case Study: Scheduling Maintenance of a Capacity Constrained Production System

The study of the maintenance scheduling problem in a production system with constrained production rate and buffer capacity is important to understand the real effect of preventive maintenance (PM) on a production process.

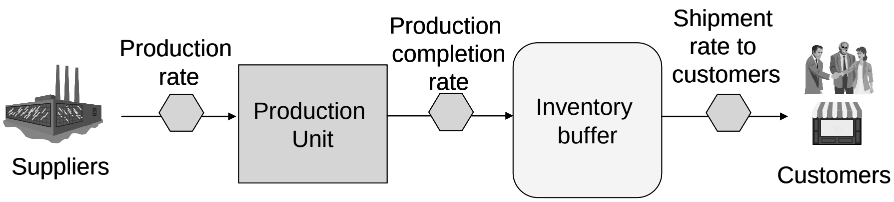


Figure 14.18. The production system

In this problem, the decision to start a specific PM activity on the production unit not only depends on the condition of this production unit, but also on the content of the inventory buffer located after the production unit. As shown in Figure 14.18, the products are stored in this inventory buffer until they are shipped to the customers.

Maintenance policies for a production unit and buffer conditions have been considered and analysed in the literature under varying situations. Many authors have used both analytical and simulation approaches to find optimal solutions minimizing, most of the time, a backlog/inventory cost function. In the simulation

[13] The reader is referred to Pidd [7] for a discussion regarding both simulation practices.

model that we will now introduce, we generalize the optimality criteria of the problem (traditionally a cost function), add production flow constraints, and consider variability in demand and lead times. Time to failure is assumed to be random. However, preventive and corrective maintenance times are assumed to be constant. Finally, the modified Powell search optimization algorithm is used to find the optimal maintenance solutions for several scenarios and for different optimality criteria.

In the next section we model the production system studied as well as various maintenance policies. The performance metrics and the methods used to optimize various parameters of the maintenance policies are discussed. Computational results from our simulation and optimization efforts are later presented and discussed. Finally, this case study concludes with a summary of findings and some useful directions for future research.

14.4.3 Modelling the Production System

The production unit is subject to failures, and corrective maintenance (CM) is required to restore the production unit's condition after its failure. During the maintenance period, the production unit does not work, which may also lead to end-customer's demand fulfilment problems. PM and CM require the system to be inoperative, but PM is less time consuming than CM. We assume that end-customers do not wait for those products not delivered on time, and therefore demand not fulfilled will be lost sales. It is also assumed that the production unit, which has limited flow capacity, never stops due to lack of supply. The buffer capacity of this production unit is finite and has been determined in the design phase of the system. Buffer size can be dynamically estimated according to the observed production unit's lead time variability, and end-customer's demand variability.

Before proceeding with the model development and discussion, we first describe the notations and definition of the main variables as follows:

Information related variables

B_{t-1} : Existing backlog of orders in $t-1$
CA_t : Decrease in system's age due to corrective maintenance action in t
D_t : Orders of units received in period t
F_t : Orders demand forecast in period t
FR_t : Fill rate of the system from 0 to t
LC_t : Time when the last corrective maintenance, for a system in t, started
LP_t : Time when the last preventive maintenance, for a system in t, started
PA_t : Decrease in system's age due to preventive maintenance action in t
PO_t : Production orders placed in t
PSW_t : Production rate switch (based on system maintenance and buffer level)
RN_t : Random number within the interval (0,1), generated in t
STM_t : Production flow stops due to maintenance
STB_t : Production flow stops due to maximum buffer capacity
SL_t : Service level of the system from 0 to t

S_t : Amount of orders finally shipped to the customers in t
ss_t : Desired time for a material unit to remain as on-hand inventory
T_t : System's age in t
TI_t : Increase of system's age in period t
TO_t : Decrease of system's age in period t
σ_t : Standard deviation of demand during lead time in t
σ_{Lt} : Standard deviation of lead time
$\lambda(T_t)$: Failure rate of the system in t

Material related variables:

I_t : Production rate, input to the work in process in period t
INV_t : Inventory of finished materials, on-hand inventory, in t
O_t : Output from the production line in period t
S_t : Amount of units finally shipped to the customers in period t
WIP_t : Work in process of the production unit in t

Model parameters:

AD : Average demand
CT : Average time of a corrective maintenance action
CC : Average cost, per time unit, of a corrective maintenance action
k : Lower required on-hand inventory to carry out a preventive action
K : Maximum buffer capacity
MPR : Maximum production rate
L : Production lead time
n : Minimum age of the system to do preventive maintenance actions
N : Maximum age of the system to do preventive maintenance actions
PC : Average cost, per time unit, of a preventive maintenance action
PT : Average time of a preventive maintenance action
$T1$: Maximum time the system operates without a failure
Z : Safety factor (based on desired/target customer service level)
α : Orders forecast smoothing factor
β_S : Fractional adjustment coefficient for the on-hand inventory
β_{SL} : Fractional adjustment coefficient for the work-in-process inventory
σ_D : Standard deviation of demand

14.4.3.1. Modelling the Material and Information Flows

In our model, it is assumed that the orders received (D_t) are immediately shipped to the customers. However, inventory constraints may reduce the amount of units finally shipped, S_t . Therefore, there may be some lost sales. The equations for the orders finally delivered, inventory, output from the production line, and work in process, are as follows:

$$S_t = \begin{cases} D_t & \text{if} \quad \mathrm{INV_t \geq D_t} \\ INV_t & if \quad INV_t < D_t \end{cases} \tag{14.6}$$

$$INV_t = INV_{t-1} + O_t - S_t \tag{14.7}$$

$$O_t = I_{t-L} \tag{14.8}$$

$$WIP_t = WIP_{t-1} + I_t - O_t \tag{14.9}$$

Equation (14.8) formalizes the output of the production unit as a delay of time L of its input. Backlog is formalized in Equation (14.10), and will help us to measure system's performance[14].

$$B_t = B_{t-1} + D_t - S_t \tag{14.10}$$

In order to place the production orders, we first prepare the forecast demand in Equation (14.11), where an exponential smoothing constant is used, since it is widely used in modelling (see *e.g.* Chen *et al.* [9]), and has been found to be a very popular practice [10]. To choose appropriate values of α, the reader is referred to Makridakis *et al.* [11]

$$F_t = \alpha D_t + (1-\alpha) F_{t-1} \text{ with } 0 \leq \alpha \leq 1 \tag{14.11}$$

Then we estimate a desired safety stock level assuming that inventory availability is measured in terms of the no-stockout probability per order cycle [12]. In this case, safety stock can be modelled as a function of the management-specified customer service level and the standard deviation of demand during lead time [13]. Assuming that the demand and lead time distributions are independent of one another, the standard deviation of demand during lead time, ss_t is calculated as follows:

$$ss_t = Z\sigma_t = Z\left(\left(L\ \sigma_{Dt}^{\ 2} + \sigma_{Lt}^{\ 2} AD^2\right)^{1/2} / AD\right) \tag{14.12}$$

where ss_t is expressed in time units using the average demand (AD) in the denominator of Equation (14.12), and Z is a safety factor, based on target customer service level. To choose appropriate values of Z, the reader is referred to Aucamp and Barringer [14]. In order to take into account the impact of the current maintenance policy, we assume that the variability of lead time (σ_{Lt}) is reviewed over time. Finally, production orders to be placed are calculated using the anchoring and adjustment heuristic [15] which has been shown to apply to this

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[14] Notice how, to allow backlogging in our model, Equation (14.6) could be modified in order to take into account the backlog (B_t) when shipping to customers. In that case, the Equation (14.6) would change as follows: $S_t = D_t + B_t$, *if* $INV_t \geq D_t + B_t$, *and* $S_t = INV_t$, *if* $INV_t < D_t + B_t$.

kind of decision-making task [16]. Thus, the production quantity at time t, PO_t, is given by

$$PO_t = Max(F_t + \beta_S (F_t ss_t - INV_t) + \beta_{SL} (F_t L - WIP_t),0) \qquad (14.13)$$

14.4.3.2. Obtaining the Production Rate

Production rate, in Equation (14.14), is then defined according to the production orders placed, in Equation (14.13), and taking into account, at the same time, the conditions of the system that will stop the production unit: maintenance that is being carried out, and/or the reach of the maximum buffer capacity. At the same time the production rate will not be able to exceed the maximum production rate (*MPR*)

$$I_t = Min(PO_t\, PSW_t, MPR) \qquad (14.14)$$

As can be appreciated in Equation (14.14), production rate is formalized by multiplying the production orders by a variable PSW (production rate switch), that will set the rate to zero if maximum buffer capacity is reached or if the production unit is under maintenance. PSW will be defined as follows:

$$PSW_t = STM_t\, STB_t \qquad (14.15)$$

Here STM_t causes the system to stop due to maintenance, while STB_t does the same in the case of maximum buffer capacity to be reached:

$$STM_t = \begin{cases} 1-(Pulse(LC_t,CT,t)+Pulse(LP_t,PT,t)) & \text{if } LC_t>0 \text{ or } LP_t>0 \\ 1 & \text{Otherwise} \end{cases} \qquad (14.16)$$

Note that when $t=0$, $LC_t = LP_t = 0$ (LC_t and LP_t, are the times when the last corrective (or preventive, respectively) maintenance, for a system in t, started):

$$STB_t = \begin{cases} 0 & INV_t \geq k \\ 1 & \text{Otherwise} \end{cases} \qquad (14.17)$$

The function Pulse, previously introduced to calculate STM_t is defined as follows:

$$Pulse(a,b,t) = \begin{cases} 1 & a<t<a+b \\ 0 & \text{Otherwise} \end{cases} \qquad (14.18)$$

14.4.3.3 Modelling the Maintenance Policy

Modelling maintenance policy first requires one to model the age of the system:

$$T_t = T_{t-1} + TI_t - TO_t \tag{14.19}$$

Obviously, age will increase when the system is running, therefore

$$TI_t = PSW_t \tag{14.20}$$

and age will decrease when the system is maintained:

$$TO_t = \begin{cases} PA_t & \text{if } PA_t <> 0 \text{ and } CA_t <> 0 \\ PA_t + CA_t & \text{Otherwise} \end{cases} \tag{14.21}$$

$$CA_t = \begin{cases} T_t & \text{if } \lambda(T_t) \geq RN_t \\ 0 & \text{Otherwise} \end{cases} \tag{14.22}$$

Where RN_t is a random number generated for every t within the range (0,1), $\lambda(T_t)$ is the age of the system, and CA_t and PA_t are decreases in the system age as a consequence of the corrective and preventive maintenance actions respectively. Note that the age of the system will neither decrease nor increase when the production unit is stopped because of the buffer reaching the maximum capacity.

We will now formalize several maintenance policies, one of them a basic[15] policy according exclusively to system's age (in Section 14.4.3.4), and others considering the buffer size as another maintenance policy control variable[16] (in Sections 14.4.3.5 and 14.4.3.6).

14.4.3.4 Modelling Age Based Maintenance

In the age based maintenance policy, if the production unit does not fail until a given time n, then it is preventively maintained. Otherwise, it is correctively maintained at the failure time:

$$PA_t = \begin{cases} T_t & \text{if } T_t \geq n \\ 0 & \text{Otherwise} \end{cases} \tag{14.23}$$

Here, we also assume that a failed production unit will be maintained correctively at failure.

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[15] The reader is referred to Dohi *et al.* [17] to review the basic preventive maintenance policies and their variations.

[16] Similar to policies formulated in Van der Duyn Schouten and Vanneste [18].

14.4.3.5 Age and Buffer Based Maintenance

In this case, we model the decision to start PM actions on the production unit as a function of the condition of the production unit (T_t) and of the content of the inventory buffer (INV_t). A generic definition of this class of policies is as follows:

$$PA_t = \begin{cases} T_t & \text{if} \quad T_t \geq n \quad \text{and} \quad INV_t \geq k \\ 0 & \text{Otherwise} \end{cases} \tag{14.24}$$

Equation (14.24) means that preventive maintenance will be carried out when the system reaches *n* periods without a failure and while the inventory buffer is higher than a certain stock level *k:*

14.4.3.6 Modified Age and Buffer Based Maintenance

Here, preventive maintenance will be carried out when the system reaches *n* periods without a failure, before it becomes too old (*N* periods), and while the inventory buffer is higher than a certain stock level *k*.

$$PA_t = \begin{cases} T_t & \text{if} \quad N \geq T_t \geq n \quad \text{and} \quad INV_t \geq k \\ 0 & \text{Otherwise} \end{cases} \tag{14.25}$$

These preventive maintenance control policies are denoted as class *(n, N, k)* policies in Van der Duyn Schouten and Vanneste [18]

14.4.3.7 Model Validation with an Example

In order to validate the behaviour patterns of the model variables, we present an example with the age and buffer based maintenance policy, characterised by the following parameter values:

L	= 5 days	k	= 50 units
α	= 0.5 dimensionless	n	= 20 days
β_S	= 1 1/day	N	= 35 days
β_{SL}	= 1 1/day	$T1$	= 40 days
CT	= 5 days	AD	= 60 units/day
PT	= 1 day	Z	= 1,645 dimensionless
K	= 300 units	$\lambda(T_t)$	={(0,0.08),(10,0.05),(30,0.05),(40,1)}

Also, initial conditions are

T_0	= 26 days
INV_0	= 0 units
WIP_0	= 307 units, and

Simulation time = 100 days

Moreover, we assume that customer's demand (D_t) is random with high variability and is distributed NORMAL (60, 20) units/day. The desired service level is 95%. There are no production rate constraints. The failure rate is a function of the system's age. Figure 14.19 shows the inventory buffer over time. Stops, especially those for corrective maintenance, cause inventory to drop, which conditions the possibility of preventive maintenance.

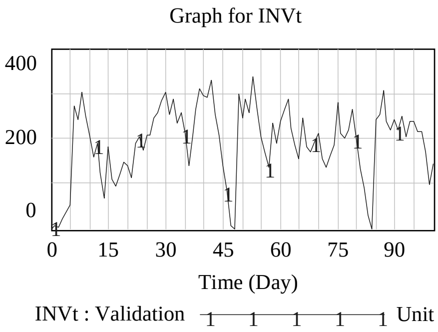

Figure 14.19. Inventory buffer in units

The system's age over time and the variables conditioning it are depicted in Figure 14.20. To appreciate its construction, the TO_t graph is repeated here.

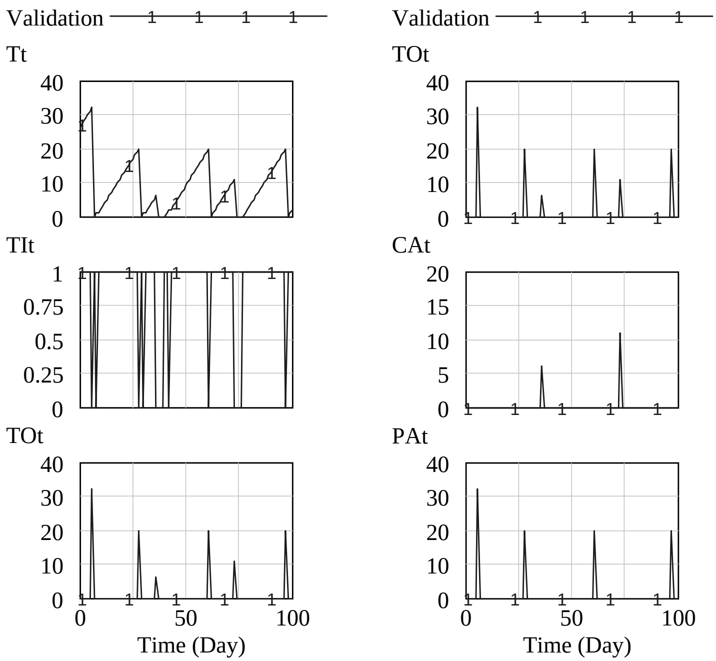

Figure 14.20. Basic variables conditioning system's age (in days)

Four preventive maintenance activities (one for age over 20 days, due to low INV_t) and two corrective maintenance activities are carried out. Figures 14.20 and 14.21 show that, as a consequence of the constrained buffer capacity, four stops of the production units are required.

14.4.4 Optimization of the PM Scheduling Policy

14.4.4.1 Optimization Techniques to Use with the Simulation Model

We now turn our attention to the optimization of the maintenance policies to be used. Our discussion also includes the identification of various payoff functions used to evaluate the system performance.

Optimization search techniques can be classified as local or global [19]. Local techniques slightly modify the current best solution in hopes of finding an improved solution. These myopic approaches risk becoming trapped in a local optimum. Global techniques have specific mechanisms for avoiding local optima.

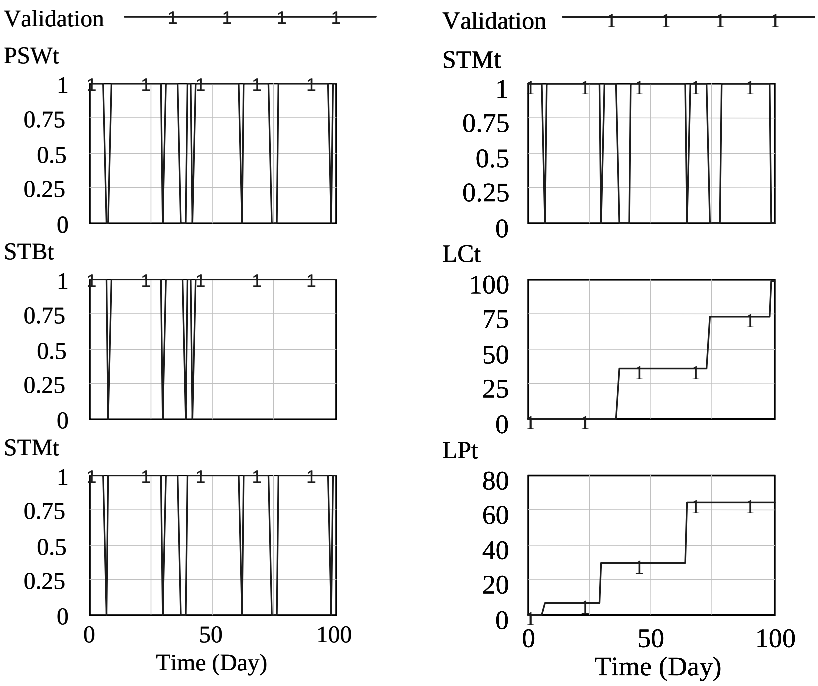

Figure 14.21. Production unit stops (in days) and maintenance times

Examples of local search techniques are the Hooke-Jeeves pattern search [20], the Nelder-Mead simplex algorithm [21], or tabu search [22]. Most local search algorithms use several simulation runs to estimate the derivative of the objective function. The algorithm searches in that direction until no improvement is found.

Then the process is repeated until no input change improves the output. The pattern search algorithm alternates between exploratory moves and pattern moves. Exploratory moves change one variable value at a time from the current best solution. Pattern moves change all variables simultaneously based on the exploratory move results. Step size automatically accelerates in promising directions, often quickly leading to the solution. The Nelder-Mead simplex method is unique because it does not require the derivative information. Instead, it takes a series of initial guesses and reflects, expands and contracts about the said points until no improvements are found. Tabu search is a local search technique, which uses adaptive memory to guide the search and to avoid local minima [23].

Examples of global search techniques are simulated annealing and genetic algorithms. These are general approaches, requiring the development of a specific algorithm and the selection of parameters to solve each problem. Simulated annealing algorithms can escape local minima by accepting inferior solutions during their searches [24]. The probability of accepting an inferior move depends on the difference in cost and the current stage of the algorithm. Genetic algorithms use crossover operations, combining parts of two good solutions, and mutation operations, modifying good solutions, to create new solutions. Nonlinear programming textbooks make general comparisons between search algorithms by describing their advantages and disadvantages. Comparisons among global search algorithms show that results that tend to be very problem-specific, and solution qualities and convergence rates that are very sensitive to parameter selection [25].

Among the numerical optimization techniques presented above, the direct-search method that does not evaluate the gradient, has been found to be very suitable for the analysis of dynamics of complex nonlinear control systems. The Powell method [26] is well known to have an ultimate fast convergence among direct-search methods. The basic idea behind Powell's method is to break the N dimensional minimization down into N separate one-dimensional (1D) minimization problems. Then, for each 1D problem a binary search is implemented to find the local minimum within a given range. Furthermore, on subsequent iterations, an estimate is made of the best directions to use for the 1D searches[17].

Some problems, however, are not always assured of optimal solutions because the direction vectors are not always linearly independent. To overcome this difficulty, the method was revised [26] by introducing new criteria for the formation of linearly independent direction vectors. This revised method, is called “The Modified Powell Method”, and is the one used in this case study. At present, there is a wide applicability of this method (see for instance the optimization module of VENSIM 5.6 [27]), and at the same time it is used in some new developments of hybrid numerical optimization techniques incorporating genetic algorithm into the method [28].

[17] The Powell method, for most m iterations, where m is the number of parameters to be estimated, yields the optimal solution to the problem with cost function of quadratic form, if the directions of m-dimensional vectors are linearly independent at every iteration step.

14.4.4.2 Metrics and Payoff Function

We have selected six different metrics of the system's performance:

- *Service Level* (*SL*), is the percentage of order cycles that the system will go through without running out of stock [29].
- *Fill Rate* (*FR*), is the percentage of units demanded that were in stock when needed. Note how, mathematically, the fill rate is going to be higher than the service level virtually in any circumstance [29].
- *Utilization of the production unit* (*U*), is the percentage of time periods that the production unit is running.
- *Availability of the production unit* (*A*), is the percentage of time periods that the system is available, *i.e.* that could be running if required. Note how availability will be, mathematically, higher or equal to the utilization (*U*) in any circumstance.
- *Mean Inventory* (*MI*), is the average inventory in the buffer over the simulation horizon.
- *Maintenance Cost* (*MC*), is the total cost of maintenance over the simulation horizon.

The mathematical definition of these six metrics is as follows (assuming that the simulation time will be a year,[18] and that the production unit works seven days a week):

$$SL = TSS/365, \text{ with } TSS = \sum_{t=1}^{t=365} UNF_t \text{ , and} \tag{14.26}$$

$$UNF_t = \begin{cases} 0 & \text{if} \quad S_t < D_t \\ 1 & \text{Otherwise} \end{cases} \tag{14.27}$$

$$FR = (TD - B_{365})/TD, \quad \text{with } TD = \sum_{t=1}^{t=365} D_t \text{ and } B_{365} = \sum_{t=1}^{t=365} B_t \tag{14.28}$$

where TD represents total demand of the customers.

$$U = TRD/365, \text{ and } TRD = \sum_{t=1}^{t=365} TI_t \tag{14.29}$$

where TRD denotes total running days of the production unit.

[18] This is to make results independent of the system's initial conditions, and to generate a reasonable number of failures of the production unit.

$$A = TAD/365, \text{ and } TAD = \sum_{t=1}^{t=365} STM_t \tag{14.30}$$

with TAD meaning total number of days with the production unit available.

$$MI = TSI/365, \text{ and } TSI = \sum_{t=1}^{t=365} INV_t \tag{14.31}$$

with TSI representing the total accumulation of buffer inventory over time.

$$MC = (TCA\ CC + TPA\ PC)\ /365, \text{ and} \tag{14.32}$$

$$TCA = \sum_{t=1}^{t=365} Pulse(LCt, CT, t) \tag{14.33}$$

$$TPA = \sum_{t=1}^{t=365} Pulse(LPt, PT, t) \tag{14.34}$$

where the TCA and TPA represent the total number corrective and preventive time over the simulation horizon respectively.

We may reasonably guess that, in their decision-making criteria, different operations management teams in the industry will give different relative weights to these payoff functions. The rationale of the process that we propose to follow is similar to the one that can be found in other multi-criteria techniques such as Goal Programming (GP) [30] or the Analytical Hierarchy Process (AHP) [31]. We will structure the decision-maker's problem by explicitly defining the objective and relevant criteria, and by assigning numerical values for their relative importance. In our case, for complex non-linear systems, the simulation and optimization will help us to understand the decision-maker's trade-offs in some detail, and to perceive the meaning and consequences of the different priorities hierarchy (see [32,33]).

As an example, in this study we have selected two profiles as "proxy-management profiles". These "proxy-management profiles" reflect the level of the maintenance function integration within the production system decision-making processes of many industrial firms, and are defined as follows:

- *A_MC profile*: management teams falling under this profile will take maintenance optimization decisions according to a local maintenance criteria of improving availability of the production unit while minimizing the maintenance cost.
- *FR_MI profile*: management teams falling under this profile will optimize maintenance according to a global operational criteria of improving the customer fill rate while minimizing the mean inventory over time in the buffer.

Let F_{A_MC} denote the target function of the A_MC profile, then:

$$F_{A\_MC} = Max\ (\ w_a\ A' + w_{mc}\ MC'\ ) \tag{14.35}$$

where A' and MC' are normalized values for the availability and maintenance cost, and w_a and w_{mc} are weights of these two variables in the target function. We consider

$$A' = A, \text{ and } MC' = MC/MC_c \tag{14.36}$$

where MC_c will be the cost of maintenance of the corresponding corrective policy (for the next simulations we took the worst case maintenance corrective cost).

Let F_{FR_MI} denote the target function of the FR_MI profile, then:

$$F_{FR\_MI} = Max\ (w_{fr}\ FR' + w_{mi}\ MI'\ ) \tag{14.37}$$

where FR' and MI' are normalized values for fill rate and mean buffer inventory, and w_{fr} and w_{mi} are weights of these two variables in the target function. We consider

$$R' = FR, \text{ and } MI' = MI/K \quad \text{where } K \text{ is the maximum buffer capacity} \tag{14.38}$$

14.4.5 Simulation and Optimization Results

We now present the results for a set of scenarios. A scenario is characterised by a proxy-management profile, a corrective maintenance time, and a maintenance policy implemented, which is defined by a set of parameters. We use the following nomenclature:

X_CT_{y*}:

- X — Target function selected to optimize maintenance policy parameters (will define weights w_a, w_{mc}, w_{fr} and w_{mi}).
- CT — Average time of a corrective maintenance action.
- {y*} — Parameters characterizing the maintenance policy. Best values for these parameters, optimizing X, will be found.

For example, A_MC_2_n*_k* describes the scenario where we have chosen to maximize the availability while minimizing the maintenance cost of the system (A_MC profile of previous section, in our example[19] with $w_a = 3$, $w_{mc} = -1$, $w_{fr} = 0$,

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[19] Note that w_a, and w_{mc}, could have different values within the same kind of management profile (*e.g.* w_a=1, w_{mc}=-1 in this case the decision maker would give the same importance to

and w_{mi} = 0), where the corrective maintenance lasts 2 days (*vs* always 1 day for preventive maintenance), and where the maintenance policy used is based on the age of the production unit (*n*) and the size of the buffer (*k*), according to Section 14.4.3.5.

Table 14.4. Results for metrics when there is no inventory buffer constraint (K=500 units)

Scenario	Payoff function weights w_a ,w_{mc}, w_{fr} ,w_{mi}	Parameter optimization results n^*,N^* &/or k^*	SL	FR	U	A	MI	MC
CORRECTIVE_2			99	100	93	93	10	19
A_MC_2_n*	3,-1,0,0	15	99	100	92	92	11	13
A_MC_2_n*,k*	3,-1,0,0	15,5	99	100	92	92	11	13
A_MC_2_n*,N*,k*	3,-1,0,0	15,35,5	99	100	92	92	11	13
F_MI_2_n*	0,0,3,-1	11	99	100	91	91	11	11
F_MI_2_n*,k*	0,0,3,-1	11,5	99	100	91	91	11	11
F_MI_2_n*,N*,k*	0,0,3,-1	11,40,5	99	100	91	91	11	11
CORRECTIVE_10			82	85	63	63	19	100
A_MC_10_n*	3,-1,0,0	3	91	91	70	70	14	43
A_MC_10_n*,k*	3,-1,0,0	4,5	91	92	72	72	14	44
A_MC_10_n,N,k	3,-1,0,0	4,35,5	91	92	72	72	14	44
F_MI_10_n*	0,0,3,-1	1	92	97	65	65	7	14
F_MI_10_n*,k*	0,0,3,-1	1,28	93	98	66	66	8	14
F_MI_10_n*,N*,k*	0,0,3,-1	1,40,28	93	98	66	66	8	14

All scenarios have the same value for Demand (N(60,20)), and for the following parameters: *MPR*: 100 units/day, *L*: 5 days, α: 0.5 dimensionless, β_S: 1 day^{-1}, β_{SL}: 1 day^{-1}, P*T*: 1 day, *T1*: 40 days, *AD*: 60 units/day, and same initial conditions. However, some other parameters will depend on the scenario: w_a,w_{mc}, w_{fr} and w_{mi} may change according to the proxy-management profile considered in each specific scenario; *CT* will change according to the time required for corrective maintenance assumed in each scenario; the same applies to *K*. The values of *n*, *N*, and *k*, will depend on the maintenance policy that is evaluated, and will be obtained for each particular scenario, as a result of a Powell optimization[20].

maximize availability than to minimize cost) in this paper we merely present a particular case, where the decision maker gives three times the importance to maximize availability than to minimize cost.

[20] Note that K could be also considered as a design parameter and a new problem could be studied considering the same approach.

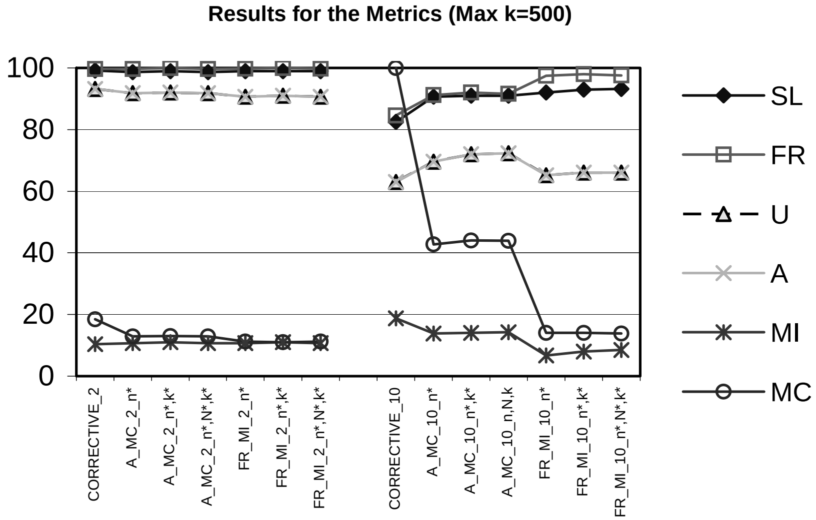

Figure 14.22. Graphical results for the metrics when there is no inventory buffer constraint

To help in this discussion, results presented in Table 14.4 are plotted in Figure 14.22. For this set of results, the buffer constraint is never reached (K=500). Therefore, the production unit never stops as a consequence of this constraint, although it may reach maximum rate capacity (*MPR*=100 units/day) more frequently.

The utilization of the system is practically equal to availability in any scenario. The maintenance activities will stop the system and force it to work later to meet the target. Results show the importance of the optimality criteria to select the maintenance policy parameters. This factor seems to be more important than the maintenance policy itself, especially in those cases where corrective maintenance has a more negative impact (*CT*=10).

Results presented in Table 14.4 are obtained for simulations with a maximum capacity of 100 units in the inventory buffer (K), and the same maximum production rate (MPR=100 units/day). These circumstances force the system to operate in tougher conditions. Buffer constraints, reached many times, are the main reason for the difference between availability and utilization in most of the cases.

Figure 14.23 helped us to discuss the results of Table 14.5. It can be appreciated that, in this type of operating conditions, the correct choice of the optimality criteria is extremely important. For CT=10, the FR_MI profile gives better results even for metrics not included in this target function (notice that this happens to MC, even when MC is in the A_MC profile target function and not in FR_MI one) because of the correct selection of the parameters. Although values for the availability are below the results for the A_MC profile for all policies in the FR_MI profile, the system utilization is better than availability when the optimality criteria to select policy parameters is based in global operational measures.

Table 14.5. Results for the metrics when there is a buffer constraint (K=100 units)

Scenario	Payoff function weights w_a ,w_{mc}, w_{fr} ,w_{mi}	Parameter optimization results n*,N* &/or k*	SL	FR	U	A	MI	MC
CORRECTIVE_2_10			75	77	47	96	100	12
A_MC_2_10_n*	3,-1,0,0	16	74	78	47	95	100	11
A_MC_2_10_n*,k*	3,-1,0,0	10,54	75	78	47	95	100	8
A_MC_2_10_n*,N*,k*	3,-1,0,0	9,35,48	75	78	47	95	100	6
F_TI_2_10_n*	0,0,3,-1	1	83	89	55	68	57	8
F_TI_2_10_n*,k*	0,0,3,-1	1,1	83	89	55	68	57	8
F_TI_2_10_n*,N*,k*	0,0,3,-1	1,10,1	83	89	55	68	57	8
CORRECTIVE_10_10			66	69	41	68	99	92
A_MC_10_10_n*	3,-1,0,0	7	69	73	44	80	100	47
A_MC_10_10_n*,k*	3,-1,0,0	5,33	71	74	45	87	100	27
A_MC_10_10_n,N,k	3,-1,0,0	3,23,28	70	74	44	87	100	27
F_TI_10_10_n*	0,0,3,-1	1	83	89	55	68	57	14
F_TI_10_10_n*,k*	0,0,3,-1	1,1	83	89	55	68	57	14
F_TI_10_10_n*,N*,k*	0,0,3,-1	1,1,40	83	89	55	68	57	14

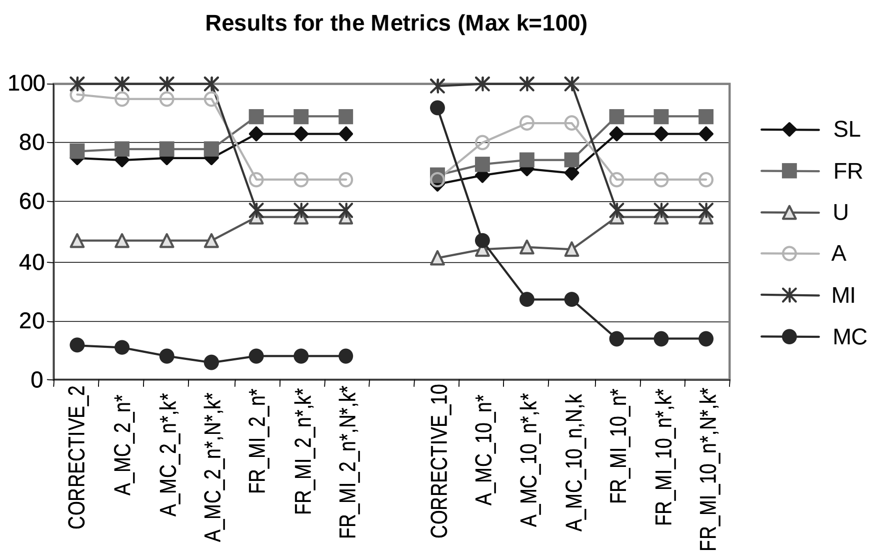

Figure 14.23. Graphical results for metrics when there is a buffer constraint (K=100 units)

14.4.6 Summary of Findings

This case studies the impact of the maintenance policies (and the optimality criteria for the selection of the parameters characterizing those policies) in the operation of a production system with constrained production and buffer capacity. Although both things may have an impact on the system's performance, our results indicate that the selection of suitable optimality criteria to obtain the values of the maintenance policy parameters is critical. Our empirical results also show the importance of basing these optimality criteria on the global operational metrics rather than on the local maintenance performance metrics. This fact is of interest when the system is more constrained in terms of production capacity and/or inventory buffer size.

This approach could be applied to a more complex production system, simply by adding the corresponding equations of the material, information and financial flows in the model. A great advantage of this approach is the possibility of a fast assessment in case of maintenance policies in which we may want to take into account different relevant state variables of the system. For instance, we could design a maintenance policy of a unit by taking into account the buffer size of three inventory locations after that production unit, receiving products from it, *etc*.

Further research may explore the relative benefits of different optimality criteria for specific industrial problems, or could consider some other technical criteria to design the maintenance of specific items.

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15

Overall Maintenance Management Assessment

15.1 Introduction

In this chapter we describe a process to obtain basic overall maintenance management performance measures. This process is important since many of the maintenance functional indicators and KPIs (like in [1, 2]) may be built from these performance measures. It is, therefore, very important to make sure that the organization captures suitable data and that data are properly aggregated/disaggregated according to the required level of maintenance management performance analysis.

We have divided this chapter into five sections, the first (next) three sections review fundamental time related variables, after their entire characterization, variables are used to calculate operational dependability measures of production items. Until this section, measures are purely technical, no economic considerations are involved. The last two sections are devoted to maintenance effectiveness and efficiency assessment. At this point economic considerations are introduced and we somehow try to assess the "profitability" of our maintenance management system, comparing the resources spent with the performance of the production and maintenance systems respectively.

15.2 Time Variables Characterization

In order to formalize the different maintenance performance measures of an item, let us first review a simple characterization of different time variables that we will use in this analysis. In order to do so, we introduce Figure 15.1 where we use the following notation:

F : *Failure event*
TBF : *Time between failures*
UT : *Up time*
DT : *Down time*

TTR : *Time to repair*
LDT : *Logistic delay time*
TTF : *Time to failure (time the item is utilized before failure)*
NUT : *Nonutilized time*

In Figure 15.1 we represent the evolution of the states of an item that has different failures over time; in the figure we can appreciate three failures: F_{i-1}, F_i and F_{i+1}. The time between two consecutive failures is called *time between failures* (TBF). For instance, the notation for the time beween failures F_i and F_{i+1} is then TBF_i and it is the result the down time and the up time of the item between those failures:

$$TBF_i = DT_i + UT_i \tag{15.1}$$

After a failure the item is in the down state during a certain down time (DT) after which it returns to the up state, where it will be in conditions to perform its required function for a certain up time (UT) until the next failure occurs. Down time will be subdivided into the time to repair (TTR), which is an active corrective or repair time, and the time the item is down due to logistic delays (LDT). Hence:

$$DT_i = TTR_i + LDT_i \tag{15.2}$$

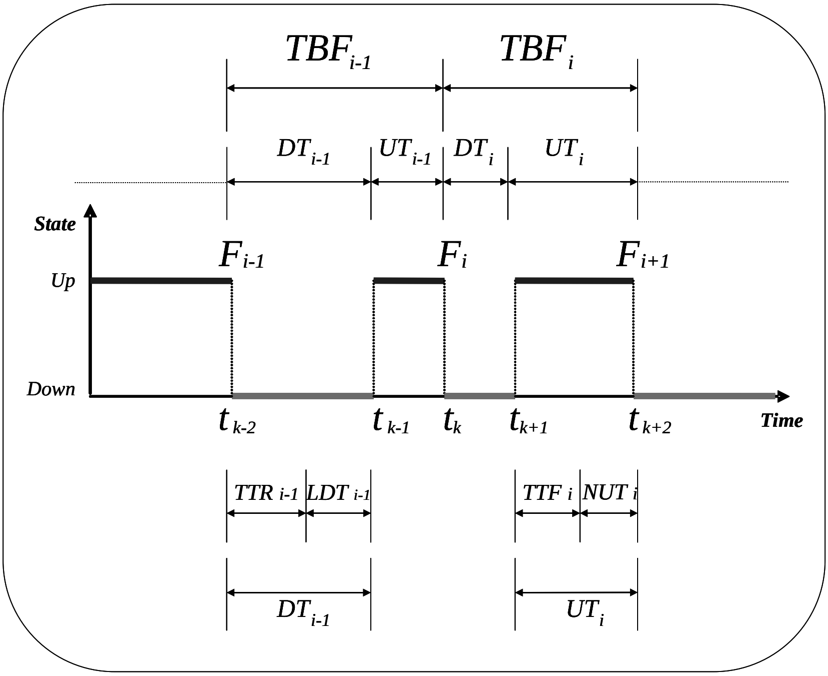

Figure 15.1. Representation of different times and states of an item sujected to failures

Also, up time will be subdivided into the time the item is utilized (UTT), which is the time the equipment is in operation, and the time the item is not utilized (NUT) defined as the time the item is in standby or idling. Hence:

$$UT_i = UTT_i + NUT_i \tag{15.3}$$

On many ocasions, all these time measures will be dissagregated. For instance, critical failure modes may require specific analysis for their elimination or control. In order to do so, we have to prepare a figure like Figure 15.1 but now customized per failure mode.

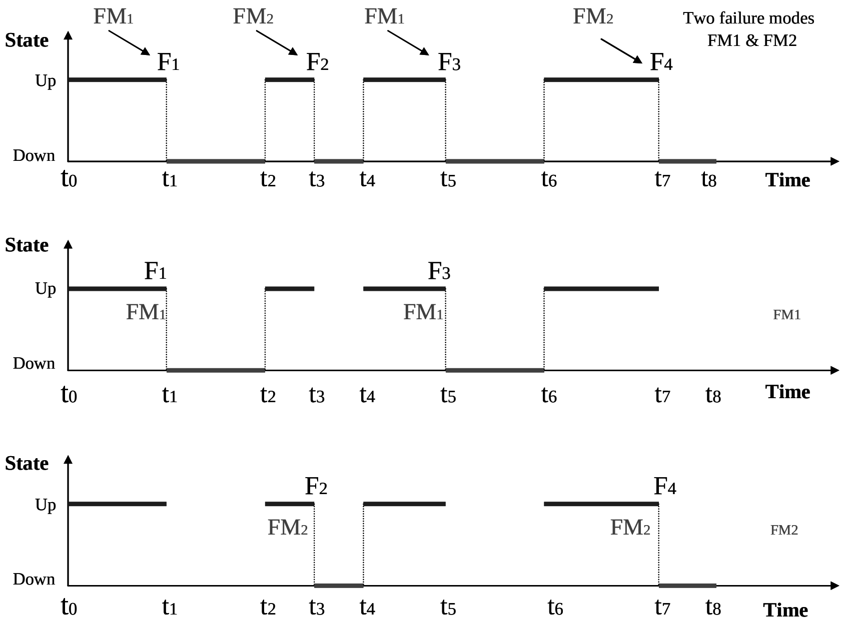

Figure 15.2. Representation of item states disaggregating per failure mode

As an example of previous process we present Figure 15.2 where we disaggregate the time and states of the item for two different failure modes that are considered in the analysis — note that any other failure mode failures would be ignored in the data that is presented in Figure 15.2. In this figure, down times for FM_1 do not compute for FM_2 and *vice versa*. Therefore, the time between failures refer to the time between two consecutive failures of the same failure mode, for instance, for FM_1, the time between F_1 and F_3 will now be $TBF_1=(t_5–t_4)+(t_3–t_1)$, and the up-time after the failure F_1 will be $UT_1= (t_5–t_4)+(t_3–t_2)$. Following the same criteria, for FM_2, time between F_2 and F_4 will be $TBF_2=(t_7–t_6)+(t_5–t_3)$, and the up-time after the failure F_2 will be $UT_2= (t_7–t_6)+(t_5–t_4)$.

These time distinctions per failure mode seem to be rather simple, but we have found that many organizations fail when capturing this data. This problem can manage to be more frequent and important for certain equipment like stand-by equipment. In this case, the times that the equipment is up and utilized are often not well differentiated, and data for failure analysis purposes is often corrupted and not worthy for our maintenance assessment purposes.

15.3 Definition of Common Time-related Measures

Assume that an item has *n* failures during a certain period of time selected for our analysis (according to above variables definition); then the following measures can be calculated:

- MTBF = Mean Time Between Failures

$$MTBF = \frac{\sum_{i=1}^{i=n} TBF_i}{n} \tag{15.4}$$

- MUT = Mean Up Time Between Failures

$$MUT = \frac{\sum_{i=1}^{i=n} UT_i}{n} \tag{15.5}$$

- MTTF = Mean Time to Failure

$$MTTF = \frac{\sum_{i=1}^{i=n} TTF_i}{n} \tag{15.6}$$

- MDT = Mean Down Time Between Failures

$$MDT = \frac{\sum_{i=1}^{i=n} DT_i}{n} \tag{15.7}$$

- MTTR = Mean Time To Repair

$$MTTR = \frac{\sum_{i=1}^{i=n} TTR_i}{n} \tag{15.8}$$

- MLDT = Mean Logistic Delay Time

$$MLDT = \frac{\sum_{i=1}^{i=n} LDT_i}{n} \tag{15.9}$$

15.4 Measuring Item Operational Dependability

Note that the following measures are now defined considering them as item operational measures, *i.e.* resulting from the performance of an item within a certain operational context — and, of course, a certain organization for maintenance, and not as inherent attributes or capabilities of that item.

15.4.1 Operational Availability

Availability will be the portion of time that the equipment is in good conditions to fulfil its function — regardless whether it is utilized or not. This operational measure can be estimated, as a percentage, using Equation (15.10), as follows:

$$A = \frac{MUT}{MUT + MDT} \times 100\% \qquad (15.10)$$

15.4.2 Operational Reliability

Operational reliability can be defined as the probability that an item fulfils a specific mission (suffers no failure) under certain operational conditions and during a given time period. Of course the reliability of an item is a function of time; the longer the time period, the lower the reliability of the item. However we can find a good estimator of the item behaviour regarding reliability assessing periodically the MTTF measure that we presented above in Equation (15.6). MTTF is also widely used in production scheduling to determine whether the next batch can be produced without interruption since it represents how long an item is expected to run before it fails [3].

15.4.3 Operational Maintainability

Maintainability can be defined as the probability for an equipment to be returned to a state in which it can fulfil the mission in a given time period, after the occurrence of a failure and using pre-established maintenance procedures.

Operational maintainability is basically related to the design and complexity of the equipment and to other aspects like the qualification of the personnel carrying out the maintenance activities, the availability of the required maintenance tools or the existence and fulfilment of the maintanance procedures.

The fundamental measure to evaluate operational maintainability is the mean time to repair (MTTR) in Equation (15.8), which measures the repair times and technical delays within the maintenance organization control. Notice that MTTR does not take into account logistic delays that may increase equipment downtime, but that may be out of the maintenance organization control.

15.5 Maintenance Management Effectiveness Assessment

In Chapter 1 of this book we discussed the concept of maintenance effectiveness. We mentioned that an effective maintenance management will allow us to arrive at a position where we will be able to minimize the maintenance indirect costs, the most important ones, those associated with production losses, and ultimately, with customers' dissatisfaction. We said that in the case of maintenance, effectiveness can represent the overall company satisfaction with the capacity and condition of its assets, or the reduction of the overall company cost obtained because production capacity is available when needed. The following measures are examples of simple metrics that we can use to track maintenance effectiveness over time in our organization:

1. Maintenance cost per unit produced

$$MCUP = \frac{Total\ \ Maintenance\ \ Direct\ \ Cost}{Total\ \ Number\ \ of\ \ Units\ \ produced} \tag{15.11}$$

2. Maintenance cost as a percentage of production cost;

$$MCPC = \frac{Total\ \ Maintenance\ \ Direct\ \ Cost}{Total\ \ Production\ \ Cost} \times 100\% \tag{15.12}$$

3. Cost of lost production due to failure/breakdowns. The cost of lost production is a cost associated to the down-time of the production unit (C_{DT} in Equation 15.13 represents the average lost production cost per unit down-time). Sometimes this cost is not available in certain organizations, or it is difficult to be estimated — especially in those where production capacity is not entirely committed. However, it will always be interesting to have an idea of the monetary value that the indirect cost of maintenance represents for our organization:

$$CLPF = C_{DT} \times \sum_{i=1}^{i=n-1} DT_i \tag{15.13}$$

4. Maintenance quality indexes. Effectiveness is often discussed in terms of the quality of the service provided, viewed from the customer's perspective. From this pont of view we could also use the following measures:

- Corrective cost as a percentage of total maintenance cost

$$CMCMC = \frac{Corrective\ \ Maintenance\ \ Cost}{Total\ Maintenance\ Cost} \times 100\% = \frac{CMC}{MC} \times 100\% \tag{15.14}$$

- Total maintenance non-quality cost

$$MNQC = CMC + CLPF \tag{15.15}$$

- Maintenance quality index. This index compares the maintenance quality cost (preventive maintenance cost) *vs* the cost of non-quality of maintenance (corrective maintenance cost plus cost of lost production due to failures — opportunity losses/deferred production, production losses due to unavailability, operational losses, impact on quality, impact on safety and environment). Of course, expected evolution of these measures over time would be like in Figure 15.3, and the index would be increasing:

$$MQI = \frac{MQC}{MNQC} = \frac{PMC}{CMC + CLPF} \quad (15.16)$$

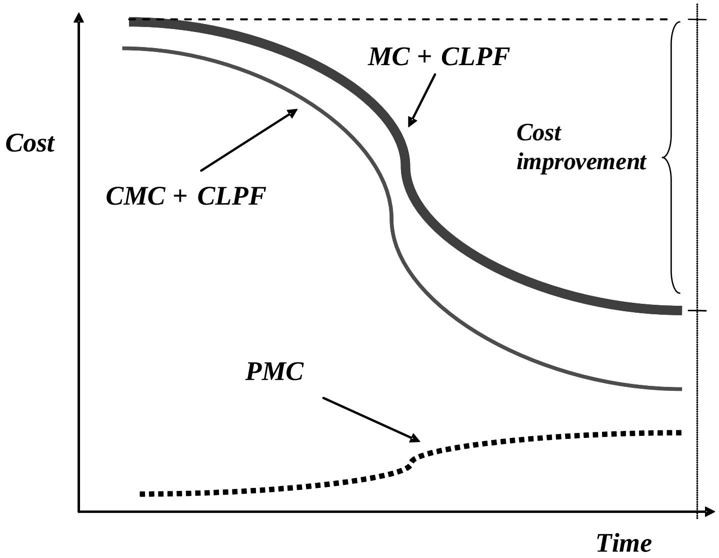

Figure 15.3. Expected evolution of quality and non-quality maintenance costs over time

5. Benchmarking measures. Previous measures may offer information regarding absolute evolution of the maintenance effectiveness in our organization. Benchmarking these measures against similar production and businesses units will offer a fundamental "relative" perspective required to ensure that our speed of maintenance effectiveness improvement is the correct one.

15.6 Maintenance Management Efficiency Assessment

In Chapter 1 we mentioned that efficiency is acting or producing with minimum waste, expense, or unnecessary effort. Therefore if we want to measure maintenance efficiency we will measure how well the different maintenance activities are being performed, not whether the activities themselves are correct. By measuring maintenance efficiency we will measure, for instance, our ability to ensure proper skill levels, proper work preparation, suitable tools and schedule fulfilment, *etc*. As we previously said, this will allow us to minimize the maintenance direct cost (labour and other maintenance required resources).

There will be maintenance efficiency measures for each maintenance management activity. As an example, we include in this section the following ones:

1. Efficiency in maintenance planning. Maintenance planning activities have different levels of intensity according to the criticality of the items. For instance, in Section 9.5 we presented an example where certain assets classified within “Category A” — critical — would receive a special treatment in terms of maintenance planning due to their high level of impact on business performance. More precisely, RCM methodology would be required for the definition of the preventive maintenance (PM) plans of these items. According to this maintenance strategy definition, efficiency of our maintenance planning activities, related to these “category A” items, could be measured as follows:

$$\frac{Number\ of\ PM\ plans\ obtained\ with\ RCM\ for\ Category\ A\ Items}{Number\ of\ Category\ A\ Items}\times 100\% \qquad (15.17)$$

2. Efficiency in maintenance scheduling. Measuring efficiency in maintenance scheduling activities will be related to the evaluation of our ability to meet all maintenance planned activities within their timeframe. A measure to track our performance in scheduling could be as follows:

$$\frac{Number\ of\ PM\ activities\ carried\ out\ within\ a\ certain\ timeframe}{Number\ of\ PM\ activities\ planned\ within\ a\ certain\ timeframe}\times 100\% \qquad (15.18)$$

   The performance of maintenance scheduling activities is especially important to be measured when carrying out big repairs or plant shut-downs. For these cases, efficiency of maintenance scheduling activities could be measured, for instance, as follows:

$$\frac{Time\ planned\ for\ the\ big\ repair\ to\ be\ carried\ out}{Real\ time\ needed\ for\ the\ big\ repair}\times 100\% \qquad (15.19)$$

3. Efficiency in maintenance execution management. Another example of efficiency measure can be obtained for maintenance execution management. In this case we have to check our ability to meet the

maintenance task schedule when carrying out the maintenance work. A measure for this could be, for instance, as follows:

$$\frac{\textit{Time scheduled for the PM to be carried out}}{\textit{Real time needed for the PM}} \times 100\% \tag{15.20}$$

Another measure of maintenance execution management, now for corrective maintenance activities, would be the mean time to repair ratio (MTTR).

4. Efficiency in maintenance logistics. In this area of maintenance management we could track whether we reduce the logistic delay time (LDT) at the minimum expense of inventory resources. In order to do so we could use RONA ratio as in Figure 13.8 or track, for instance, a rather simple measure like

$$\frac{MLDT \times C_{DT}}{\textit{Working capital requirements for maintenance inventory}} \tag{15.21}$$

5. Other efficiency measures for other maintenance management activities could be obtained (like for instance: managing maintenance manpower, managing maintenance contracts, *etc*.); at the same time, these measures should be benchmarked to other measures in different production lines or business units with similar equipment.

15.7 References

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[2] Mather D, (2005) The maintenance scorecard. New York: Industrial Press, Inc.
[3] Campbell JD, Jardine AKS, (Editors) (2001) Maintenance excellence: Optimizing equipment life-cycle decisions. New York: Marcel Dekker.

16

Failures Impact on Life Cycle Cost Analysis

16.1 Introduction

Life cycle costing is a well-established method used to evaluate alternative asset options. This methodology takes into account all the costs arising during the life cycle of the asset. These costs can be classified as the ‘capital expenditure’ (CAPEX) incurred when the asset is purchased and the ‘operating expenditure’ (OPEX) incurred throughout the asset’s life.

In this chapter we explore different aspects related to the ´non reliability` cost within the life cycle cost analysis (LCCA), and we describe three basic models found in the literature (constant failures rate, deterministic failures rate and Weibull distribution failures rate) that include in their evaluation processes the quantification of the impact that could cause the diverse failure events in the total costs of a production asset. The chapter also contains a case study in which the above-mentioned concepts and models were applied to the life cycle cost assessment of a specific asset. Finally, we present a summary of results and discuss the limitations of the different models. The chapter concludes by presenting possible directions of future research work.

Product support and maintenance needs of systems are more or less decided during the design and manufacturing phase [1]. These decisions have a high impact in the total life cycle of the system, specially those related to the “reliability” factor (like for instance decisions related to the quality of the design, the selection of technology, the technical complexity, the costs of preventive/corrective maintenance or the maintainance levels and maintainability). Clearly, these aspects have a great influence on the possible expectations to extend the useful life of the production systems to reasonable costs (see, for instance, [1—3]).

Let us now highlight some of the most important milestones in the development of the LCCA methodology [4]:

- *1933.* The first reference of a “Life Cycle Analysis” carried out by one of the Federal Departments of the Government of the United States, the *General Accounting Office (GAO),* appeared. The analysis was related to the purchase of machinery;

- *1960.* The *Logistics Management Institute* of the United States developed an investigation in the area of obsolescence engineering for the Ministry of Defense. The final result of this investigation was the publication of the first Life Cycle Cost Manual in 1970;
- *1975.*The Federal Department of Supplies and Services of the United States developed logistics and acquisition techniques based on the LCCA;
- *1979.* The Department of Energy introduced a proposal (44 FR 25366, April 30, 1979) which was intended to foster evaluations of LCCA for all new constructions and major modifications in government facilities;
- *1980—1985.* The American Society for Testing and Materials (ASTM) developed a series of standards and databases orientated towards easing the search of the necessary information for the application of the LCCA;
- *1992.* At the University of Virginia, Fabrycky and Blanchard, developed the LCCA model (see details in [5]), in which they include a structured process to calculate the costs of non-reliability starting from the estimate of constant values of failures per year (constant rate of failures);
- *1980—1985.* David Willians and Robert Scott of the consulting firm RM-Reliability Group, developed a model of LCCA based on the Weibull Distribution to estimate the frequency of failures and the impact of the Reliability Costs (see [6]);
- *1999.* Within the European Project EUREKA, specifically inside the line of investigation denominated MACRO (Maintenance Cost/Risk Optimization Project), the Woodhouse Partnership Consulting Group developed an LCCA commercial software denominated APT Lifespan.

In recent years, this research area has continued its development as much at academic level as at industrial level. It is important to mention the existence of other methodologies that have emerged in the area of LCCA, such as: Life Cycle Costs Analysis and Environmental Impact, Total Costs Analysis of Production Assets, among others [7]. These methodologies have their particular characteristics although, regarding the estimation process of the costs for failure events impact, they propose reliability analysis usually based on constant failure rates.

The rest of this chapter is organized as follows. Section 16.2 reviews basic aspects of the LCCA techniques and discusses the problems related to the real determination of the asset's cost. The subsequent sections are devoted to the characterization of the impact of reliability of the life cycle cost (Sections 16.3 and 16.4) and to explain basic models dealing with this issue (Section 16.5). Section 16.6 contains a case study where we applied the above-mentioned concepts and models to the life cycle cost assessment of a specific asset. In Section 16.7 a summary of results is presented, as well as a discussion about the limitations of the different models. Finally, the chapter presents some concluding remarks and provides directions for further research.

16.2 Basic Elements of the LCCA

To evaluate the costs associated with the life cycle of a production system, a collection of procedures that group together exists in the denominated Techniques of Life cycle Costs Analysis. The early implementation of the costs analysis techniques allows an evaluation in advance of the potential design problems and to quantify the potential impact in the costs along the life cycle of the industrial assets [7]. Below some basic definitions of Life cycle Cost Analysis are presented.

Kirk and Dellisolla [4] define the LCCA as a technique of economic calculation that allows the optimization of the decision-making associated with the design processes, selection, development and substitution of the assets that conform a production system. It is intended to evaluate in a quantitative way all the costs associated with the economic period of expected useful life, expressed in yearly equivalent monetary units (dollars/year, Euros/year, Pesos/year).

Woodhouse [8] defines the LCCA as a systematic process of technical-economical evaluation, applied in the selection and replacement process of production systems that allows consideration of economic and reliability aspects simultaneously, with the purpose of quantifying the real impact of all the costs throughout the life cycle of the assets (US$/year), and in this manner, be able to select the asset that contributes the largest benefits to the productive system.

The great quantity of variables that must be managed when estimating the real costs of an asset throughout its useful life generates a scenario of high uncertainty [7]. The combination of inflation, rise/decrease of costs, reduction/increase of purchasing power, budget limitations, increase of competition and other similar characteristics, has generated a restlessness and interest about the total cost of the assets. Often the total cost of the production system is not visible, in particular those costs associated with operation, maintenance, installation tests, personnel training, amongst others. In Figure 16.1 an island can be observed in which, by way of a simile, the costs of smaller uncertainty (costs of simple estimate) are located in the superior part above water level, and the costs of more uncertainty, begin to appear below water level (costs whose estimates are more complicated).

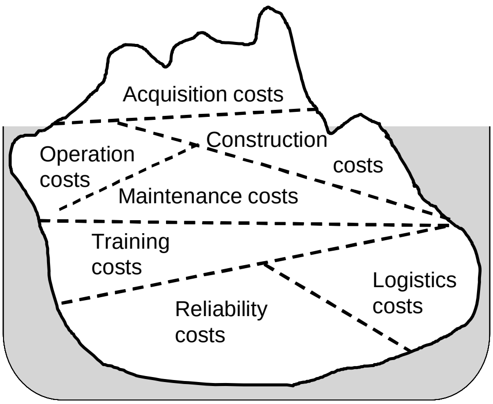

Figure 16.1. Cost uncertainty

Additionally, the dynamics of the economic scenario generate problems related to the real determination of the asset's cost. Some of them are:

- The factors of costs are usually applied incorrectly. The individual costs are inadequately identified and, often, they are included in the wrong category: the variable costs are treated as fixed (and *vice versa*), the indirect costs are treated as direct, *etc*.;
- The countable procedures do not always allow a realistic and timely evaluation of the total cost. Besides, it is often difficult (if not impossible) to determine the costs, on a functional basis;
- Countless times the budgetary practices are inflexible with regard to the change of funds from one category to another, or from one year to another.

To avoid the uncertainty in the costs analysis, the studies of economic viability should approach all the aspects of the life cycle cost. The tendency towards the variability of the main economic factors, together with the additional problems already enunciated, have resulted in a move towards erroneous estimates, causing designs and developments of production systems that are not suitable from the cost-benefit point of view. It can be anticipated that these conditions will worsen, unless the design engineers assume a higher grade of consideration of the costs. Inside the dynamic process of change, the acquisition costs associated to the new systems are not the only ones to increase, but rather the operation and maintenance costs of the systems already in use also rise it in a quick manner. This is mainly due to a combination of factors such as:

- Inaccuracies in the estimates, predictions and forecasts of the events of failures (reliability), ignorance of the probability of occurrence of the different failure events inside the production systems in evaluation;
- Ignorance of the deterioration processes behaviour;
- Lack of forecast in the maintenance processes and ignorance of modern techniques of maintenance management;
- Engineering changes during the design and development;
- Changes in one's own construction of the system;
- Changes in the expected production patterns;
- Changes during the acquisition of system components;
- Setbacks and unexpected problems.

16.3 Cost Characterization in Different Phases of the Equipment Life Cycle

The cost of a life cycle is determined by identifying the applicable functions in all of its phases, calculating the cost of these functions and applying the appropriate costs during the whole extension of the life cycle. So that it is complete, the cost of the life cycle should include all the costs of design, fabrication and production [9]. In the following paragraphs the characteristics of the costs in the different phases of an asset's life cycle are summarized. These categories and their constituent elements compose a breakdown structure of the cost that is shown in Figure 16.2.

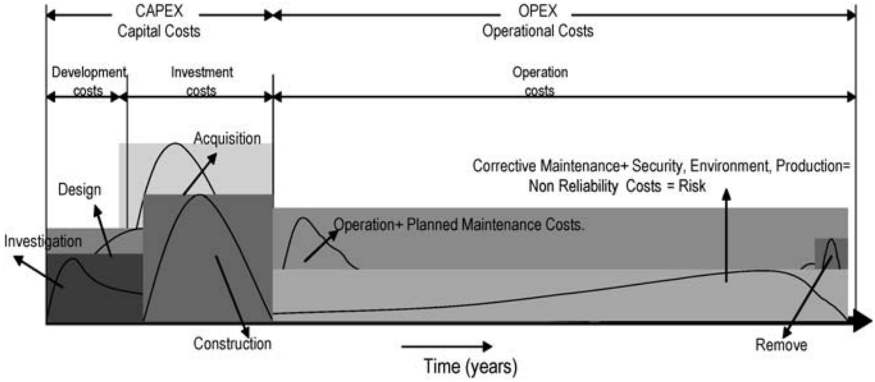

Figure 16.2. Cost strutcure in the asset/equipment life cycle

The main categories of costs presented in the previous figure are now described [10]:

- Research, design and development costs: initial planning, market analysis, product investigation, design and engineering requirements, *etc.*;
- Production, acquisition and construction costs: industrial engineering and analysis of operations, production (manufacturing, assembly and tests), construction of facilities, process development, production operations, quality control and initial requirements of logistics support;
- Operation and support costs: operations inputs of the production system, planned maintenance, corrective maintenance (depending on the reliability Factor) and costs of logistical support during the system's life cycle;
- Removal and elimination costs: elimination of non-repairable elements along the life cycle, retirement of the system and recycling material.

From the financial point of view, the costs generated throughout the life cycle of the asset are classified into two types of costs:

- *CAPEX:* Capital costs (design, development, acquisition, installation, staff training, manuals, documentation, tools and facilities for maintenance, replacement parts for assurance, withdrawal);
- *OPEX:* Operational costs: (manpower, operations, planned maintenance, storage, recruiting and corrective maintenance — penalizations for failure events/low reliability).

16.4 Reliability Impact on Life Cycle Cost

Woodhouse [8] outlines that to be able to design an efficient and competitive productive system in the modern industrial environment, it is necessary to evaluate and to quantify in a detailed way the following two aspects:

- Costs: the aspect that is related to all the costs associated with the expected total life cycle of the production system. Including: design costs, production, logistics, development, construction, operation, preventive and corrective maintenance and withdrawal;
- Reliability: the factor that allows the prediction of the form in which production processes can lose their operational continuity due to events of accidental failures and the evaluation of the impact on the costs that the failures cause in security, environment, operations and production.

The key aspect of the term reliability is related to the operational continuity. In other words, we can affirm that a production system is "reliable" when it is able to accomplish its function in a secure and efficient way throughout its life cycle. Now, when the production process begins to be affected by a large quantity of accidental failure events (low reliability), this scenario causes high costs, associated mainly with the recovery of the function (direct costs) and with growing impact in the production process (penalization costs).

The total costs of non-reliability ([8,11]) can be characterised as follows:

- Costs for penalization:
  - Downtime: opportunity losses/deferred production, production losses (unavailability), operational losses, impact on quality, impact on security and environment.
- Costs for corrective maintenance:
  - Manpower: direct costs related with the manpower (own or hired) in the event of an unplanned action;
  - Materials and replacement parts: direct costs related to the consumable parts and the replacements used in the event of an unplanned action.

The impact on the costs that an asset of low reliability generates is associated directly with the behaviour of the following two indexes:

- The mean time between failures (MTBF): systems with short MTBF reflect low values of reliability and a high number of failures:

$$MTBF = \sum \frac{time\ \ between\ \ failures}{number\ \ of\ \ failures} \qquad (16.1)$$

- The mean time to repair (MTTR): systems with long MTTR, reflect low maintainability values (*i.e.* a large quantity of time is needed to be able to recover their function):

$$MTTR = \sum \frac{time\ \ to\ \ repair}{number\ \ of\ \ \ failures} \tag{16.2}$$

Failure behaviour of much production equipment shows a lack of reliability aspects analysis in the design phase [8]. This situation results in an increase in the operation costs affecting the profitability of the production process. It is necessary to keep in mind that almost two-thirds of the life cycle cost of an asset or system are already determined in the preliminary conceptual and design phase (70%—85% of value creation and costs reduction opportunities) [12].

16.5 Models to Assess Reliability Impact on LCCA

The use of the LCCA techniques has increased in a remarkable way, mainly due to the development of a large number of methodologies, which propose simple methods to evaluate different designs or alternative uses of human and economic resources — available at the moment — to develop a production system [7]. The reader is referred to Asiedu and Gu [13] for a review about the state of the art of LCCA techniques. Most of the methodologies proposed in recent years include basic techniques to quantify the economic impact of the failures. But let us now describe the three basic methods that we have found which estimate the reliability impact within the LCCA.

16.5.1 Constant Failure Rate Model

In general terms, the constant failures rate model for LCCA requires the following activities (see details in [8,14]):

1. Determination of the operational conditions of the system. Describe the manner of the system operation (for instance: full load, half load, no-load, *etc*.) and the production capacities to satisfy;
2. Determination of the utilization factors. These factors should indicate the functioning state inside each operation mode;
3. Identify the different options to be evaluated. Select the existent alternatives that can be covered with the demanded production needs;
4. Identify, for each alternative, all the basic costs categories: initial investment, development, acquisition, planned maintenance, and so on;
5. Determine, for each alternative, the costs for non-reliability. Identify the main types of failures and the occurrence frequency per year — which will be a constant value throughout the life cycle of the asset (this aspect is detailed later on);

6. Determine the critical costs. Identify the costs categories of higher impact, and analyse those factors increasing the costs (propose control strategies);
7. Calculate the net present value (*NPV*) for the cost of each alternative. This requires the definition of the discount factor and the expected period of useful life for each evaluated alternative;
8. Select the winning alternative. Compare the total costs of the evaluated alternatives and select the option generating lesser cost for the expected useful life period.

With regard to the quantification of the costs of non-reliability (in point 5), the constant failure rate model proposes the following procedure:

1. Define the types of failures (f) where f = 1…F for F types of failures;
2. Define the expected frequency of failures per year δ_f. This frequency is assumed as a constant value per year for the expected cycle of useful life. The δ_f is calculated starting from the following expression:

$$\delta_f = \frac{N}{T} \tag{16.3}$$

   where *N* is the total number of failures and T is the expected number of years of useful life;
3. Calculate the costs per failure C_f. These costs include costs of replacement parts, manpower, penalization for production loss and operational impact (in US$/failure);
4. Calculate the total costs per failures per year TCP_f. The TCP_f is calculated starting from the following expression:

$$TCP_f = \sum_{f=1}^{F} C_f \delta_f \tag{16.4}$$

   where *f* is different modes of failures and *F* is the total number of failure modes considered. C_f is the cost associated with the failure *f* , in US$/failure, and δ_f is the frequency of the failure mode *f*, expressed in failures per year;
5. Calculate the total cost per failure in present value $NPV(TCP_f)$. Given a yearly value TCP_f, the current quantity of money (today) that one needs to start saving (today), to be able to pay this annuity for the expected number of years of useful life *T*, for a discount rate *i*. The expression to use to estimate the $NPV(TCP_f)$ in present value is shown next:

$$NPV(TCP_f) = TCP_f \frac{(1+i)^T - 1}{i \times (1+i)^T} \tag{16.5}$$

Later, the rest of the evaluated costs (investment, planned maintenance, operations, *etc*.) are added to the costs calculated for non-reliability. The total cost is then calculated in present value for the selected discount rate and the expected years of useful life. Finally, the result obtained is compared to the total costs of the other evaluated options.

16.5.2 Deterministic Failure Rate Model

The deterministic failures rate model for LCCA proposes the following steps [5]:

1. Define the production process to evaluate;
2. Identify the possible alternatives that will cover the production demands — systems to evaluate;
3. Define, for each alternative, the detailed cost structure. The method classifies the costs in five categories:
   - Research and development costs
   - Construction and production costs
   - Preventive maintenance costs
   - Corrective maintenance cost — costs for non reliability (this step is detailed later on)
   - Disassembly — withdrawal costs .
4. Quantify, for each alternative, the costs for each one of the defined categories;
5. Identify, for each alternative, the factors with higher cost contribution per cost category;
6. Propose strategies, for each alternative, helping to minimize the impact on cost of the selected factors;
7. Quantify, for each alternative, the total costs — in annual equivalent value *A* — for a discount rate *i* and a number of years of expected service *t*;
8. Select the alternative that generates the lowest costs throughout the expected useful life period.

This method is quite similar to the constant failure rate model and it differs basically in two aspects:

- The total cost is estimated in equivalent annual values (*A*);
- The frequencies of failures may vary, in a deterministic way, for the different periods of time of the life cycle.

In relation to the quantification of the costs of non reliability (in point 3), this model proposes to evaluate the impact of the failures in the following way:

1. Identify, for each alternative, the main failure modes *f* where $f=1\ldots F$, for *F* failure modes;
2. Define, in a deterministic way and for each failure mode, the expected frequency of failures $\delta_f^{\,t}$ for the year *t*. The frequency of failures per year is considered deterministic, since it is defined starting from failures records, databases and/or experience of maintenance and operations personnel. In

this case the designer has to find out proper information related to every failure frequency of the various failure types;

3. Calculate the failures cost C_f (in US$/failure). These costs include: costs of replacement parts, manpower, production loss penalization and operational impact;
4. Calculate the costs per failure mode per year $CP_f^{\ t}$:

$$CP_f^{\ t} = \delta_f^{\ t} C_f \tag{16.6}$$

5. Convert, to present value, the costs for failure type per year $NPV(CP_f^{\ t})$. Given a future value $CP_f^{\ t}$, the present value is calculated for every year (t) to a discount rate and for a specific period of time:

$$NPV(CP_f^{\ t}) = CP_f^{\ t} \frac{1}{(1+i)^t} \tag{16.7}$$

6. Calculate the total costs per failure in present value $NPV(TCP_f^{\ t})$. All the costs for failure types, in present value, are added until the expected number of years of useful life (T):

$$NPV(TCP_f^t) = \sum_{t=1}^{T} NPV(CP_f^t) \tag{16.8}$$

7. Calculate the annual equivalent total cost AETC. Given a present value $NPV(TCP_f^{\ t})$, calculate its annual equivalent total cost AETC for the expected number of years of useful life T and the defined discount rate i:

$$AETC = NPV(TCP_f^t) \frac{i(1+i)^T}{(1+i)^T - 1} \tag{16.9}$$

Finally, the rest of the evaluated costs (investment, planned maintenance, operations, *etc*.) are added to the cost calculated by non-reliability, and the total cost is calculated in annual equivalent value. The result obtained is then compared for the different options.

16.5.3 Weibull Distribution Failure Rate Model

In terms of cost analysis structure, this model is similar to the constant failures rate model; the main difference is that now the non-reliability cost is estimated with failure frequencies calculated from a Weibull distribution function (see details in [6]). In relation to the quantification process of the non-reliability cost, this model proposes to evaluate the impact of the failures in the following way:

1. Identify, for each alternative to evaluate, the main types of failures. This way for certain equipment there will be *f=1… F* failure modes;
2. Determine, for each failure mode, the "times to failure" (operational times). This information will be gathered by the designer, based on failure records, databases and/or experience of the maintenance and operations personnel;
3. Calculate the cost of failures C_f (in US$/failure). These costs include replacement of parts, manpower, production loss penalization and operational impact costs;
4. Determine the frequency of expected failures δ_f using the Weibull distribution function. To do so we will use the following notation:

δ_f : Frequency of failures;
t_f : Time between failures;
MTBF : Mean time between failures (inverse of the frequency);
Γ : Gamma function (see values in [15]).
α : Characteristic life
β : Shape parameter.

If we assume that the random variable t_f is distributed according to a Weibull function of parameters $\alpha>0$ and $\beta>0$, its density function is

$$f(t_f) = (\beta t_f^{\beta-1})e^{-\left(\frac{t_f}{\alpha}\right)^{\beta}} \text{, for } t_f \geq 0 \tag{16.10}$$

The mean μ is

$$\mu = \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{16.11}$$

The variance is

$$\sigma^2 = \alpha^2\left(\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{2}{\beta}\right)\right) \tag{16.12}$$

The MTBF is the expected value of the random variable t_f, *that* is equal to the mean μ:

$$MTBF=\mu=\alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{16.13}$$

The parameters α and β, are calculated from the following expressions:

$$\alpha = \exp\left(\frac{\dfrac{F}{\sum_{i=f}^{F} A_{fi}} - \left(\sum_{i=f}^{F} A_{fi} Ln(t_{fi})\right)}{\left(\sum_{i=f}^{F} A_{fi} - Ln(t_{fi})\right) - \left(\sum_{i=f}^{F} A_{fi} Ln(t_{fi})\right)} \right) \tag{16.14}$$

$$\beta = \frac{\sum_{i=f}^{F} A_{fi}}{\sum_{i=f}^{F} \frac{1}{Ln(t_{fi})} \left(1 - Ln(\alpha)\right)} \tag{16.15}$$

where

$$A_{fi} = \frac{Ln\left(Ln\left(\dfrac{1}{1 - \dfrac{f}{F+1}}\right)\right)}{Ln(t_{fi})} \tag{16.16}$$

In Equations (16.14)—(16.16), f is the number of the specific failure event, F is the total number of evaluated failures and t_{fi} is the time between the failures in issue:

$$\delta_f = \frac{1}{MTBF} \tag{16.17}$$

5. Calculate the total costs per failures per year TCPf , costs generated by the different failure events, with the following expression:

$$TCP_f = \sum_{f}^{F} \delta_f C_f \tag{16.18}$$

The equivalent total annual cost represents the value of the money that will be needed, every year, to pay for the problems caused by failure events during the expected years of useful life.

6. Calculate the total costs per failure in net present value $NPV(TCP_f)$. Given a yearly value TCP_f, this is the amount of money that needs to be saved (today) to be able to pay this annuity for the expected number of years of useful life T, and for a discount rate i. The expression used to estimate the $NPV(TCP_f)$ is

$$NPV(TCP_f) = TCP_f \frac{(1+i)^T - 1}{i(1+i)^T} \tag{16.19}$$

Finally, as in previous models, the rest of the costs evaluated (investment, planned maintenance, operations, *etc*.) are added to the cost calculated for non-reliability and the total cost is obtained in annual equivalent value. The result is then compared for the different options.

16.5.4 Summary of Key Aspects and Limitations per Model

Let us then see a summary of key aspects and limitations for the utilization of the models that we have reviewed:

- Constant Failures Rate Model

  This model is regularly used in the initial phases of production systems design, since it provides quick costs estimates that can guide the process of alternatives selection. This method should not be used to make conclusive decisions, since it may generate high levels of uncertainty in non-reliability costs estimations, which may lead to erroneous decisions, especially in those cases where costs per failure are a critical category.

  The main *limitation* is related to the manner of estimation of the reliability impact on costs, since the model considers constant failures frequencies throughout the life cycle of the asset. This is not the norm because failure frequencies change as the years pass, due to the influence of different factors (such as the type of operation, the quality of preventive maintenance, the quality of materials, *etc*.).

- Deterministic Failures Rate Model

  This method is frequently used in the intermediate phases of the project for these stages better precision is possible with the different system alternatives to evaluate. At this time, searching for reliability data becomes easier. This model could be used to make conclusive decisions in cases where the reliability data gathered comes from good quality records and databases.

  This method is more realistic than the previous one. It demands that the designer identifies failure frequency behaviour patterns. Nevertheless, the failures frequencies are assumed deterministic and therefore the entire process relies on the designer's capacity to get proper failure data.

  The main limitation of this model is related to the process of failure frequency information gathering. It is important that this information is based on suitable historical records and well sustained statistical databases. In their defect, information could be obtained through surveys directed towards people that have a lot of experience in areas like operations, processes and maintenance. Moreover, knowledge about potential alternatives which are being evaluated would also be valuable.

- Weibull Distribution Failures Rate Model:

This method is typically used in the final phases of the project, with more precise reliability information that is adjusted to the operational context of the different alternatives to evaluate. In relation to the process of reliability data gathering, the designer should demand from the manufacturers detailed and good quality information about the more important types of failures and, if possible, for similar operational conditions.

This model estimates the expected value of the time between failures using the Weibull distribution function. Starting from this probabilistic value of MTBF, the model quantifies the frequency of failures per year and the costs for non-reliability. The main limitations of this method are:

- Regardless of the use of the Weibull distribution, the model quantifies the impact of the non-reliability annual costs in a constant way over the years of expected asset useful life;
- It restricts the reliability analysis to the exclusive use of the Weibull distribution, excluding other existent statistical distributions, which could also be used in the calculation of the MTBF and failure frequencies.

16.6 Case Study

In this case study we will apply the three previous models to the analysis of the non reliability cost of certain gas compressor located in a refinery plant. The information was gathered from the maintenance records of the refinery. Table 16.1 presents the times between failures t_f for the 24 failure events during 10 years of useful life of the gas compressor.

Table 16.1. Times between failures

5	7	3	7	2	4	3	5	8	9	2	4	6	3	4	2	4	3	8	9	4	4	7	4

16.6.1 Case Study — Constant Failure Rate Model

This model proposes to evaluate the impact of the failures in the following way:

- Define the failure modes (f) where $f=1\ldots F$ for F failure modes. In this case, it is assumed $F=1$ failure mode;
- Define the expected frequency of failures per year δ_f , using Equation (16.3).

N=24 events
T=10 years
δ_f =2.4 failures/year

This frequency is assumed as a constant value per year for the expected years of useful life;

- Calculate the cost per failure C_f (this cost includes costs of replacement parts, manpower, production loss penalization and operational impact):

C_f=5,000.00 US$/failure

- Calculate the total costs per failures per year TCP_f (using Equation 16.4):

TCP_f =12,000.00 US$/year

- Calculate the total cost per failure in present value $NPV(TCP_f)$, (using Equation 16.5), for a period $T=10$ years and discount rate $i=10\%$:

$NPV(TCP_f)$=73,734.80 US$

16.6.2 Case Study — Deterministic Failure Rate Model

This model proposes to evaluate the impact of the failures in the following way:

- Identify, for each alternative to evaluate, the main failure modes (f). Where $f=1\ldots F$, for F failure modes. For this case F=1 failure mode.
- Define in a deterministic way for each failure type, the expected occurrence frequency for period of time $\delta_f^{\,t}$. The frequency of failures per year is defined starting from failures records (Table 16.2). The expected frequency of failures per year is shown in Table 16.2.

Table 16.2. Frequencies of failures per year

Year	1	2	3	4	5	6	7	8	9	10
$\delta_f^{\,t}$ in failures/year	2	3	3	1	3	3	3	1	3	2

- Calculate the costs of failures C_f (in US$/failure):

C_f=5,000.00 US$/failure

- Calculate the cost per failure mode and year $CP_f^{\,t}$ (using Equation 16.6). The $CP_f^{\,t}$ for a 10 years expected useful life are shown in Table 16.3.

Table 16.3. Cost per year for failures. In US$/year

Year	1	2	3	4	5	6	7	8	9	10
$CP_f^{\,t}$ =	5,000	15,000	15,000	5,000	15,000	15,000	15,000	5,000	15,000	10,000

- Convert to present value the costs of failure type per year $NPV(CP_f^{\,t})$ (using Equation 16.7). Given a future value $CP_f^{\,t}$, the present value is calculated for every year (t) for a discount rate $i=10\%$. The results in present value are shown in Table 16.4.

Table 16.4. Costs in present value for failure (US$)

Year	1	2	3	4	5
$NPV(CP_f^{\,t})$	4,545.40	12,396.70	11,269.70	3,415.10	9,313.80

Year	6	7	8	9	10
$NPV(CP_f^{\,t})$	8,467.10	7,697.40	2,332.50	6,361.50	3,855.40

- Calculate the total costs per failure in present value $NPV(TCP_f^{\,t})$, using expression (using Equation 16.8). All the costs for failures types in present value are added for the expected years of useful life $T=10$ years:

$NPV(TCP_f^{\,t})$,=69,954.67 US$

- Calculate the annual equivalent total cost *AETC*, use expression (using Equation 16.9), for the expected years of useful life $T=10$ years and the discount rate $i=10\%$:

AETC =11,335.97 US$/year

16.6.3 Case Study — Weibull Distribution Failure Rate Model

Let us now follow the process as presented in Section 16.5.3:

- Identify, for each alternative to evaluate, the main failure modes (f) where $f=1\ldots F$, for F failure modes. We assume F=1 failure mode;
- Determine the time between failures t_f, see Table 16.1;
- Calculate the costs of failures C_f (in US$/failure);

C_f=5000.00 US$/failure

- Determine the expected frequency of failures δ_f with the Weibull distribution, (using Equations 16.13, 16.14, 16.15,16 .16 and 16.17):

α =5.396
β =2.515

$$MTBF = \mu = \alpha\Gamma(1+\frac{1}{\beta}) = 5.396\,\Gamma(1.397) = 5.396 \times 0.887 = 4.788 \text{ months}$$

where the value $\Gamma(1.4)$=0.88726 is obtained from the tabulated values chart of the Γ function (in Kececioglu, 1991). Then the frequency of failures will be

δ_f=1/(4.788)=0.2088 failures/month=2.506 failures/year.

- Calculate the total costs per failures per year TCP_f (using Equation 16.18):

TCP_f=12,530.00 *US$/year*

The equivalent annual total cost of 11.000 US$ represents the value of money that will be needed every year to pay for the problems caused by failures, during the 10 years of expected useful life;

- Calculate the total costs per failures in present value $NPV(TCP_f)$ (using Equation 16.19), for a period T=10 years and discount rate i=10%:

$NPV(TCP_f)$=76,991.42 US$

16.6.4 Case Study — Discussion of Results

A summary of results is shown in Table 16.5.

16.7 Concluding Remarks

This chapter analyses the reliability factor and its impact on life cycle cost. We have found that this factor has a very high impact on the total life cycle cost of assets. However, it is common to find a clear absence of proper consideration of failure events during that cycle. Ignorance and lack of technical evaluation — mainly during the equipment design phase — of those aspects related to asset reliability leads to a final real equipment performance showing higher (than expected) total operational costs (costs that were not considered initially) jeopardizing the profitability of the production process. We have presented up-to-date methods to deal with these issues, their pros and cons, and suggested time windows for their better potential utilization.

Table 16.5. Results for the unreliability costs per model

Unreliability costs by model	Considerations
Constant Failure Rate Total costs per failures in present value: $NPV(TCP_f) = 73{,}734.80\$$	Value that represents the quantity of money (today) that one needs to be able to cover the annual expenses projected by failures in 10 years, with a discount factor of 10%. The frequency of failures per year is constant throughout the 10 years; this means that it is expected that the frequency of failures will not change in time and the costs of failures will also be a constant value per year.
Deterministic Failures Rate Annual equivalent total cost: $AETC = 11{,}335.98 \frac{\$}{year}$ $NPV(TCP_f{}^t), = 69{,}954.67$ US$	The obtained annual equivalent total cost, representing the mean value of money that will be needed every year to pay for the problems of failures, during the 10 years of expected useful life, with a discount factor of 10%. The frequency of failures varies every year throughout the expected cycle of useful life.
Weibull Distribution Failures Rate Total costs per failures in present value: $NPV(TCP_f) = 76{,}991.42\$$	The interpretation is similar to the Constant Failure Rate Model. The difference is that the frequency of failures is estimated with the mean time between failures (MTBF) calculated from the Weibull distribution. This model also proposes to keep constant the frequency of failures for each one of the years of expected useful life.

Regarding possible interesting directions of future research work, we do believe that the utilization of the following advanced mathematical methods could be of major interest in the short term:

- Advanced reliability distribution analysis [16—19];
- Monte Carlo simulation techniques [20];
- Markov simulation methods [21—23];
- Stochastic methods [24—27].

These methods will help to diminish the uncertainty within the process of total life cycle cost estimation. We believe that a unique LCCA model can suit all specific analysis requirements. It seems, however, that the development of more elaborated models, addressing specific needs such as a reliable cost-effective asset development, will be required.

16.8 References

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17

Maintenance Continuous Improvement Through Organizational Efficiency

17.1 Introduction

High-quality products cannot be made unless every operator in the workplace becomes an expert on his or her equipment and knows how to use it to build quality into the process. Eliminating defects improves not only quality but all production aspects such as capacity, cycle times, material losses, inventories and delivery times. At the same time, by increasing efficiency in generating the existing products we also foster the appearance of new products and the use of new equipment [1].

Maintenance has been defined as the most basic of all production activities and therefore operators — and employees in general — becoming involved in maintenance activities is a must for reaching excellence in production. However, the question is: How can we create ownership of the manufacturing process among all employees? There is no simple answer. The process of involving employees in general, and operators in particular, in maintenance activities requires a certain time and framework in order to be successful. In this chapter we briefly describe this framework; we will characterise different tools that can be used to improve maintenance continuously through people involvement.

Many of the concepts that we present in this chapter are taken from the Total Productive Maintenance (TPM) philosophy [2]. TPM seeks to engage all levels and functions in an organization to maximize the overall effectiveness of production equipment. Workers in all departments and levels, from the plant-floor to senior executives, will be involved to ensure effective equipment operation. The overall effectiveness of production equipment will therefore be reached through a fundamental organizational change, allowing higher levels of organizational efficiency.

17.2 Creating People Ownership of the Manufacturing Process

There are certain elements (we summarize five) forming a framework that should be in place in case we pursue people ownership of the manufacturing process, according to the TPM philosophy [3] (Figure 17.1):

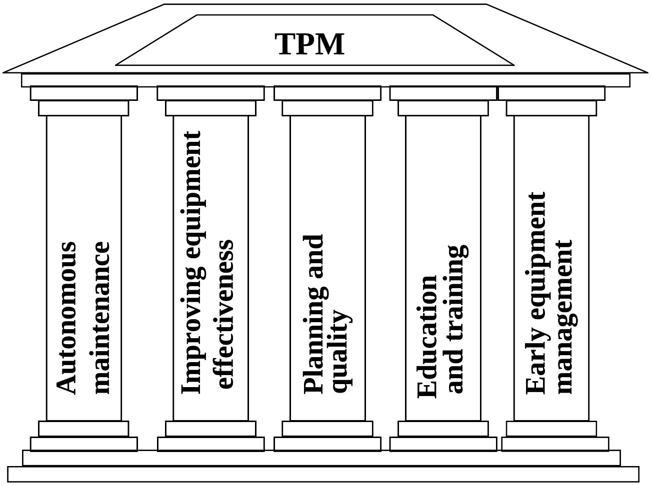

Figure 17.1. Fundamental pillars of the TPM methodology

1. *Autonomous maintenance.* To allow the people who operate equipment to take responsibility for some of the maintenance tasks. Maintenance staff are seen as developing preventive actions and general breakdown services, whereas operating staff take on the "ownership" of the facilities and their general care (autonomous equipment management). Maintenance staff typically move to a more facilitating and supporting role where they are responsible for the training of operators, problem diagnosis, and devising and assessing maintenance practice.
2. *Improvement of the equipment effectiveness.* This is a function for which TPM involves all company employees in identifying and examining all losses which may occur in the equipment — downtime losses, speed losses and defect losses.
3. *Maintenance planning and quality.* Having a systematic approach to all maintenance activities. This requires the determination of the preventive maintenance required for each piece of equipment, the creation of standards for maintenance, and the setting of respective responsibilities for operating and maintenance staff.
4. *All staff education and training in relevant maintenance skills.* The new responsibilities of operating and maintenance staff require that everyone

has all the necessary skills to carry out these roles. TPM places a heavy emphasis on appropriate and continuous training.

5. *Early equipment management*. The aim is to move towards zero maintenance through "maintenance prevention" (MP). MP involves considering failure causes and the maintainability of equipment during its design stage, its manufacture, its installation, and its commissioning. As part of the overall process, TPM attempts to track all potential maintenance problems back to their root cause so that they can be eliminated at the earliest point in the overall design, manufacture and deployment process.

In the following sections we pay special attention to these elements of the TPM philosophy framework, leading to potential maintenance improvements and especially to those that were not discussed previously in this part of the work.

17.3 Introducing Autonomous Maintenance (AM)

17.3.1 Defining the Process

Autonomous maintenance is a methodology to attain the involvement of the operators in their equipment maintenance. The main purpose of AM is to stabilize the equipment conditions to a certain standard and to make their deterioration process slower. Normally, the introduction of an autonomous maintenance program may take several years, and there is a set of steps [4] that needs to be followed:

1. *Initial cleaning.* To eliminate powder and dirt in order to avoid accelerated deterioration and to improve the inspections and repairs, to facilitate the lubrication activities and to detect and to treat hidden problems.
2. *Elimination of pollution sources and inaccessible areas*. To eliminate sources of dirt fundamentally in areas that are difficult to clean and lubricate. Also to reduce lubrication and inspection times, improving the inherent maintainability and reliability of the equipment.
3. *Cleaning and lubrication standards definition*. To preserve the basic operation conditions of the equipment.
4. *General inspection standards definition.* To train the operators for the inspection, diagnosis and correction of minor failures. We will then improve the reliability of the equipment.
5. *Autonomous inspection.* To develop a check-list of autonomous maintenance. To ensure we understand the relationship of the equipment with the product quality.
6. *Standardization.* Ensure that the work standards are appropriate. Enhance operators’ comunication role. Ensure previous steps are under control.
7. *Autonomous management.* At this point the operators can maintain the equipment in optimal conditions. There is also the ability to control quality

defects. Management skills such as spare parts management and maintenance cost control are in place.

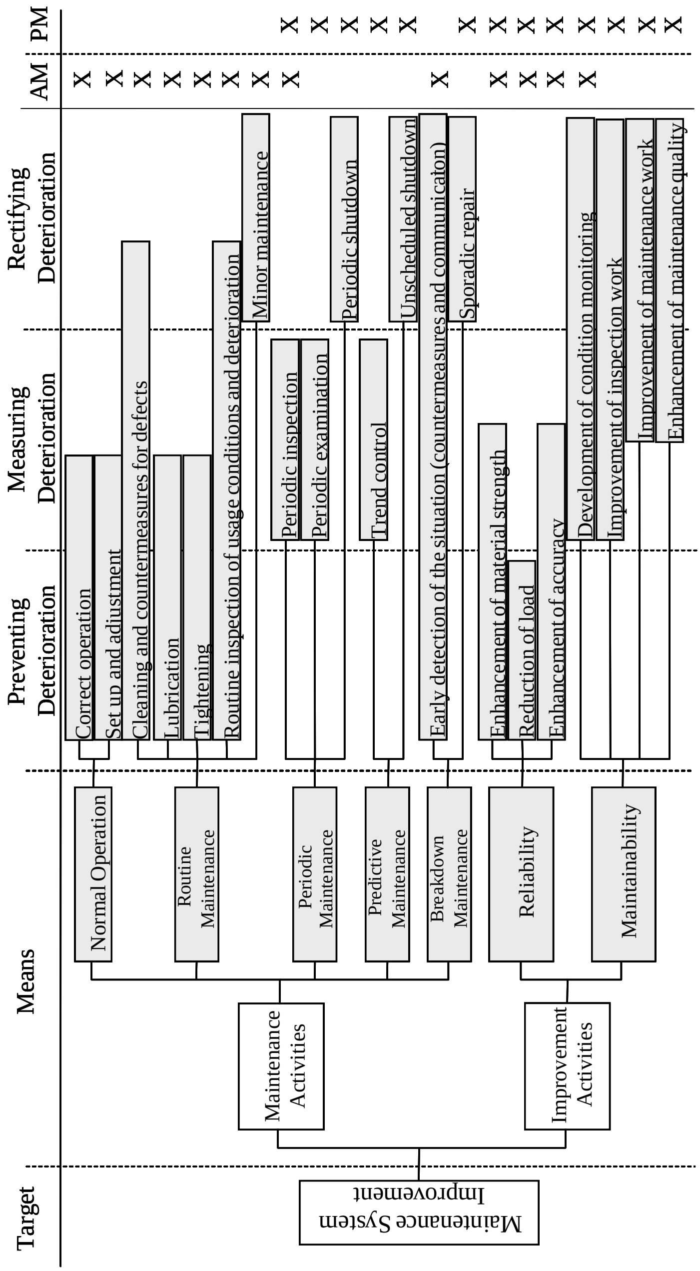

Figure 17.2. Example of maintenance continuous improvement system

Autonomous maintenance and management will allow us to develop a complete continuous improvement system for maintenance, like the one presented, as an example, in Figure 17.2. This example includes improvement activities and how they relate to the prevention, measuring and rectification of deterioration.

17.3.2 Defining the New Functions

The autonomous maintenance defines new functions for the operators and the maintenance teams as follows:

Maintenance department functions:

- Scheduled and predictive maintenance;
- Maintainability improvements;
- Deterioration verification and equipment restoration;
- Support operators in their autonomous maintenance;
- Definition of maintenance standards;
- Maintenance research and development activities.

Production department functions:

- Deterioration prevention;
  - Ensuring proper equipment operation;
  - Activities to maintain basic equipment operating conditions (cleaning, lubrication, torque fixing bolts, *etc*.);
  - Adjustments (in set-up and operation);
  - Data recording (failure, defects, *etc*.);
  - Work with the maintenance department to implement improvements.
- Deterioration verification;
  - Daily inspections and other periodic inspections.
- Equipment restoration;
  - Carry out minor repairs (simple parts replacements and periodic repairs);
  - Report, fast and correctly, about equipment faults and potential failures;
  - Help maintenance teams in eventual repairs.

In AM operators and maintenance technicians interact frequently, especially configuring *small groups*; these groups support a wide activity in equipment problems solving. In order that this activity is successful it is necessary to verify that the following three conditions are fulfilled in the *small group* [4]:

- The members of the small group have the will to do the things;
- The group has the skills to do them;

- A place exists where their mission can be developed.

People in small groups should be very much committed to improving their own knowledge and technical training. As the reader may guess, AM requires, in general, important operators and maintenance teams training in everything related to the functions of the equipment and their different failure modes. For instance, basic operators' abilities that are considered necessary for AM are the following:

- To detect abnormalities with respect to equipment or product quality;
- Ability to "sense" abnormalities;
- Strictly follow the rules of proper operating conditions and procedures;
- Take the proper corrective action quickly in the event of an abnormality;
- Understand the relationship between product quality and equipment.

17.4 Pursuing Overall Organizational Effectiveness

Each and every person in the organization, from workers to general managers, will be involved in reaching ideal utilization of the production resources. In order to do so, it will be necessary to identify and eliminate all kinds of losses that could take place, losses that we might summarize in different fundamental types according to the operation resources that we refer to (see Figure 17.3).

If we now concentrate on the equipment, we aim to maximize Overall Equipment Effectiveness (OEE), which is defined, according to Figure 17.3, as follows:

$$OEE = \frac{Theoretical\ time}{Manned\ time} \times 100\% \tag{17.1}$$

OEE is found to reach average values around 50—60% in companies where maintenance management is neither properly developed nor integrated with production management. According to the JIPM, OEE values can reach up to 85% when total productive maintenance programs are in place.

Similar comments are applicable to the rest of the production resources, so we could obtain ratios for the overall manpower, energy and materials effectiveness (OMPE, OENE and OME respectively) as follows:

$$OMPE = \frac{Value\ added\ time}{Manned\ time} \times 100\% \tag{17.2}$$

$$OENE = \frac{Effective\ energy}{Energy\ input} \times 100\% \tag{17.3}$$

$$OME = \frac{Final\ \ product}{Material\ \ input} \times 100\% \tag{17.4}$$

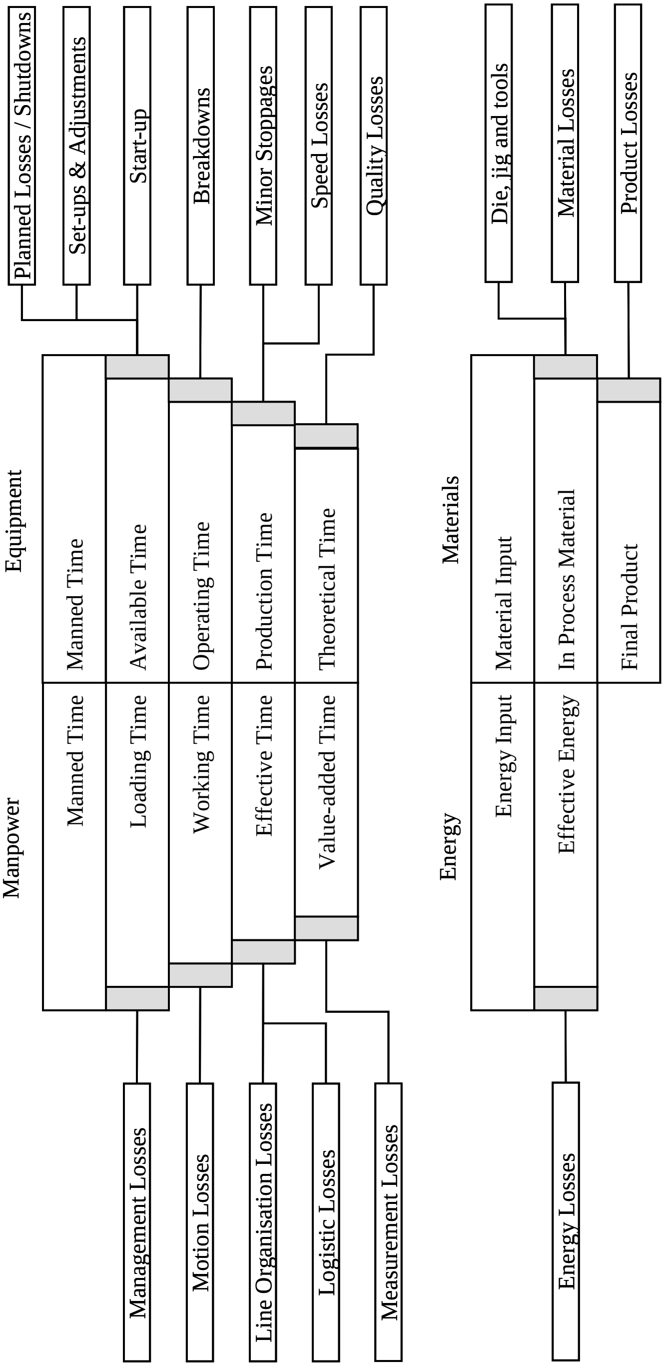

Figure 17.3. Big losses in production resources

17.5 Maintenance Planning and Maintenance Quality

The development and the implementation of a good maintenance planning program – and its corresponding management system – are critical activities of the total productive maintenance philosophy and these activities need to be properly planned.

	Phase 1 : Reduction of MTBF dispersion	**Phase 2 :** Equipment useful life cycle extension	**Phase 3 :** Periodic restoration for elimination of the deterioration	**Phase 4 :** Useful life cycle prediction
Preparation and improvement of the maintenance planning (MP) system	**Step 1:** Assessment of the current status of the equipment			
	Step 2 : Restoration of operating conditions and weak points improvement			
	Step 3 : Introduction of a data management system - CMMS			
Time Based Maintenance		**Step 4 :** Development of predetermined maintenance (periodic maintenance)		
Condition Based Maintenance			**Step 5 :** Development of the predictive maintenance system	
MP system assessment	**Step 6 :** Evaluation of the management system for maintenance planning			

Figure 17.4. Example of a process to achieve a maintenance planning management system

Of course, it is important to ensure that we follow the correct process, or sequence of steps, to reach a successful maintenance planning system.

As an example, let us study the roadmap presented in Figure 17.4. In this figure we present the process of the maintenance planning system development followed in a multinational company where autonomous maintenance is already in place in many of its production units. This company has divided the maintenance planning system implementation into four phases: 1) Reduction of mean time between failures, 2) Equipment useful life cycle extension, 3) Periodic restoration for the elimination of the deterioration and 4) Useful life cycle prediction. Each phase consists of different steps, and all the phases include a common assessment step, dedicated to review what was introduced in the system at that phase. Note that these phases are proposed regardless of the method that is used, in accordance with the criticality of the item, designing the maintenance plan (as explained in Chapter 11).

Although we have previously discussed most of these topics in this work, it is again important to underline the attention that this company pays, in its MP roadmap, to the first phase named "Reduction of the MTBF dispersion". This phase is basically dedicated to carrying out "preparation activities" which are required to reach real operational dependability improvements through a maintenance planning system. The purpose of this phase is to eliminate potential equipment weak points that may sometimes decrease the mean time between failures, create a high variability of this measure, and that may lead to wrong decisions when fixing time intervals for preventive maintenance activities. Note that this is closely aligned with suggestions that were made when discussing these topics in Chapters 10 and 11. It is clear that before starting the maintenance planning process, we need to carry out this work in order to handle proper equipment reliability and maintenance data sustaining the study of maintenance activities to manage critical failure modes. Expected evolution of the time dedicated to maintenance activities presented in the example of Figure 17.4, should be as in Figure 17.5

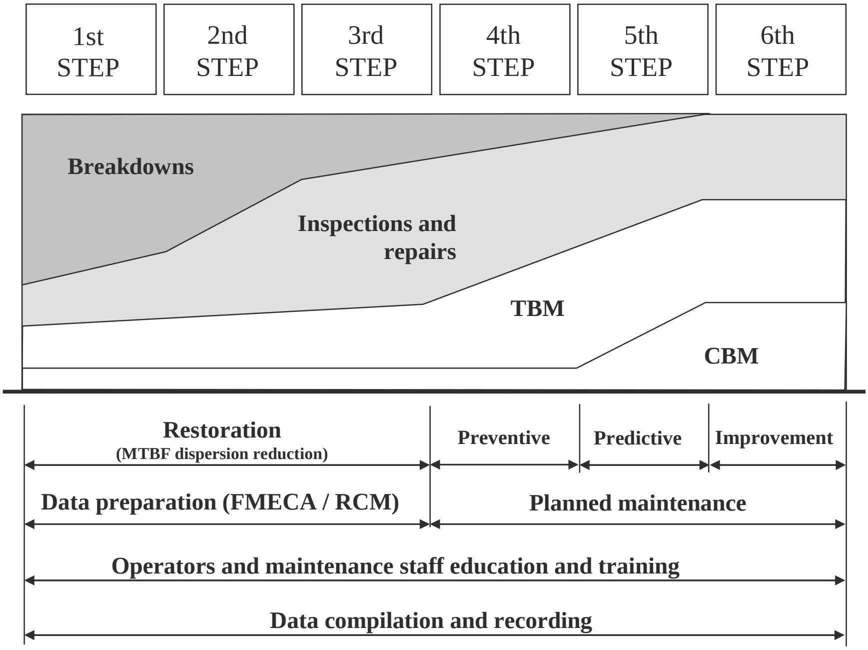

Figure 17.5. Expected time dedication to maintenance activities over time

As we saw in Section 17.3.2, once the autonomous maintenance (AM) is introduced, the maintenance department holds the responsibility for the development and the implementation of the time based and condition based maintenance programs (Phases 2, 3 and 4 in our example in Figure 17.4). In this new context, these tasks have to be accomplished in coordination with the people responsible for the AM program, and with the following purposes:

- The periodical, or condition based, restoration of the equipment to suitable operating conditions through the elimination of deterioration;

- Facilitate the maintenance task development and the quality of the maintenance work. This is possible if we merely study the maintenance tasks and properly structure them with convenient procedures and technical instructions;
- Simplify the maintenance materials management by translating the unscheduled materials requirements to scheduled ones.

17.6 Early Equipment Management for Maintenance Prevention

In TPM philosophy [2], maintenance prevention was initially understood as a significant aspect of project engineering, serving as an interface with maintenance engineering, and therefore involving activities to be carried out within the preparatory phase of the equipment.

Maintenance prevention activities are directed to reduce the time between the equipment design and their stable operation. In many organizations these type of activities are known as *early equipment management* activities, that can be basically divided into activities devoted to:

- Reduce the start-up time of new machines, systems and facilities;
- Minimize the needs for maintenance after their installation;
- Incorporate existing recent improvements to acquired equipments;
- Ensure that the acquisition of new equipment is based on their *Life Cycle Cost* (LCC);
- Integrate the equipment engineering project with their future maintenance.

It is clear that many of these activities can also be carried out on existing equipment and therefore maintenance prevention activities are not necessarily related only to the preparatory phase but can also take place during the operational phase of the equipment.

Root cause failure analysis (RCFA) techniques can be used with this purpose, and many of the chronic maintenance activities in existing equipment can be eliminated — and with them weak points of our maintenance system. This set of methods can conjugate with more serious changes of the equipment design, which may need major engineering efforts. Moreover, suitable utilization of the CMMS systems as expert systems may offer interesting ways for maintenance prevention and improvement.

17.7 Improving Maintenance Through Education and Training

The operators will assume, following the introduction of a TPM program, major responsibility and participation in many decision making processes within the organization. Therefore they must be prepared to carry out the opportune analyses and to accomplish these tasks. It is advisable that, before beginning any TPM program, the operators receive information and training on each of the following aspects:

- Introduction to the TPM;
- General and specific inspection techniques;
- General and specific diagnosis techniques;
- Problem solving methods;
- Techniques for specific operational environments, equipment, *etc*.

We must not forget to underline the need for constant education and training updates for the different people in our organization. In this respect, TPM promotes very specific training, specific to the equipment and facilities and to the problems that occur with them. The method is called the "one point lesson method" [4] and it is targeted to the *small groups* of work.

The "one point lesson method" promotes lessons on specific aspects of the facilities, which relate to the daily activity and these take place in brief intervals during the working day. The purposes of this type of lesson are the following:

1. To transmit the knowledge and technical aptitude in order to be able to make concrete actions towards improvement;
2. To penetrate into the theoretical knowledge and to improve the practical capacity, when necessary, at the opportune moment and in good time;
3. To raise the level of general competence of the *small groups* of work.

17.8 References

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18

The E-maintenance Revolution

18.1 Introduction

The term e-maintenance has been in use since early 2000 as a component of the e-manufacturing concept[21] [1], which profits from the emerging information and communication technologies used to implement cooperative and distributed multi-user environments [2]. E-maintenance is a new concept that can be defined as a maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (*i.e.* ICT, Web-based, tether-free, wireless, infotronics technologies) but also e-maintenance activities (operations or processes) such as e-monitoring, e-diagnosis, e-prognosis…

Section 18.2 outlines the reasons why the concept of e-maintenance has emerged recently. Most of the explanation for this rests with the new capabilities provided by e-maintenance. These capabilities are then described in Section 18.3 according to their impact on the relateded maintenance types and strategies, maintenance support and tools, and finally maintenance activities. If the e-technologies provide some of these capabilities, maximising the e-maintenance benefits on the overall maintenance efficiency requires more than technology. As shown in Section 18.4, it needs models, methods or methodology in order to make e-maintenance a key element for acting on the operational requirements to carry out the global system performance. From this opposition “capabilities *vs* needs”, Section 18.5 presents a state of the art of the e-maintenance field. The contributions are classified according to the capabilities and the needs which are aimed at being met. Finally, some concluding remarks are presented in Section 18.6.

[21] E-Manufacturing is a transformation system that enables the manufacturing operations to achieve predictive near-zero-downtime performance as well as to synchronize with the business systems through the use of web-enabled and tether-free (*i.e.* wireless, web, *etc.*) infotronic technologies [1].

18.2 Factors for the Emergence of E-maintenance

The emergence of e-maintenance can be attributed to two main factors:

- The need for using *e-technologies* to increase maintenance efficiency, velocity, proactivity... and to optimise maintenance related workflow.

  E-technologies can play a crucial role in support of the challenge to be able to choose the right maintenance decision, at the right time and at the right place for optimising the global plant and product performances.

  To begin with, the Web allows universal access by having independent connectivity for different kinds of platforms using open standards for publishing, messaging, and networking. Since the Web enables multimedia support, both interactivity and extensibility, it can seamlessly include new forms of content and media [3]. The developments in database and object technologies enable users to connect to back-end databases and legacy applications via user-friendly Web interfaces. Future smart transducer will have a built-in Ethernet module and support direct plug-and-play on the Internet without the need for a connection to a PC or a separate Ethernet card, as is the case with today's systems.

  Furthermore, wireless technology brings cost reduction (no wiring), flexibility in manufacturing floor layout and information availability [4]. Remote data transmitting, monitoring and controlling through the network are facilitated by tether-free technologies, computerized data processing, remote sensing, and broad-band communication. It enables the equipment in your factory to share its data, files and even permit remote equipment operation from anywhere in the world [5].

  The door to new interconnected system abilities is open. New ways of communication means mobile terminals and data access modes to improve cooperation possibilities. Mobility inside the cooperative system is for example, a major contribution which allows users to work together in new places [6].

  In summary, e-technologies increase the possibilities (1) to utilize data from multiple origin and of different type, (2) to process larger volumes of data and to make more advanced reasoning and decision-making, and (3) to implement cooperative (or collaborative) activities. The implementation of these e-technologies to the benefit of the maintenance area is the first reason for the emergence of e-maintenance.
- The need to carry out a global system performance, which imposes on the maintenance area the following requirements: openness, integration and collaboration with the others services of the e-enterprise[22].

[22] The e-enterprise, a combination of "point-and-click" net business models and traditional "brick-and-mortar" assets, is transforming business in the twenty-first Century. These next-generation organizations share four key characteristics: (1) speed and real-time responsiveness to customer demand, (2) an iterative "launch, learn, and re-launch"

After having optimized the different services of the enterprise, essentially due to computer science and the different theories of automatic control and of optimization, it appeared that a global optimization needed other approaches, other theories and other tools. The key words are then integration, computer integrated manufacturing, openness and open systems, interoperability [8]. E-manufacturing, teleservice and virtual enterprise are some of the first resulting concepts that have already been developed and applied in the industry [9].

Now these requirements become more and more pressing in the maintenance area [10], due to the fact that the maintenance decisions have characters of system integration, in the sense that they are not limited to the maintenance function scope but entail co-ordination with objectives of other functions wherein a co-ordinated decision is addressed between maintenance and production [11].

Consequently, e-maintenance can be considered as a major pillar that supports the success of the integration of e-manufacturing and e-business (Figure 18.1).

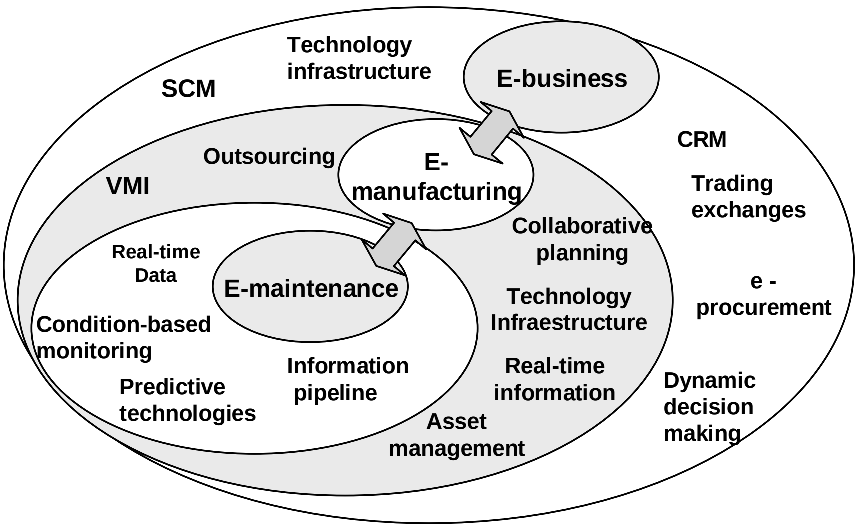

Figure 18.1. Integration among e-maintenance, e-manufacturing and e-business systems [12]

There are opportunities for successfully responding to the objectives of integration and global optimization but it needs more than technology. It needs models and, according to the complexity of the systems concerned (an enterprise) and the heterogeneity of the existing models, this modelling activity is a difficult one [8]. Providing these new models, methods or

approach, (3) holistic and rigorous methodologies to define strategy, process, application, and technology architecture , and (4) alignment of technology with the business model [7].

methodology in the context of the maintenance integration is the second main reason which explains the emergence of e-maintenance.

18.3 The E-maintenance Capabilities

18.3.1 E-maintenance, the New Areas of Advantage

The perceived advantages of e-maintenance can be classified according to their link with the three following areas:

- Maintenance type and strategies;
- Maintenance support and tools;
- Maintenance activities.

18.3.2 Potential Improvements of Maintenance Type and Strategies Provided by E-maintenance

18.3.2.1. Remote Maintenance

By means of information, wireless (*e.g.* Bluetooth) and Internet technologies, users may log in from anywhere and with any kind of device as soon as they have an Internet connection and a browser. Any operator, manager or expert also has the capability to link remotely to a factory's equipment through Internet, allowing them to take remote actions, such as setup, control, configuration, diagnosis, debugging/fixing, performance monitoring, and data collection and analysis [13]. Consequently the manpower of the machine builder retained at the customer's site is reduced and there are facilities for him to diagnose the problems when an error occurs and to improve the preventive maintenance thanks to machine performance monitoring [9].

At the moment, one of the greatest advantages for e-maintenance is the ability to connect field systems with expertise centres located at distant geographical sites [14], notably allowing remote maintenance decision-making [15] that adds value to the top line, trim expenses, and reduce waste. The contribution to the bottom line is significant, making development of an asset information management network a sound investment [16].

Moreover, the Web enablement of computerized maintenance management systems (known as e-CMMS) and remote condition monitoring or diagnostic (known as e-CBM) avoids the expense and distraction of software maintenance, security and hardware upgrade [17]. Computer science experts can add new features and/or migrations without the users even noticing.

18.3.2.2 Cooperative / Collaborative Maintenance

E-maintenance symbolises the opportunity to implement an information infrastructure connecting geographically dispersed subsystems and actors (*e.g.* suppliers with clients and machinery with engineers) on the basis of existing

Internet networks. The resultant platform allows strong cooperation between different personnel, different enterprise areas (production, maintenance, purchasing, *etc.*) and different companies (suppliers, customers, machine manufacturers, *etc.*).

An e-maintenance platform introduces an unprecedented level of transparency and efficiency into the entire industry (Figure 18.2) and it can be an adequate support of business process integration [18]. As a result, there is the chance to reduce interfaces radically, may that be between personnel, departments or even different IT systems. The integration of business processes significantly contributes to the acceleration of total processes, to an easier design (lean processes) and to synchronize maintenance with production, maximizing process throughput and minimizing downtime costs. In general, this leads to less process errors, improved communication processes, shorter feedback cycles and hence improved quality.

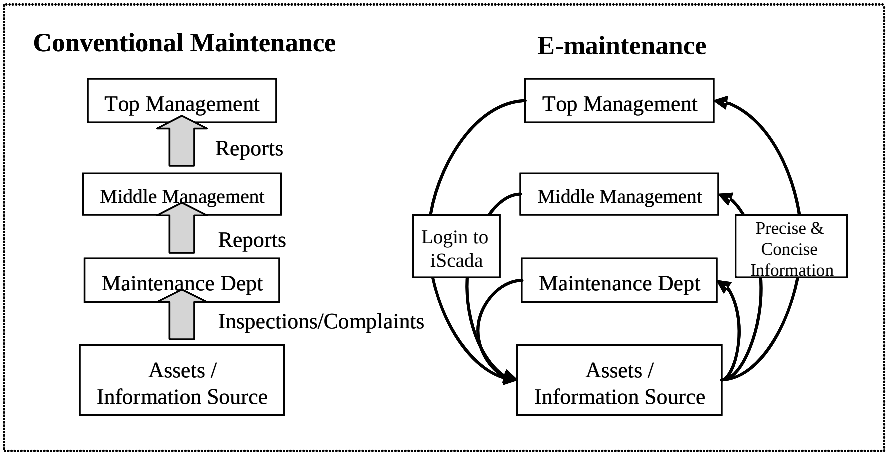

Figure 18.2. Implementing e-maintenance (http://www.devicesworld.net)

In short, e-maintenance facilitates the bi-directional flow of data and information into the decision-making and planning process at all levels [4]. By so doing, it should automate the retrieval of the accurate information that decision makers require to determine which maintenance activities to focus resources on, so that return on investment is optimised [19].

18.3.2.3 Immediate / On Line Maintenance

The real time remote monitoring of equipment status coupled with programmable alerts enable the maintenance operator to respond to any situation swiftly and then to prepare any intervention with optimality. In addition, high rate communications allow one to obtain several expertises quickly [20] and to accelerate the feedback reaction in the local loop connecting product, monitoring agent, and maintenance support system. It has almost unlimited potential to reduce the complexity of traditional maintenance guidance through online guidance based on the results of decision-making and analysis of product condition [21].

In this context, potential applications of e-maintenance include formulation of decision policies for maintenance scheduling in real time based on up-to-date information of machinery operation history and anticipated usage.

18.3.2.4 Predictive Maintenance

The e-maintenance platform allows any maintenance strategy, and the improvement of the utilization of plant floor assets using a holistic approach combining the tools of predictive maintenance techniques. This is, for example, one of e-maintenance major issues [1].

The potential applications in this area include equipment failure prognosis based on current condition and projected usage, or remaining life prediction of machinery components. In fact, e-maintenance provides companies with predictive intelligence tools (such as a watchdog agent) to monitor their assets (equipment, products, process, *etc*.) through internet wireless communication systems to prevent them from unexpected breakdown. In addition, these systems can compare product performance through globally networked monitoring systems to allow companies to focus on degradation monitoring and prognostics rather than fault detection and diagnostics [12].

Prognostic and health management systems that can effectively implement the capabilities presented herein offer a great opportunity in terms of reducing the overall Life Cycle Costs (LCC) of operating systems as well as decreasing the operations/maintenance logistics footprint [22].

18.3.3 Potential Improvements of Maintenance Support and Tools Provided by E-maintenance

18.3.3.1 Fault/Failure Analysis

The rapid development in sensor technology, signal processing, ICT and other technologies related to condition monitoring and diagnostics increases the possibilities to utilize data from multiple origin and sources, and of different type [23]. In addition, by networking remote manufacturing plants, e-maintenance provides a multi-source knowledge and data environment [4].

These new capabilities allow the maintenance area to improve the understanding of causes of failures and system disturbances, better monitoring and signal analysis methods, improved materials, design and production techniques [23].

18.3.3.2 Maintenance Documentation/Record

The e-maintenance platform provide a transparent, seamless and automated information exchange process to access all the documentation in a unified way, independently of its origin, equipment manufacturer, integrator, end-user (see Figure 18.3). Information such as the task completion form is filled in once by the user and can be dispatched to several listeners (software or humans) that registered for such events [8].

At the device level, goods are checked out from stores against a work order or a location and the transaction is recorded in real time. The massive data bottlenecks between the plant floor and business systems can be eliminated by converting the raw machine health data, product quality data and process capability data into information and knowledge for dynamic decision-making [1]. In addition, these intelligent decisions can be harnessed through web-enabled agents and connected to e-business tools (such as customer relation management systems, ERP) to achieve smart e-service solutions [12].

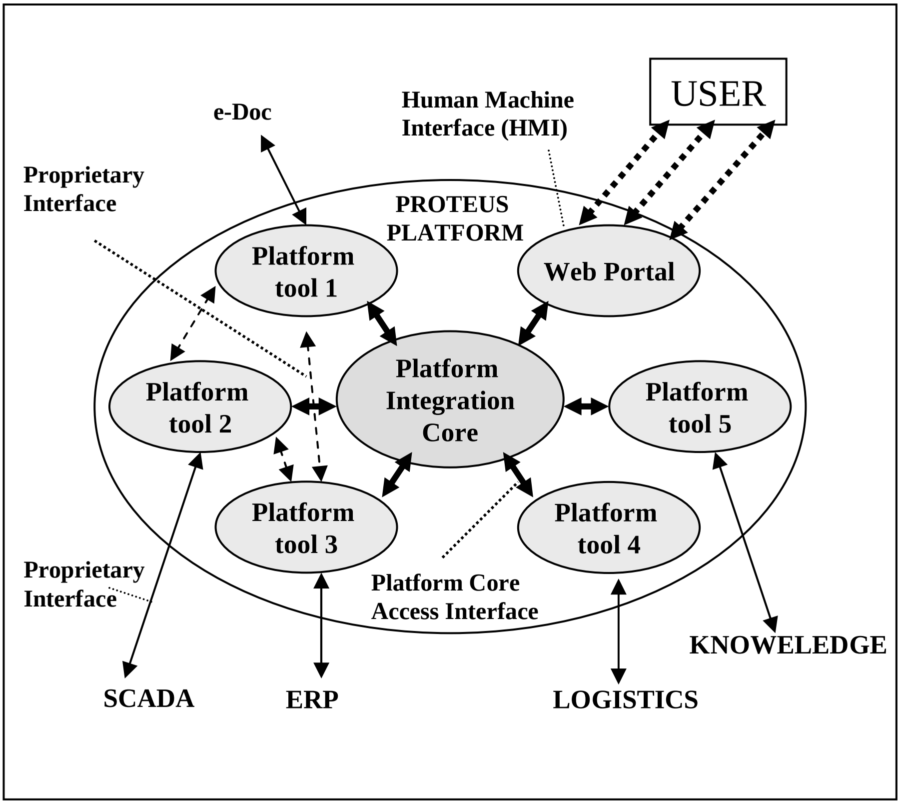

Figure 18.3. PROTEUS platform [8]

18.3.3.3 After Sales Services

With the use of internet, web-enabled and wireless communication technology, e-maintenance is transforming manufacturing companies into service businesses able to support their customers anywhere and any time [24].

18.3.4 Potential Improvements of Maintenance Activities Provided by E-maintenance

18.3.4.1 Fault Diagnosis/Localization

E-diagnosis offers experts the ability to perform on-line fault diagnosis, share their valuable experiences with each other, and suggest remedies to the operators if an anomalous condition is occurring in the inspected machine [25]. In addition, lock-outs and isolation can be performed and recorded on location thanks to wireless technology and palm computing.

Consequently, the amount of time it takes to communicate a production problem to the potential expert solution provider can be reduced, the quality of the information shared can be improved and thereby, the resolution time reduced [5]. All these factors contribute to increase the availability of production and facilities equipment, reduce mean time to repair (MTTR), and significantly reduce field service resources/costs.

18.3.4.2 Repair/Rebuilding

First, remote operators could, via the e-connection, tap into specialized expertise rapidly without travel and scheduling delays. Downtimes could conceivably be reduced through direct interaction (trouble shooting) with source designers and specialists [14]. Second, diagnosis, maintenance-work performed and parts replaced are documented on the spot through structured responses to work steps displayed on the lap-top.

18.3.4.3 Modification/Improvement – Knowledge Capitalization and Management

The multi-source knowledge and data environment provided by e-maintenance allows efficient information sharing and, thereby, important capabilities of knowledge capitalization and management. With the availability of tools for interacting, handling and analyzing information about product state, the development of maintenance engineering for Product Life Cycle (PLC) support including maintenance and retirement stages (disassembly, recycling, reuse, and disposal) is becoming feasible [21].

18.4 Challenges for E-maintenance

18.4.1 E-maintenance Requirements

There are not only perceived advantages of e-maintenance, but technological, informational or organisational needs for e-maintenance implementation. These needs are related to the maintenance type and strategies, maintenance support and tools and maintenance activities.

18.4.2 Needs for E-maintenance Related to Maintenance Type and Strategies

18.4.2.1 Remote Maintenance

There are still business and human related issues that have to be resolved before the actual application of remote maintenance. To begin with, an important restraining force is the security and reliability concern arising from transactions over the Internet [14]. Risk management in e-maintenance activities involves a trade-off between protection on the one hand and functionality, performance and ease-of-use on the other [17]. Then, it is necessary to concentrate efforts on human resource restructuring, maintenance agreement and training [9]. Each maintenance employee (technician, engineer or leader) has to become capable of dealing with the speed of information flow and understanding the overall structure.

At the moment, a reliable, scalable and common informatics platform between devices and business including implementation of wireless, Internet and Ethernet networks still have to be developed in order to implement successfully the e-maintenance system [12].

18.4.2.2 Cooperative/Collaborative Maintenance

The construction of an e-maintenance system involves a variety of cross-platform information integration issues, such as the development of data transformation mechanisms, the design of communication messages, the selection of data transmission protocols, and the construction of a safe network connection [13]. The goal is to develop an e-maintenance platform providing support to e-collaboration among suppliers, design and process engineers as well as customers within the scope of asset management. To satisfy this, two additional requirements must be fulfilled [23]:

- The total information flow should be structured according to a common e-maintenance semantic terminology and framework;
- The company maintenance, economics and business systems must be harmonised to communicate with each other and to produce the essential key figures needed for both strategic and day-to-day business decisions.

These requirements are parts of the enterprise integration, which has been identified by Zhang *et al.* [10] as the first challenge to overcome for building a platform for e-maintenance. Due to a lack of efficient inter-operation among the plant software systems, research on "highly-integrated" e-maintenance systems, which meet overall demands, is a promising research area [26]. A successful process integration in the e-maintenance context also requires that the maintenance (logistical) processes must be stable and capable, *i.e.* the structure does not change on short term perspective and the processes are of high quality [18].

There is also a lack of cooperative systems formal models. This is why the efficiency of cooperation within a complex computerized remote system (with several different tools, with a particular cooperation algorithm...) is still a preoccupation for industrialists who are users of these systems [6].

18.4.2.3 Distributed Maintenance

In order to implement the e-maintenance system successfully, a distributed computing, optimization and synchronization system for dynamic decision making needs to be developed [12]. As the e-maintenance system includes a very large volume of data, information and knowledge, some of the more simple processing should be decentralised to a level as low as possible, *e.g*. to the sensor level [23].

18.4.2.4 Predictive Maintenance

The challenge to manage to predict failures and disturbances, and to estimate the remaining lifetime of components, mechanical systems and integrated systems is an extremely tough one for researchers and engineers [23]. Unlike numerous methods available for diagnostics, prognostic methods are still in their infancy and the literature is yet to present a working model for effective prognostics. When looking at the standards and standardization proposals that exist today, it can be concluded that the sensor module, the signal processing module, the condition monitoring module, and the diagnostic module can all be partially developed using standards or standard means. By contrast, it is time to start focusing research on the prognosis and decision support modules [27].

An effective and efficient predictive-based machine condition prognosis is necessary for modern plants [28], but does not yet exist due to the inconsistent set of heterogeneous models used by the different designers of partial maintenance processes [29]. On this route we are only taking the first steps today. For the next steps, a deepening of our knowledge in many of the technological areas involved is needed, and in addition it is necessary to find holistic approaches and methodologies to integrate the different techniques involved [23].

To support these objectives, predictive intelligence (algorithms, software and agents) and mapping of relationship between product quality variation and machine and process degradation are required [12]. In addition, to provide accurate prdictions, the degradation analysis has to take into account the machine operational environment throughout its life cycle [30].

18.4.3 Needs for E-maintenance Related to Maintenance Support and Tools

18.4.3.1 Maintenance Documentation/Record

The e-maintenance platform has to support inventory and operation guidance (*e.g*. by using bar code reader, handhelds, laptops, scanners…) and to provide access possibilities to external catalogues [8]. It also has to collect, record and store information regarding (1) degradation modes, (2) degradation sections of the machine, (3) degradation frequency, (4) degradation time and place, (5) time required preventing degradation, (6) cost required to prevent degradation, (7) suggested and/or applied maintenance practices, *etc*. [1]. The success of this collaborative maintenance platform depends on having a multi-tasking and multi-user operating environment, and a fast and easy-to-manage database for international experts to use to retrieve or store their aggregated knowledge and experiences [3].

18.4.4 Needs for E-maintenance Related to Maintenance Activities

18.4.4.1 Inspection/Monitoring

There is still a clear need for generic systems, which can offer integrated monitoring solutions by enabling information processing at different abstraction and representation levels and be customisable to diverse applications [31]. Distributed, autonomous monitoring is fundamental to the penetration of e-maintenance to the cutting edge of high capital and highly productive plant. A highly advanced sensor network should previously be presented [30], and the development of intelligent agents for continuous, real time, remote and distributed monitoring and analyses of devices, machinery and systems can be necessary.

18.4.4.2 Modification/Improvement – Knowledge Capitalization and Management

One of the most urgent industrial problems is how to realise knowledge-based operation and maintenance of plants [10]. The information flow collected by the e-maintenance platform has to be used for behaviour learning and rule extraction purposes. Hence, a knowledge base system can be achieved through intelligent conversion of data into information, and information into knowledge [1]. This knowledge capitalization aims at creating a corporate memory (*i.e.* a structured set of knowledge related to the firm experience in a field domain) of enterprise [32].

18.5 State of the Art in E-maintenance

18.5.1 Introduction

The different contributions developed in e-maintenance aim at responding to one (or more) of the four following issues: (1) providing standards, (2) designing an e-maintenance platform, (3) formalizing the e-maintenance processes and (4) implementing an e-maintenance system (*i.e.* platform + processes).

18.5.2 Standards Development in E-maintenance

The industrial deployment of e-maintenance is supported today by different standards to help engineer for developing particular e-maintenance platform/architecture related to the system to be maintained. The main existing standards are:

- IEEE 802.11x, EN457:1992 – ISO7731;
- IEC 62264 (Enterprise – Control system Integration) based on ANSI/ISA S95;
- ISO 15745 (Industrial automation application integration framework);

- MIMOSA[23] (Machinery Information Management Open System Alliance) – IEEE 1232[24];
- ISO 13374 (Condition monitoring and diagnostics of machines);
- EN60204-1:1997/IEC60204-1 (Safety of machinery).

Some of them have been developed within the Condition Based Maintenance (CBM) technology and specifically within CBM systems. In this area, the standardization proposals promoted by the organizations of MIMOSA and OSA-CBM and the published standards IEEE Std 1451, IEEE Std 1232, and ISO 13373-1 have been examined in depth by Bengtsson [27].

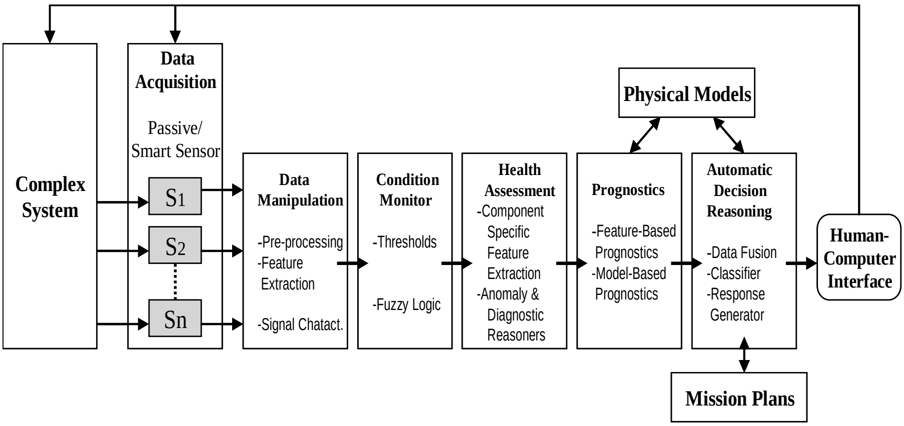

Figure 18.4. OSA-CBM architecture [35]

Interconnectivity of the islands of maintenance and reliability information is embodied in e-maintenance. Therefore, the e-maintenance network must provide for the open exchange of equipment asset related information between condition assessment, process control, and maintenance information systems. It can be developed from a collection of information islands in several ways: by using a single proprietary system, buying a custom bridge, building a custom bridge, or using an open systems bridge [16]. The last solution seems to be the most promising. Moreover, the adoption of MIMOSA specifications can facilitate the integration of asset management information, provide freedom to choose from a broader selection of software applications, and save money by reducing integration and software maintenance costs. MIMOSA provides a standard set of asset management data fields in its Common Relational Information Schema (CRIS) that software developers can adopt for their open systems [33]. CRIS spans all technologies, with tables for site information, measurement data, alarms, sample

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[23] http://www.mimosa.org/.
[24] The purpose of these standards is to provide formal models of diagnostic information to ensure unambiguous access to an understanding of the information supporting system test and diagnosis [IEEE Std 1232-2002].

test data, and blob data (binary large object fields for drawings and photographs). Special maintenance and reliability tables define fields for events (actual, hypothesized and proposed), health and estimated asset life assessment, and recommendations.

From MIMOSA CRIS and emerging standards such as the IEEE Standard 1232, an industry led team has developed the OSA/CBM (Open System Architecture for Condition-Based Maintenance) architecture. They have demonstrated that OSA/CBM facilitates interoperability of Condition-Based Maintenance software modules [35]. This functional architecture has been described in terms of seven functional layers[25] (see Figure 18.4) interacting to form a complete integrated system. It incorporates the use of persistent (*e.g.* database) data, which is accessible from each layer, as well as persistent data support features such as trending, "black box" recording, machinery parameters (*e.g.*, equipment nominal operating information), and equipment/process connectivity information. The OSA-CBM framework supports a variety of information models for persistent data, such as object-oriented databases, blackboard structures, or data dictionaries [34]. These standards are to be regarded as a mean of building e-maintenance platforms or e-maintenance systems. In the following section, some of the most promising platform developments are presented.

18.5.2.1 E-maintenance Platform Development

An e-maintenance platform is usually made up of software, new technologies permitting the use of e-service for maintenance. A recent literature review related to this topic with emphasis on web technology and multi-agents system has been presented by Campos and Prakash [36]. After having described the latest developments in the application of Information and Communication Technologies, more specifically, Web and Agent Technologies, Campos *et al.* concluded that the current developments in these areas are still at the rudimentary stage. For Jardine *et al.*, the reasons that advanced maintenance technologies have not been well implemented in industry might be (1) lack of data due to incorrect data collecting approach, or even no data collection and/or data storage at all, (2) lack of efficient communication between theory developers and practitioners in the area of reliability and maintenance, (3) lack of efficient validation approaches, (4) difficulty of implementation due to frequent change of design, technologies, business policies and management executives [37].

However, there exist considerable incentives in developing appropriate tools, methods or systems for solving these issues. Take, as an example, the IP sensor (Internet Protocol based sensor) developed by Tao *et al.* Adopting embedded internet technology, the proposed sensor is feasible for distributed networking application with advantages of accessibility, integration and expandability [30]. Working as a watchdog agent, it provides a powerful tool to gather information at plant level of the distributed application to enable remote maintenance engineer transparently monitoring and operating the field devices over the Internet.

[25] A detailed description of the inputs and outputs required for all the given layers is available through the OSA/CBM website (http://www.osacbm.org).

Alternatively, to solve the problem of integrating information processing and information flow controlling in the maintenance tasks, Zhang *et al.* construct an information flow based system model for covering information acquisition and exchange both in the range of single industrial environments and among associated upstream as well as downstream enterprises. On the basis of this model, a (multi)agent-based platform is built using web services, FIPA standard (Foundation for Intelligent Physical Agents) and a JAVA programming environment [10]. A similar approach (based on four basic types of agents: data acquisition, diagnostics, prognostics and maintenance decision-making ones) was proposed by Li *et al.* [26]. They prototyped an agent-based platform first applied to a single machine and then extended to the factory level with many different pieces of equipment and an enterprise level for global production.

In addition, several e-maintenance platforms have been developed and some of them are still used today.

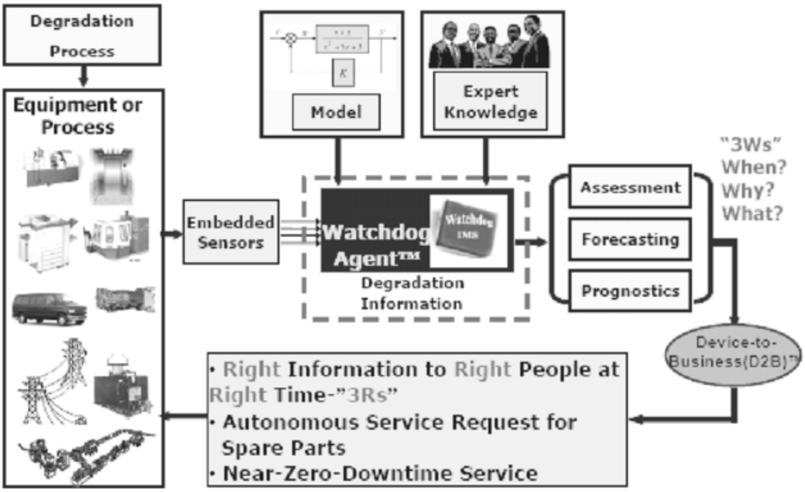

Figure 18.5. Architecture of the Device-to-Business (D2B™) platform [38]

As a first example of an e-maintenance platform we present the Device-to-Business (D2B™) platform. This platform was developed at the IMS centre (Intelligent Maintenance System Centre) in USA, in the first academic e-maintenance project, under the responsibility of Professor J. Lee from Wisconsin University and Jun Ni from Michigan University. This centre is a result of an important initiative sponsored by the USA NFS (National Science Foundation) and industrial people. It supports, in the domain of e-maintenance, the deployment and experimentation of the Device-to-Business (D2B™) platform (see Figure 18.5) based on a core-enabling element: the Watchdog Agent™, which is a prognostics-based "digital doctor" [39].

The goal of the D2B™ platform is to provide transformation of raw data (or information through EIA) from device level to widely compatible web-enabled formats (*e.g*. XML) so that many web enabled applications can be performed [38]. Once device information is available at this level, users from various part of the network in different geographical locations can share the same information for different but synchronized applications [12]. One promising issue then consists in integrating Watchdog capabilities into product and systems for closed-looped design and life-cycle management as proposed by PROMISE[26] (consortium on product embedded information systems for service and end of life) [39].

In the long term, the objective of PROMISE is to allow information flow management to go beyond the customer, to close the product lifecycle information loops, and to enable the seamless e-transformation of Product Lifecycle Information to Knowledge [40]. This system will allow all actors that play a role during the lifecycle of a product (managers, designers, service and maintenance operators, recyclers, *etc*.) to track, manage and control product information at any phase of its lifecycle (design, manufacturing, middle of-life, end-of-life) at any time and any place in the world.

The PROMISE vision is to bring about innovations on web-enabled smart e-service technologies, including intelligent product degradation assessment methodologies, e-prognostics, and e-maintenance system technologies to enable manufacturers and customers to have products and production machines with near-zero-breakdown conditions. This is why three working areas of the project are relating to e-maintenance issues:

- Area 1: E-Maintenance and E-Service Architecture Design Tools (design of e-maintenance architecture as well as its platform for e-service applications);
- Area 2: Development of Watchdog Computing for Prognostics (development of advanced hashing algorithm for embedded product behaviour assessment and prognostics);
- Area 3: Web-based and Tether-Free Monitoring Systems (development of "interface technologies" between the product e-service system platform and web-enabled e-business software tools).

In parallel with PROMISE, the new European project DYNAMITE[27] (Dynamic Decisions in Maintenance) aims at creating an infrastructure for mobile monitoring technology and creating new devices which will make major advances in capability for decision systems incorporating sensors and algorithms [23]. The key features include wireless telemetry, intelligent local history in smart tags, and on-line instrumentation.

A second example of the e-maintenance platform is the TELMA platform[28]. Located at the University of Nancy I, this platform has been designed by a group of teachers and researchers wishing to have at their disposal a training platform in the areas of maintenance, tele-maintenance and e-maintenance [41]. In this way, the platform is designed for (1) a local use in the frame of conventional training

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[26] http://www.promise.no.
[27] http://osiris.sunderland.ac.uk/~cs0aad/DYNAMITE/Index.htm.
[28] http://www.aip-primeca.net.

activities, (2) a remote use via Internet for operation on industrial e-services (*i.e.* Tele-monitoring), and for accessing to production data, performance data, and (3) a use for e-teaching and e-learning as application support of courses in the e-maintenance domains. From a research point of view, the platform is currently used to demonstrate the feasibility and the potential benefits of approaches in relation to e-maintenance. In particular, it supports the deployment of the prognosis process introduced by Muller *et al.* [42].

TELMA is a platform materializing a physical process dedicated to unwinding metal strip (see Figure 18.6). Connected to this physical process is an automation part of the platform which is composed of control screens, control boards, PLCs (*i.e.* TSX Premium with Web Interface), Altivar for Engine control with Web Interface, Web-Cam, Remote I/O. A PLC is fully dedicated to generating degradations and failures from software algorithms or by modifying I/O signals.

Some mechanical parts have also been added to simulate other failures and degradations. The maintenance part of the platform is built on the CASIP[29] (Computer Aided Safety and Industrial Productivity) product supporting a local real-time maintenance system, a centralised maintenance system (with Oracle) and some remote stations [43]. A lot of hardware and software components for running the maintenance actions well such as OPC server, EmpaciX CMMS, a Technical Data Base System called Adivitium, *etc*., is integrated through SQL-Server and Oracle to this maintenance system. Thus this e-maintenance TELMA platform has the following functionalities:

- Intelligent agents (on-line services) directly implemented at the shop-floor level into the PLCs of the components (smart systems) for continuous, real time, remote and distributed monitoring and diagnosis of devices to establish the device health condition [44]. These embedded agents allow transforming raw data into an intelligent and useful form for maintenance considerations (current degraded process situation). They are today a sub-concept of the Watch-Dog agent;
- Infotronics platform supporting the data *vs* information *vs* knowledge processing, storing and communication on each level (shop floor and business) but also between the two levels. It uses PLCs, Field-Buses, Real-Time data-base (Local Data Center), Ethernet, Oracle data-base (Global Data Centre), CMMS, *etc.*;
- Services (off-line) among users for aided decision-making in front of the degraded situation. These services materialize, for each expert, the assessment of the (current degraded) process performance, then the prognostics of the future situation (if the degradation is evolving) and of its expected performances and finally the decision to be taken to control the process in its optimal performance state. The assessment of the predictive process performance is developed on economic, production, reliability and availability criteria enabling to optimization the main CRAMP parameters by keeping, of course, a priority on safety [45].

[29] http://www.predict.fr.

18.5.3 E-maintenance Processes Formalization

A global e-maintenance system integrates a set of shop-floor processes (prognosis, diagnosis, monitoring, *etc*.) to master more efficiently the manufacturing system degradation as well as a set of enterprise processes (cost, management, policy, *etc*.) to master more efficiently the capability of the whole enterprise system [29]. The literature on design, development and integration of these processes[30] is huge, including theories and practical applications. As this section does not aim at delving into this area, the reader is referred to the two recent review papers proposed by Venkatasubramanian [46] and Jardine *et al.* [37].

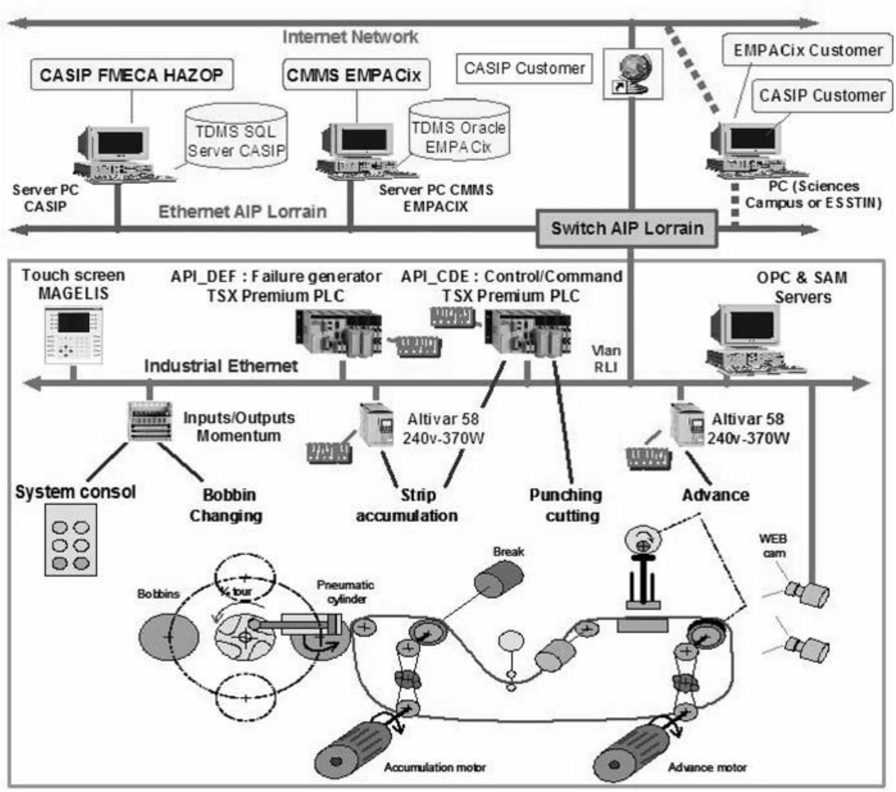

Figure 18.6. TELMA platform description [42]

In the first of these, Venkatasubramanian gives a broad overview of the various approaches to automated fault diagnosis and describes the state-of-the-art efforts in terms of industrial applications in the field. He also discusses the relevance of automated process hazards analysis to abnormal events management in product lifecycle management. In the second paper, Jardine *et al.* summarise

[30] Especially (e-)condition monitoring, (e-)diagnostic and (e-)prognostic.

recent research and development in machinery diagnostics and prognostics of mechanical systems implementing CBM. Various techniques, models and algorithms have been reviewed following the three main steps of a CBM program, namely data acquisition, data processing and maintenance decision-making, with an emphasis on the last two steps. Different techniques for multiple sensor data fusion have also been discussed.

18.6 Concluding Remarks

Economically, information technology applications in production systems have not always been profitable. The first waves of e-business turned out to be a disaster for too many participants. However, the impact of technological advancement is typically overestimated in the short run, but underestimated in the long run [47]. E-maintenance, as a sub-component of e-business, is probably following the same path. Indeed, the design of an e-maintenance system can be used as a guideline for the integration of various processes related to an e-maintenance platform by combining processes, structures and IT requirements, although not a “structure follows IT” approach but rather a “new IT structure enables new process structure” philosophy is proposed [18].

Some companies have investigated e-maintenance for several years ago [48] and have now already adopted it with significant impact on business process changes. Some e-maintenance platforms/systems exist (Section 18.5) where the resulting e-maintenance infrastructure replaces the conventional hierarchical structure by a heterarchical or intelligent one as advocated by the IMS[31] (Intelligent Manufacturing Systems) worldwide initiative [49].

Among the future common industrial/academic working/research directions, several can be underlined:

- Incorporation and adaptation of new technologies concerning “intelligence devices” (PDA, smart tags…);
- Industrial adoption and integration of the relevant standards (*e.g.* interoperability requirements);
- Modelling and implementation of the new processes (e-monitoring, e-prognosis, e-logistics…);
- Need of theory and tools for mastering the behaviour of the interactions of the system-maintenance-economy model, and maintenance decision support system for cost effective decisions;
- Development of new infotronics-based e-maintenance systems integrating new protocols for collaboration and negotiation, maintenance workflow, maintenance web services, and so on.

This chapter shows that e-maintenance is more than the implementation of a maintenance strategy, or a maintenance plan, or a maintenance type. It is a revolutionary change rather than an evolutionary advance [50]. In the future, the

[31] http://www.ims.org

academic challenge consists in structuring the e-maintenance knowledge in order to define a new framework, and more precisely, a new scientific discipline called "e-maintenance".

18.7 E-maintenance New Terminology

We will now present in this section several emerging terms used within the e-maintenance field, that could be of interest for the reader:

- *Collaborative maintenance*. A collaborative maintenance strategy can manifest itself in a wide variety of ways, such as online condition-based or real-time manufacturing process control monitoring, direct access to technical assistance, organization or procedural changes, customized employee training, storeroom management, onsite support, or enterprise asset-management integration tools. Collaborative maintenance is not a technology or a software solution; rather, it is a customized business strategy - unique to each situation [51];
- *Remote maintenance*. Remote maintenance is considered as a distributed process incorporating remote product monitoring, computerized decision-making, and online maintenance guidance [21];
- *E-manufacturing*. E-manufacturing is a transformation system that enables manufacturing operations to achieve predictive near-zero-downtime performance as well as synchronizing with the business systems through the use of web-enabled and tether-free (*i.e.* wireless, web, *etc*.) infotronics technologies [1];
- *E-diagnostics*. The SEMATECH Company defines e-diagnostics as the capability to enable an authorized equipment supplier's field service person to access any key production or facilities equipment from outside the IC maker's facility/factory via network or modem connection [25]. Access includes the ability to monitor remotely, diagnose problems or faults, and configure/control the equipment to bring it into a full productive state rapidly and within security, safety, and configuration management guidelines;
- *E-decision-making (or decision support).* This process integrates information necessary to support a "decision to act" based on data and information from other processing blocks and external constraints (safety, environmental, operational goals, financial incentives, *etc*.), and provides prioritised notifications with recommended maintenance and/or operational changes [25];
- *Information-based maintenance*. The overall concept of information-based maintenance is that of updating decisions for inspection, repair, and maintenance scheduling based on evolving knowledge of operation history and anticipated usage of the machinery, as well as the physics and dynamics of material degradation in critical components;
- *Semantic e-maintenance (s-maintenance)*. The collaborative e-maintenance is based on the notion of semantics. Systems in the network share the

semantics created for the common architecture of e-maintenance platform. The creation of domain ontology such as using knowledge and competencies in the network leads to development of corporate memory of enterprise. This memory supports the techniques of knowledge management and permits to capitalize this acquired knowledge [32].

18.8 References

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