Methodologies and Techniques for Advanced Maintenance

by

Lorenzo Fedele

Sapienza University of Rome, CNIM – Italian National Committee for Maintenance

contributions by
Massimo Concetti (CNIM) and Giampiero Mercuri (CNIM)

Working Group Coordinator: Serena Liccardi (CNIM)

Preface

The literature on the technical and scientific theory of maintenance and other related disciplines (maintenance engineering, statistical dependability, etc.) is substantial and relatively exhaustive today.

Despite the fact that it is quite probably true that technological and scientific progress does not take place through great leaps forward, but through small, continuous steps, which are not made by individual scientists, but by mankind as a whole, we cannot forego reflection on the changes underway in our time, which almost seem to constitute the arrival at the top of a peak, after a journey travelled at increasingly high speed during the Twentieth Century.

The spread of the personal computer, the Internet and the most disparate range of virtual environments of communication and “socialisation” has been a profound and radical step forward in people’s professional and private life styles, which must be taken into account in drawing up the umpteenth publication on a scientific subject.

This is the starting point we want to set out from in writing this volume. The world is not changing; the world has changed, and this has an important influence on the way we study, conduct research, experiment and publish the results of our research.

I have dealt with maintenance for many years, both from the academic point of view of study and research and from the professional and institutional points of view, as Secretary General of the Italian National Committee for Maintenance, with the ambitious objective of facilitating the spread of a culture of maintenance, which is basic to pursuing the objectives of safety, the quality of life, the economic viability of management and development that is compatible with environmental requirements.

From this point of view, maintenance is not only planning, organisation and management of inspections and technical intervention in a more or less efficient manner over a period of time in order to ensure continuity of operation. It is much more. It is a fundamental discipline in dealing with many of the world’s problems. If nothing is created and nothing is destroyed, in fact, it is obvious that everything has to be maintained. So maintenance is also a philosophical concept of life, which in some ways is more in harmony with Oriental spiritual trends than with prevalently Western positivist and rationalistic views and the illusion of coming to understand the mystery of life through analysis, instead of through the apparently more primitive symbolic path, which is a synthesis of rationality and imagination.

Maintenance is an indicator of civilisation, respect for our neighbours, ethics and intellectual honesty, even before it is an indicator of material efficiency. In this sense, it entirely adheres to the new technologies of communication that play such an important part in our everyday lives.

As science fiction has long portrayed, in fact, men and things seem to be destined to become the elements of a network of virtual communication, which probably represents our life better than the scientifically theorised and perceived space-time continuum, which is considered a mere instrument or model serving and benefiting man, even today, who is capable of perceiving only 3% of what takes place around him, on the neurological level.

So we shall be dealing in this book with the integration of maintenance in this virtual platform that we call advanced maintenance, even through the presentation of several actual case studies.

Therefore the first question we want to answer is: what is maintenance, and why is it so important? The second question is: what do we mean by advanced maintenance and why does it seem so important to introduce this definition with respect to the definitions that already exist? Finally, the third question is: how can advanced maintenance be operationally implemented?

If we succeed, especially by dealing with actual case studies, in arousing the reader's curiosity and wonder and provoking thought that places today's most widespread visions under discussion and even overturns them, and if we succeed in arousing the reader's interest from the first to the last page, we will be able to say that we are satisfied.

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Part I
BASIC MAINTENANCE

Chapter 1
Introduction

What does maintenance mean and what is the etymology of the word? Has the original meaning changed, or has it evolved throughout man's history and, in particular, in recent years? How can maintenance be placed, historically, with respect to other technical and scientific disciplines? What has made maintenance a subject of growing interest in recent years?

What are the prospects for development of this science and what branches of study and research are of greatest interest, with a view to scientific progress?

What are the scientific obstacles (cultural, social, methodological and technological) to the progress of maintenance?

How can these obstacles be overcome?

Starting from several general questions may help us organise and state the information synthetically, facilitating the transmission of contents and the formation of a personal culture on the subject.

Starting from questions also serves the purpose of placing what has been theorised and written on maintenance in discussion and therefore placing ourselves in discussion as well.

But then, it should also be noted that maintenance has an origin that is tied above all to the problem of satisfying contingent requirements, with procedures related to the experience of maintenance personnel.

In fact, maintenance owes its development essentially to industrial progress in recent centuries – namely, to the need to be competitive and the "discovery", which is obvious, moreover, that concrete and any other construction material have a characteristic development of their own, which is generally more limited than may be believed, with respect to the applications for which we use these materials.

Furthermore, advanced maintenance, a concept we have arrived at through extension of the meaning of maintenance due to its connection with all of the related disciplines (we could speak of maintenance and asset management or asset maintenance), is related to today's widespread data processing and communications technologies, creating a clear distinction with respect to what is meant by traditional maintenance.

But then the field of application of maintenance, like advanced maintenance, is extremely vast. There are many methodologies and technologies that can and must be referred to.

It is difficult to choose the best methodologies and technologies on a case-by-case basis.

In effect, this is an exquisitely engineering, planning and management task, with important implications on optimisation (the time horizons are generally extended; the reference environment is extremely competitive and the value of the assets is quite consistent: errors in judgement may therefore be particularly serious).

In this book, therefore, the theme will be dealt with above all by dealing with actual cases of application.

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Chapter 2
Planning and Managing Maintenance

2.1 The Phenomenon of Maintenance

The analysis of post-industrial society brings out the spread of attention towards social phenomena that imply increasingly greater spaces for the dimension of maintenance. We refer in this connection to:

- the transversal nature of many aspects and components of development;
- a strong characterisation of economic and social transformation, in terms of continuous technological innovation;
- the pervasive nature of innovation, in both social and technological terms;
- the expansion of tertiary productive activities, which have reached the level of the services economy itself.

In this context, the culture of maintenance is progressively becoming a transversal class of activities, due to the importance it has taken on in various areas, the consistency of the activities performed, the growth in the relative demand and renewed requirements of sedimentation and stratification of the cultural and scientific base.

The desire to preserve and maintain material property has been expressed since ancient times. Translating this desire into the related and variously structured activities, however, is a direct expression of the times and different societies involved, which thus brings out two pairs of significant relationships within the ambit of man's attitude towards maintenance:

- the man-time relationship;
- the man-object relationship.

Maintenance requires timed, long-term actions, which are often wide-ranging and strictly programmed over time. Lack of action is in itself sufficient to provoke the deterioration of objects and plants, whose maintenance, moreover, is not guaranteed by the performance of occasional corrective action. Time is a potential that must be used in the best possible manner.

Maintenance is influenced by the man-object relationship, through the various possible attributes that man confers upon the object itself, in terms of quantity, quality, durability, value, functions and the related structures and systems[1].

In twenty-first century society, a relationship of coexistence seems to be configured between man and object, which is realised through the permanence and duration of the object itself, thanks to the growth of the maintenance services that accompany the burgeoning assortment of increasingly refined and complex objects that surround us.

In terms of the technical concept of maintenance, there are two strategies that can be adopted in the maintenance of objects and plants: prevention and correction.

The spirit of maintenance is and must always be recognised as essentially preventive.

True maintenance does not consist of actions that are performed after a breakdown has occurred[2]. The inspiring principle of maintenance is distinguished from pure and simple correction, which is performed through repairs that depend upon the abilities, improvisation and manual capabilities of individuals, through a succession of absolutely unplanned activities.

The structuring and development of the concept of maintenance, understood as the idea of maintaining objects and complex systems in a good state of repair – or better yet in so-called normal operating condition – is definitely one of the most important aspects of contemporary technical thought, as it has developed during the course of industrial evolution in the XX century.

In the field of production, the passage from manual labour to mechanisation, automatic actions and automation – as the result achieved by widespread electronics – has determined an important and definitive fracture between the producer and user, thus conferring the dignity of an independent science to maintenance.

The availability of resources for maintenance, finally, has become an indicator of the level of economic development of a country and of the competitive position of a company.

Recourse to several indicators, such as the rate of maintenance[3], allows us to distinguish developed countries from developing countries, by studying the evolution of the function of maintenance.

In developing countries, insufficient maintenance activities are often one of the factors that slow development of the economy down, by triggering a process of uncontrolled growth in the demand for machinery and plants, which are used, abandoned, cannibalised and perhaps replaced, but hardly ever maintained.

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[1] Historically, various types of man-object relationships have been noted: spiritualist, ascetic, positivist.

[2] A failure or breakdown is an incident that can theoretically be avoided, through successive intervention to valorise and implement continuous improvement of objects and plants.

[3] Indicators made up of many variables, which take into due account the expenses of standardisation, maintenance and social security.

In general terms, various different configurations of the demand for maintenance can be seen:

- extension and enhancement of maintenance activities in the ambits (geographical area and/or sector), which lack services today;
- refinement and specialisation of intervention in ambits that are already served;
- innovation to transfer new technologies and models of management;
- externalisation or, better yet, tertiary expansion to include the service.

Through progression of maintenance services towards the tertiary sector and resorting increasingly to external providers, the competence acquired in the industrial sector can be made available to satisfy the demand from generally underserved sectors (management of complex networks, infrastructures, health, public services, territory).

The demand for specialisation comes prevalently from the industrial sector and is solicited by several important factors:

- quality, which is a condition that cannot be foregone if the possibility to compete is to be preserved; this is also understood as economically viable management and transparency towards consumers;
- safety, which is an imperative duty;
- the environment, which is one of the new frontiers for competition, as well as the unavoidable challenge of sustainable development and the quality of life.

Although the environment is one of the factors that stimulate the industrial sector, within the ambit of territorial management, the problems of maintenance and environment increasingly tend to be superimposed and integrated, continuously providing new confirmation and legitimacy of the proposal, formulated by many interlocutors, of including the theme of environment in the category of maintenance; it would thus be possible for ecological and environmental themes to acquire the cultural, scientific and managerial background of maintenance that has led to the foundation of the new science of terotechnology in the Anglo-Saxon world.

The foundations of this science are identified with reference to a now consolidated system of:

- culture of human resources management and evaluation of property (analysis of profitability, costs and benefits, analysis of alternatives, analysis of the life cycle);
- culture of maintenance techniques;
- culture of maintenance management (monitoring, planning and scheduling of inspections and intervention, evaluation of costs and the return on investments).

2.1.1 Maintenance in the Industrial Scenario: a New Factor of Competitiveness

Sector figures show a phase of expansion that becomes particularly meaningful for the industrial sector, the institutional seat of “productive know-how” that is increasingly becoming a candidate as a possible referent for “maintenance know-how”, understood in its most modern sense, as a result of the considerations made above[4].

The ability to ensure continuous improvement and realise a learning organization is the most adequate response today to respond to the growing demand for competitiveness of companies doing business on the global market, whose development is configured according to the model that is now known as the spiral of Juran. So the changes that characterised industrial development in the Eighties are being consolidated in company organisations, through the increasingly widespread diffusion of:

- Industrial Automation and Computer Integrated Manufacturing (CIM);
- Logistics;
- Just in Time (JIT);
- Total Quality Control (TQC) and Total Quality Management (TQM).

Automation and CIM involve greater complexity in plants and extremely heavy capital investments; this translates into a demand for a higher degree of availability[5] of machinery and plants.

The introduction of pull type management strategies, such as Just in Time, requires high performance from the best plants, in terms of dependability, to compensate for both lower stock levels (of both raw materials and components and inter-operational materials) and for the greater operational regularity required of the management system with the use of kanban.

The instruments for quality control and management (TQC and TQM) require greater dependability of productive means and more accurate calibration and adjustment of plants.

Additionally, the demand for greater product quality and higher levels of service, as well as the need for greater plant flexibility with modest operational costs should not be neglected.

Parallel to this, the management of maintenance for increasingly complex productive resources and systems has also undergone considerable change in order to adapt to the new context. Evolution has been developing through the meaningful contribution of three primary factors:

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[4] In the industrial sector, one of the strategic lines of the maintenance function, is, strangely enough, to prevent its own self destruction, through reductions in the cost of maintenance, with the same established objectives, obtained through intervention on the planning of products and processes, on layout, organisation and, above all on company culture.

[5] Aptitude of a system and its logistical supporting organisation to provide performance as required in the time required.

- the experience gained in logistical support activities for complex products and systems (especially within the ambit of military supplies);
- the experience gained in the maintenance of machinery and plants in several industrial sectors (especially in the processing and aeronautics industries);
- the Japanese experience in the management of production, product quality and productive processes;
- the development of logistics.

The speed of intervention and solution of a problem when a breakdown occurs is often compromised by a low degree of maintenance possibilities and by the insufficient definition of the logistical organisation supporting maintenance.

It is now a consolidated opinion that maintenance must not exhaust its duties in a more or less rapid intervention following accidental breakdowns.

The growing costs of plants and the critical elements related to their blockage, in fact, have marked the passage from the old concept of maintenance to a new formulation and new functions.

Total Productive Maintenance (TPM) is the most recent approach developed in industrial circles to face the problem of global efficiency of plants and machinery.

The characterising element of TPM is the global approach to plant problems, which are managed in a unitary and non-sectorial manner, with an entrepreneurial formulation typical of global cost management.

One of its peculiar characteristics is the separation and tracing of several articulated and complex company management problems to specific and simpler elements, such as the dependability of plants and the prevention of errors and breakdowns, and the successive reconstruction in the wider context of implementation of Just in Time and Total Quality strategies.

2.2 Maintenance Engineering as a Mix of Planning and Management

It appears quite clear that the growing sophistication of plants, the increasingly high level of automation and the considerable increase in costs have given maintenance an important position in all industrial companies.

Nevertheless, it is equally clear that the changes brought out require an important organisational change, adequate operational instruments and, above all, highly automated information and management systems, connected to inspection systems designed to monitor and control signals from the plant.

Maintenance engineering is therefore the connecting element between management and performance, through research, planning, training, involvement and commitment to implement continuous improvement.

But there is often confusion between the various aspects of the problems involved in planning and managing maintenance. There are many aspects to the problem, which transversally involve the entire business of the company; the following can be identified among the most important ones:

- product, machinery, plant and system design;
- the choice and implementation of maintenance policies and strategies;
- the construction of a logistics system;
- maintenance management;
- diagnostics;
- the performance of maintenance intervention;
- the information system.

Planning and realisation of maintenance systems and the Maintenance Logistical Support System (MLSS), through increasingly intense use of information models and systems, are matters of concern for maintenance engineering.

The following models are worthy of mention:

- the analytical models, designed to identify the criteria of evaluation for system component breakdowns;
- the organisational models, which seek rules, methods and procedures for the economic management of maintenance.

The following analytical models may be identified:

- models of interpretation of breakdown behaviour (originating from reliability studies);
- models of analysis of breakdown patterns, the effects and critical elements (Magec, Fmeca or Amdec);
- models of technical economic analysis (Life Cycle Cost);
- models of optimisation of projects (Project Management, Design to Cost, Design to Life Cycle Cost);
- models of analysis for the renewal of components (Level of Repair Analysis).

Among the models of organisation and management, on the other hand, we may distinguish:

- the Terotechnological Model;
- Reliability Centred Maintenance (RCM);
- Total Productive Maintenance (TPM).

The informative system, for all intents and purposes, constitutes the obvious difference between the old and new and must become the bearing element of the maintenance system and the means of integration with the rest of the plant.

There are subsystems that correspond to these aspects, which, within the ambit of every company organisation, play an essential role in design and actualisation of product, machine and plant maintenance.

Several of these subsystems will be dealt with specifically in depth in the following chapters.

2.2.1 Product, Machinery, Plant and System Design

With reference to the first of these aspects, it is always opportune to distinguish between the various parameters expressed:

- the characteristics of reliability of machinery and plants (Mean Time To Failure and Mean Time Between Failures);
- the characteristics of machine and plant maintenance capabilities (Mean Time To Repair); with reference to this parameter, the possibility to distinguish the logistical component is particularly important (Mean Delay Time);
- the availability of plants and machinery (Intrinsic Availability, Achieved Availability, Operational Availability).

The number and complexity of the characteristics and parameters involved lead, at times, to confusion between:

- reliability: the aptitude of a system to function without breakdowns;
- maintenance feasibility: the aptitude of a system to be repaired and maintained in normal operating condition;
- operational availability: the probability that a system, utilised under established conditions, will function satisfactorily at any given time, operating in an actual logistic environment.

The above-mentioned characteristics are strongly inter-related, but the methodologies and techniques to utilise for them are extremely different.

The first two fall within the design specifications of the plant, while the third is the result of the design of the supporting logistical system. Their definition, however, can only be necessarily unitary, if realised as a function of achieving the primary objective of an industrial plant, namely the profitability of the company.

2.2.2 The choice of Maintenance Policies and Strategies

The validity of the forecasts of reliability of plants and machinery is strongly conditioned by their correct operation during the period of production – namely the choice of an adequate maintenance policy and establishment of the right maintenance/production ratio.

The manner of performance of maintenance in industrial plants, which can commonly be differentiated, may be traced in the first instance to five types, which correspond to just as many widely diffused policies in the industrial world:

- incidental maintenance (to repair breakdowns), which takes place when breakdowns occur and is the oldest and most spontaneous form of maintenance. Intervention of this kind should be envisioned only in the event the stoppage does not create technical, production or quality-related problems;

- preventive maintenance (cyclic, programmed, systematic), characterised by intervention performed on the basis of the theoretical determination of the duration of several components that are considered fundamental for the operation of the machine, which are subject to wear and tear. It is performed periodically according to a previously established schedule (on the basis of definite elements and data on the operation of the machine and/or plants) in all cases where the machine/line constitutes a bottleneck and in all cases where it is not possible to obtain data that permit the forecast of the time that will elapse before the machine/line breaks down. Preventive intervention is performed to avoid traumatic breakdowns, rapid reductions of productive capacity with respect to established standards and drops in quality. This type of maintenance, although it is still quite widespread, entails a considerable increase in plant management costs;
- second condition maintenance, which considers breakdowns as the terminal point of progressive deterioration, which can be detected through monitoring of signals from the key elements; it is performed at variable intervals, in all cases in which it is not necessary to perform preventive maintenance and it is possible to programme the maintenance intervention, in harmony with the management of production, avoiding traumatic interruptions in production, partial losses of production and/or quality. The programming of intervention is based on elements such as:
  - the characteristics of machine operation and maintenance;
  - periodical inspections;
  - product/processing quality control;
  - information and/or reports of personnel assigned to the machine/line.
- Maintenance for improvement, which implies “engineering” of maintenance service and leads to constantly questioning even consolidated habits and patterns.
- Total Productive Maintenance (TPM), which pursues the objective of maximum dependability at the minimum cost of maintenance, utilising the cultural matrix of Total Quality, which – initially made up of the set of new Japanese productive techniques created in the manufacturing industry – was developed in the processing industry and has received original contributions in Europe. TPM is based on three fundamental assumptions:
  - prevention, above all through monitoring;
  - continuous improvement, as a dynamic attitude oriented towards continuous research of the causes of breakdowns and maintenance intervention in general, and the removal of such causes;
  - self-maintenance, understood as the tendency for the production operator to develop all of the elementary inspection and maintenance activities directly in the field; the operator thus plays a fundamental and active role in the maintenance of the vehicle, machinery or system entrusted to him.

Historically, it can be asserted that over thirty years have passed since the methods and techniques of preventive maintenance became widespread. They were later developed in a more or less orderly manner:

- predictive maintenance;
- productive (or proactive) maintenance;
- maintenance for improvement;
- TPM.

While it is possible to define productive maintenance as a mixture of preventive and predictive maintenance, TPM can be considered a system of total productive maintenance, which goes beyond the schematisation of the types of maintenance (for breakdowns, preventive, on condition, improvement), integrating, with a view to continuous improvement, all of the operational and logistical support aspects; TPM unites the improvement of maintenance feasibility with productive maintenance[6].

The adjective “total” brings out the important characteristics of TPM:

- management of total costs;
- total efficiency;
- total quality;
- total prevention;
- total involvement and participation;
- total productivity;
- total maintenance.

In terms of types of maintenance, the cultural changes brought out have led to a different allocation of resources in recent years, in particular:

- incidental maintenance settles in at 50%, on the average;
- statistical preventive maintenance carries a weight of about 20% – 30% of resources;
- maintenance according to condition is around 20%;
- the activity of maintenance improvement, conducted by small groups, accounts for less than 10% of the total resources.

2.2.3 The Construction of a Logistics System

Within the ambit of TPM, the entire process of maintenance must be managed on the basis of a maintenance plan, which will have the function of connecting the various maintenance programmes, through which it will provide for management of maintenance intervention on systems that are already operational, and the plant

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[6] TPM is often defined as profitable PdM (Efficient Productive Maintenance) for the substantial economies that it produces with a wide and extensive diffusion in productive sectors.

characteristics that will determine the project specifications and specifications of the supporting logistics system, which is the crucial element for passage from planned to realised maintenance.

For any reparable system, but for complex products and systems and industrial plants in particular, due to their articulation and complexity, the construction of an adequate Maintenance Logistics Support System (MLSS)[7], or the set of structures, materials, activities and actions that guarantee the definitive operational capability of the industrial plant, has acquired decisive importance.

An MLSS is therefore made up of:

- maintenance organisation;
- maintenance plans, programmes and procedures;
- technical documentation;
- personnel;
- equipment;
- spare parts;
- an information system;
- diagnostic instruments and equipment;
- techniques and instruments to identify breakdowns and isolate causes.

The MLSS ensures the availability of the instruments to plan and manage reliable and correctly maintainable plants with controllable maintenance costs, while TPM provides the cultural basis and methodology to obtain the involvement of all operators, to eliminate every functional anomaly and any waste, with a view to continuous improvement.

2.2.4 The Management and Performance of Maintenance

The objectives of the subsystems of management and performance of maintenance are to achieve the technical and economic optimisation of maintenance, seen in the enlarged concept of TPM; the most important activities can be traced to:

- definition of the proper level of maintenance, through optimisation of the maintenance/production ratio;
- definition of the procedures of programming and performance of intervention;
- the economic optimisation of global costs (direct maintenance and lack of maintenance);
- planning and optimisation of consumption of resources earmarked for maintenance, even through recourse to appropriate information technology supports;
- optimisation of performance (high levels of efficiency);

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[7] The concept of MLSS was introduced at the beginning of the Eighties by the United States Department of Defence, with the definition of Integrated Logistics Support (ILS); only later was ILS extended beyond military ambits.

- involvement of personnel;
- improvement of user/customer relations;
- control and guarantee of the quality of performance.

With reference to programming intervention, it is possible to distinguish between the following types of maintenance:

- ordinary maintenance, which is characteristic of periods of normal plant activity. This obviously constitutes the largest component; ordinary maintenance, which is subject to planning, must guarantee aging of the system that is coherent with the designers expectations;
- extraordinary maintenance, which includes all intervention on the plant that goes beyond planned ordinary intervention, in terms of both complexity and costs; it generally determines an increase in the value of the plant, after a certain time in its useful life.
- revamping, which consists of a veritable refurbishment of the plant under changed conditions of operation or different requirements imposed externally.

The macro-processes that the management subsystem must in any case ensure are:

- management of resources and works;
- management of external performance;
- management of technical materials;
- management of means of work, plants and services;
- system inspection.

Each of these macro processes can be divided into processes involving additional activities.

2.2.5 Diagnostics and Analysis of Breakdowns and the related Effects

Periodical verification of the operational status of the plants and machinery permits determination of their degree of reliability and maintenance needs[8]. The objective is to define:

- analysis of breakdowns/failures;
- analysis of effects;
- how and when to intervene on the plant;

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[8] It may be performed when the machine/plant is idle (even only through visual inspection) or in movement (visual inspection, non-destructive tests, etc.).

It is opportune for periodical visits to be performed with the definition of structured inspection itineraries with different methods, according to whether they are performed on idle or operating plants and machinery.

- what materials are necessary for intervention;
- how to reduce preventive intervention.

The contribution of machine/line operators is particularly important for diagnostics, providing they are available and willing and receive sufficient training and motivation.

The operator, in fact, may perceive:

- anomalies of position (unscrewed bolts, machinery out of axis, etc.);
- abnormal noise;
- odours that indicate overheating or malfunction;
- vibrations.

TPM provides for an extension of the meaning of diagnostics, placing the accent not so much on the need to diagnose failures or abnormal operation, as much as to identify, diagnose and eliminate the causes of anomalies in operation[9].

In this sense, we refer to two principle types of failure:

- accidental failure, provoked by the intervention of external agents;
- breakdowns due to deterioration, due to all of the various “natural” phenomena of aging (wear and tear, abrasion, fatigue, etc.).

In the case of accidental failure, the cause is presented with the reason for the specific event or “special” event, but which, in any case, is not natural or “normal”; in this case the diagnosis of the cause and the implementation of radical intervention for its removal are possible.

In the case of failure due to wear and tear, a distinction can be made between:

- natural deterioration, which is therefore inevitable;
- and accelerated deterioration, provoked by shortfalls that have taken place in the phase of design, maintenance or operation, all of which belong to the category of errors that can be avoided.

When analysis of breakdowns/failures has been performed, it is necessary to:

- define the principle manner of failure and the components involved;
- select the critical components;
- develop a cause and effect analysis for each failure;
- identify the symptoms or signs of failure;
- analyse the operational aspects.

A complex system or machine, in any case, has a limited number of reasons for failure, which concern an equally limited number of contents and critical components (generally a score or so).

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[9] TPM functions with reference to the classification of breakdowns, implementing intervention for continuous improvement, whose immediate result is to control all phenomena of control and breakdown.

The greatest difficulty lies in extrapolating the critical components from the myriad of components that make up the machine. The use of modules for the disassembly of the machine on various levels may be of assistance in this task.

The critical indicators (to be attributed to the manner of failure) allow us to define the priority criteria of intervention; the weak signs provide indications to activate inspection plans, the reasons for failure suggest intervention for improvements.

Generally, the critical indicators are made up of the product of two weights: the first is related to the failure, but is measured in terms of the lack of availability of the machine, and the second is related to the aspects of the plant. The two weights are combined in the critical matrix, which permits the attribution of a system of points to every manner of failure and the organisation of maintenance or improvement intervention in harmony with a classification of priority related to the indicators.

The matrix constructed in this manner permits preventive analysis of improvements that may be achieved in relation to specific operations that may be performed in various directions:

- horizontal: by intervening on the availability of the machine (reducing the frequency of failure and down time);
- vertical: intervening on critical points of the plant (through improvement of plant flexibility).

Awareness of the operational conditions provides the elements to propose modifications relative to the feasibility of maintenance, support logistics and procurement of materials.

Awareness of the manner of failure and the relative critical points provides the basis for evaluation of the effects that the failures may produce in an industrial plant, with reference to production, quality and safety.

Analysis of the effects on production must lead to an evaluation of the seriousness of the down-time consequent to the failure of the components, subsystems, set, plant or factory.

Indicator values may be assigned to each of them, which may be obtained from pre-defined matrixes, built for the type of productive activity and/or machinery.

For this purpose, it is necessary to refer to the organisational structure of the works typified, with reference to the level of interconnection of the plants; thus, it is possible to identify:

- plants with a low level of interconnection: these are generally plants on line with a low level or no interconnection (the only interconnection is derived directly from the productive flow);
- strongly interconnected plants: in which the functional failure of a subsystem can be due to breakdowns in other subsets or machines; in this case it is of fundamental importance to identify the input interfaces of each subset.

Industrial plants are characterised by increasing levels of complexity and self-sufficiency in terms of operation.

One of the most important management objectives is to guarantee operation: the operator replaces the worker; the maintenance personnel replace the operator.

2.2.6 The Information System

The technological and organisational innovations that have characterised industrial production in recent years have made significant contributions to changing the importance and role of information technology, which improves the manner and efficiency of management.

Integrated information technology systems have spread in the field of maintenance, as well, for the technical management of machinery and operational management of maintenance.

Information technology systems fundamentally fulfil the task of providing complete “visibility” of the maintenance system.

The objective to pursue is the realisation of an information system that assists maintenance in the phase of seeking failures, in intervention and re-planning of maintenance as a function of the indications coming from the management of the plant itself.

The approach of TPM and of all of the most recently introduced maintenance policies calls for extensive recourse to preventive maintenance, not so much of the statistic type, but according to the condition of the machinery.

The problem of an approach of this type is to succeed in identifying the symptoms of failure at the right time or, in any case, to intervene in an abnormal situation in operation of the machine.

This problem is considerably simplified by the latest generation of machinery, equipped with diagnostic devices capable of controlling many important parameters and detecting operational anomalies.

If the machines that call for continuous monitoring of controlled parameters are analysed, an additional problem for maintenance personnel crops up; to succeed in filtering, with the mass of information arriving from the machines, the few meaningful bits of information for maintenance purposes, for the machine history and manner of failure[10].

The information system may be developed precisely in this direction, in order to respond in a clear and rapid manner to this type of problem and ensure an effective benefit to the maintenance personnel.

A system of this type will envision the employment of an expert system, capable of “intelligently” managing the incoming information, of providing a reading and interpretation of that information and suggesting the most appropriate intervention in relation to the various situations.

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[10] In many cases the interpretation of the data collected may require the intervention of additional professional figures that possess specific competence different from the competence of the machine operator.

It is possible to build an entire information system around the expert system, with all of the procedures for intervention and the manner of connection with company realities, in order to achieve:

- management of works and resources, whose fundamental purpose is to request the work order;
- technical plant management, whose fundamental purpose is the management of the machine and plant;
- management of continuous improvement;
- management of maintenance engineering.

The new information system must then be able to interface the expert system with the machines and other components, such as:

- the sensors, whose task is to collect signals from various plant machines;
- the communication networks, when ensures the exchange and flow of information throughout the factory;
- the front-end, a computer that provides for continuous monitoring of signals and their selection, to send only the important ones to the expert system it is connected to;
- the model of interpretation of failures, which permits us to forecast the duration and behaviour of the machines.

These elements are then integrated with the standards present in all traditional information technology systems:

- the plant database;
- the system of management of works and resources;
- the system of plant management.

2.2.7 Conclusions

It has been seen how, historically, the maintenance culture of the processing industry has been deeply enriched by the contributions of the manufacturing industry, which is evolving towards forms of integration and automation of productive plants and services (internal and external), with important impact on the organisational structure of the factory, the professional figures present and on maintenance, which assumes a central function on the management level.

In speaking of the manufacturing industry, of automation and organisation, the decisive contribution of the Japanese model of production cannot be neglected, which has conditioned plant culture through its most significant element, in an extremely meaningful manner: the global nature of the approach.

Problems are not dealt with in the ambit of sectorial strategies, where the achievement of an objective sometimes entails the sacrifice of others; a global vision must be acquired, instead, which makes TPM an obligatory road to take, in terms of maintenance, in this process of change.

Another important change of orientation in the development of the industrial system is included in this context.

In fact, the culture of conservation has appeared and is beginning to replace the culture of substitution, which testifies to the passage from an industrial to a post-industrial phase.

The symbol of this new industrial revolution is definitely automation.

Through automation, the responsibility of the process goes back to the productive system, eliminating many staff and operational support figures, as well as dividing “those who do and those who think”.

The spread of the culture of maintenance, in any case, constitutes the fundamental element for the assertion of the concept of “maintaining” as opposed to the concept of “building again”.

Today, the problem of correctly maintaining and managing industries, infrastructures and services has become the central facto of civil development, in a framework of sustainable development.

The increase in prosperity has brought a great increase in property and an important increase in the population in recent years; this leads to increasing use of resources and a serous problem of environmental impact.

Precisely for this reason, it can be asserted that raising the quality of life essentially means maintaining instead of building, preserving instead of consuming.

In technical industrial terms, this means keeping existing plants in efficient operating condition, both to preserve productivity and guarantee the protection of the environment; it means applying the principles of continuous improvement of plants and, in an even more massive manner, of services.

In order to work in this direction, it is necessary to perform maintenance, utilising the technologies and methods of improvement maintenance and TPM.

Systems operators must perform initial maintenance intervention and have the motivation to conserve. Outside of industrial companies, this is also true for museum attendants, building porters, bus drivers or train engineers, and the managers of water purification systems.

Such, therefore, is the objective it is necessary to strive and work for in coming years.

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Chapter 3

The Life Cycle of Products and Systems and Logistical Engineering

3.1 The Life Cycle

During the phase of planning of a system, situations often occur in which the complexity of models of dependability and the number of parameters in play create a very complex framework, in which it would be almost impossible to make any decision relative to system choices, technologies, initial component quality and engineering, etc., in the absence of in-depth analysis conducted with appropriate methods of research.

The purpose of logistics engineering is precisely to provide the project criteria and parameters to guarantee the containment of costs throughout the life cycle of the system and, in particular, during its useful life.

Obviously, for this to occur, it is necessary to be aware of the costs and to impute them correctly. A "*life-cycle cost analysis*" must be performed for this purpose, namely, a process of evaluation of the alternative configurations, promoted with the use of figures of merit related to the life cycle. The evaluation starts as early as the initial decision-making process and is successively refined and extended throughout the successive phases of design and development, until an operational configuration of the system is achieved.

Definitively, the cost estimate entails the use of many techniques, which depend upon the availability of various categories of data, ranging from the definition of a cost structure to a cost estimate and from the formulation of a cost model to the definition of a cost profile: all of this permits estimation of the cost profile over the period of the life cycle foreseen (after deflating the costs, of course, to reflect the actual budget estimates). This profile may be represented as shown in Figure 3.1.

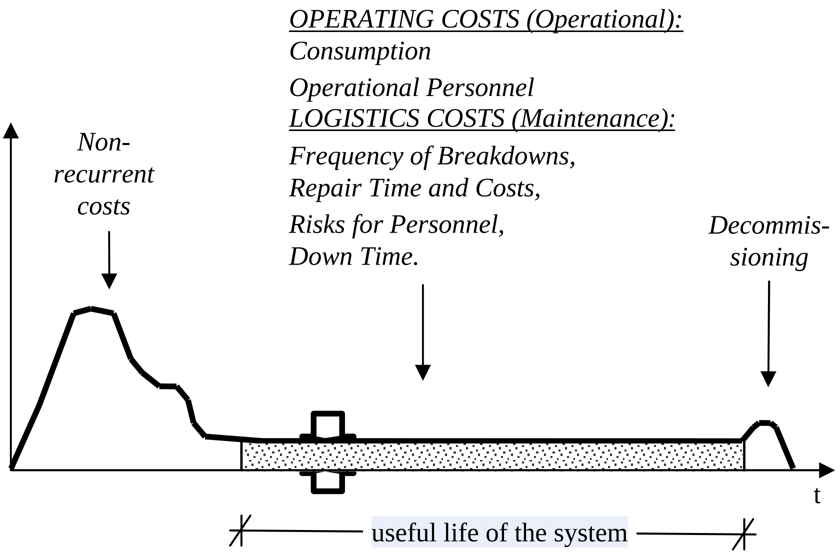

Fig. 3.1 Life cycle cost profile

The Life cycle of a system can fundamentally be divided into three parts:

- Planning, development and production;
- Useful life;
- Decommissioning.

With reference to the useful life cycle, the costs can also be divided and associated with:

- Industrial costs;
- Costs during the useful life of the system.

3.1.1 Industrial Costs

The life of a product or system starts when the market identifies the need for it and the time is ripe to launch it commercially. At this time, an initial nucleus of human resources decides to tackle a technological challenge, in the attempt to develop an initial idea for confrontation outside the nucleus; to obtain sufficient elements to establish, with a reasonable degree of certainty, the effective usefulness, convenience and commercial potential of the product or system in question.

Once the initial research has provided positive results, the problem is transferred to specialised technicians, capable of developing a feasibility study, which will require greater human resources because of its more complex nature; this will inevitably cause the costs to grow. Even before this phase is concluded, as soon as the group becomes aware that it is capable of dealing with the challenge in a positive manner, the successive stage of planning begins (generally defined as *Project Definition and Validation*) in order to cut down the "time to market" as much as possible, which is commercially essential for some products and systems. In this phase two competing firms or consortiums are often involved, if the idea for implementation originated from a Purchasing Organisation (generally a State Administration), so as to guarantee the possibility to choose from among different projects and ideas for realisation.

When the phase of the call for tender is finished, the project is definitive. An additional cost must now be defrayed in order to effectively implement and develop the project (*Design and Development*). In the United States, and more rarely in Europe, when the project has been developed a new call for tender is made for engineering and production. The assignee acquires the results of the previous phases to complete and market the product and pays the relative *royalties*.

The phases described up to this point are necessary, independently of the entity of the production it is desired to perform and the entanglement of the respective cost curves provides the value of "non-recurrent costs" – namely, the costs that must be sustained even if the phase of production is never effectively implemented. In the next phase, on the other hand, the cost curve varies depending on how much it is desired to produce, considering that the greatest costs here are due to the purchase of the materials and remuneration of the labour (even if it is less specialised than in earlier phases). At the end of this itinerary (3 – 10 years) the product is ready to go on to the customer, for whom it will have an almost constant cost for its entire useful life (20 – 30 years).

3.1.2 Costs During the Useful Life

It has been seen[1] that about 60% of the costs (namely for the total area of the curve) for the entire life cycle of the product can be imputed to its useful life, and therefore for the period in which the product is used by the customer, as the sum of:

- *Operating costs:* these costs tend to reduce as automation increases (reduction of operator personnel) and with the increasingly greater attention towards the reduction of energy consumption.
- *Maintenance costs:* due to the reduction of financing for the periodical renewal of systems and the consequent forced extension of the useful life of systems already in service, maintenance costs have become "cost drivers" for the entire life cycle of the product;
- *Costs for capital losses and damage to the image:* this is a category of costs that vary according to the type of system, but which both the supplier and the

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[1] Source: CASD = Centro Alti Studi per la Difesa (Italy). [High Defence Studies Centre]

customer often fail to take into due consideration. It should suffice to consider that for an industrial plant, an armaments system or clinical examination equipment, even the loss of human lives could fall within this category. The fact that the life cycle has been successfully extended to 25 years is due to the greater attention dedicated during the phase of design to the problem of *Growth Capability*, which has increasingly made it possible to have a more modular product, capable of being successively modified and improved (*middle life improvement*) at lower costs than in the past.

- *Cost of decommissioning:* this is a cost that can sometimes be transformed into proceeds, such as in the case of sale of the system, now obsolete for the first user, to a third party. Sometimes, however (in complex cases) the cost can be quite high, as in the case of nuclear power plants, some industrial plants or in general where decommissioning involves an environmental impact.

For these reasons, the battle of cost reduction must evidently be fought primarily in the phase of constant costs, seeking to abate maintenance costs and therefore breakdowns, definitively, in addition to operating costs, which tend to be limited, in any case. The conclusion we arrive at is aptly included in a general trend in which modern companies seek to achieve the quality standards that customers have learned to demand. That quality is well integrated with the importance given above to logistical support as a necessary instrument in reaching company objectives.

Only by requesting and explicitly controlling the development of the logistics engineering system can the customer be sure that he is purchasing a valid system from every point of view: otherwise, the need to be competitive could induce the producer to avoid costs for the development of activities that are not compulsory, but these savings translate into an increase in system maintenance costs, which are entirely defrayed by the customer[2].

Currently, new methods of work, such as Simultaneous or Concurrent Engineering, and new information technology and organisational, such as Continuous Acquisition & Life-cycle Support (CALS) permit the engineering of the product or system concurrently with its logistical support, keeping an eye on costs throughout the life cycle. Considering that the reduction of funds for investments in some sectors, especially Defence, has forced users to employ equipment for much longer periods of time than what would theoretically be appropriate, when it would behove them to make a change due to obsolescence, it has been seen that in addition to having to provide for expansions, improvements and modifications in

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[2] Concerning the relationship between producer and user, in any case, several approaches to the problem of maintenance are possible, in the sense that the producer can decide to take on the maintenance expenses relative to:

- the entire system relative to the production;
- The entire system, but only for a certain period following its commissioning;
- Several elements of the system, leaving the customer to provide maintenance for the others;
- None of the elements of the system

advance, equipment must be made as sustainable as possible at the lowest possible cost.

This is the point upon which the future market hinges.

3.1.3 Logistical Engineering

Logistical engineering is a multidisciplinary field that is part of the field of systems engineering and primarily includes:

- estimates and "forecasts" of values of dependability and maintenance capability, as well as verification of their correspondence to the operational reality;
- the management of processes that permit developers to influence the design of the primary system, with considerations relative to support and the cost of the life cycle;
- planning preventive maintenance and organisation of corrective maintenance activities for repairable systems.
- the definition of logistical support;
- the selection and calculation of quantities of spare parts for maintenance needs[3];
- the definition of maintenance instruments and equipment.

Interest in these problems has grown rapidly in recent years, in line with the technological, sociological and economic evolution of the modern world.

The use, among other things, of information technology design, development and production systems (CAMD/CAM) and Integrated Engineering *(Concurrent Engineering)* has enabled us to make increasingly rapid technological progress, which has led to more and more complex systems and products. Although it is true that the need to renew systems and products with greater frequency is becoming increasingly pressing because they rapidly become obsolete, it is also true, however, that this tendency has been greatly compensated for by the birth of problems correlated to the strong economic crisis, which has led to procrastination in the purchase of new systems, thereby favouring a lengthening of the useful life of systems already purchased.

The decrease in financial resources available to purchase new systems (and also partly for the maintenance of systems already in use) has resulted in increased awareness of logistical engineering and the parallel discipline of Integrated Logistical Support (ILS). In fact, ILS ensures that systems planning and planning of the relative means of support are coordinated, to minimize the cost of the life cycle of the product. This is done simply by improving the integration of all of the support elements. This is a management function that provides for the initial planning, investments and controls to ensure that the customer or final user purchases a sys-

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[3] Maintenance understood as the set of actions to ensure the efficiency of plants at the minimum global cost possible

tem that not only satisfies his requirements of operational performance, but also permits timely and economic maintenance throughout the life cycle.

The collaboration between the technical design components of the industry (technical management) and the most sensitive components relative to post-sales assistance (logistical management and technical assistance) is the fruit of this modern vision of the productive reality. In order for this collaboration to be effective, it must start in the initial phases of the project, be continuous and avail itself of software instruments that permit synthetic correlation of analysis and reliability forecast, maintenance capability, testing capability, technical specifications, contractual and project objectives data. This activity, defined as logistics support analysis, concerns all of the elements of support and is one of the fundamental aspects upon which the estimate of the cost of the life cycle of a product (the *in service phase)* is based and is one of the most effective instruments of *concurrent engineering.*

3.1.4 Concurrent Engineering

The growing complexity of modern products, or, better yet, of the needs of consumers or users, requires a new approach in development. This not only concerns the dimension of *time to market* of the problem, but also and above all the quality necessary for the complete satisfaction of the customer's needs. The most important consequence, in this sense, in the modified competitive scenario, is fundamentally the need to "shorten" the distance between those who create, design, produce and distribute the product and those who use it. This is a need that is felt above all by large companies, where all of the phases of work associated with production are divided among several responsible parties, without considering that the need for specialised competence of a functional type tends to raise cultural and language "barriers" within the organisation. This all translates into continuous growth in times and costs for the development of new products.

The group approach, which aims to detect all of the actual needs of the final customer who uses the products, and is an obligatory path for companies that want to maintain a competitive advantage that can be defended in their sector, is called *concurrent* or *simultaneous engineering,* At the same time, the need of companies to have suitable products for changing market needs and demands, provoking the need to decrease the time necessary for the development of new or renewed products – namely to reduce the *time to market,* corresponds to this strategic choice.

It is an inter-functional process that requires an initial effort in terms of time and resources in the phase of definition of the product, whose aim is to modify the overall management of the traditional steps followed in manufacturing a product, which typically include: identification of new opportunities, technical feasibility of the product, macro design, selection of the product solutions that can be realised, industrialisation, production, quality control and delivery.

It is a serial process, generally involving a flow of requests for modifications from the organisations interested, which gradually increases until it reaches a peak when the product is made available to the final customer. The revision generates a series of considerable extra costs, due to the management of new drawings and technical documents, the preparation of new equipment, re-elaboration and other impacts on various project activities.

It is evident that the heavy costs are reduced a great deal when the modifications are successfully limited in the initial phase of the manufacturing process: experience has taught us that in order to plan well the first time, it is necessary to eliminate late changes, which are mostly caused by the serial nature of the activity between planning and production. For this reason, *concurrent engineering* focuses on processing costs in a phase upstream of the processing itself, seeking to influence the total costs of the product when the changes can be implemented easily and rapidly at the computer, evaluating alternative product processing, materials, the *make or buy* policy, etc.

Concurrent engineering consists precisely of a series of actions and procedures that are necessary to effectively organise work in order to:

- obtain, verify and create priorities for the needs of the potential user;
- develop various product and processing solutions;
- evaluate the global alternatives in relation to the customers' demands, commercial and productive limitations.
- divide the process into levels of analysis that lead to the definition of subsystems and components, without losing sight of the customer the product is targeted for.

Among other things, computer simulations and predictive methods are employed in order to do this, to significantly contain the costs of product development. Again, we are speaking of cultural change for the company, with respect to the classical method of working, which calls for the creation of prototypes, their measurement, recycling with design, etc. In order to satisfy the need to transfer and translate the customers voice and his perception of the product with respect to the competition, in all of the activities of product development, market research is used (interviews, questionnaires, etc.) to be able to count on the availability of updated information on customer needs.

3.2 CALS

The abbreviation CALS, which stands for *Computer Aided Logistics Support* was coined in 1985 by the US DoD. Later, in 1990, it was adopted by NATIO as the acronym for *Computer Aided Acquisition and Logistical Support,* and was again changed in 1993, when it became *Continuous Acquisition and Life Cycle Support.* Finally, in order to focus attention on the possible civil applications, the abbreviation was utilised with the meaning of *Commerce at Light Speed.*

Substantially, this indicates a global strategy that is proposed to regulate the exchange of information between the supplier and user, through the information technology network, throughout the life cycle of the product, through the adoption of a set of procedures and standards to generate, access, manage, maintain and distribute digital data. Although CALS was created, as we stated above, as a military requirement, it also applies to any sector where the large scale integration of technical and/or economic data is required, such as in airline aviation, the automotive industry, construction, in transportation, etc.

The primary objectives of CALS are:

- integration of Design, Production and Logistical Support processes, in order to reduce the times and costs of development and production and to improve the quality from the customer/user point of view. Within the military environment and for armaments systems, customer satisfaction is measured in terms of availability and economical viability of maintenance in service of the armaments system (Life Cycle Cost);
- transmitting information electronically between the purchaser – customer and supplier – industry, within the various customer organisations (i.e. Government Organisations) and between participating industries and the same company.

Initially (this is a phase that has already been overcome in the US) the exchange of information took place through standards and with a partially automated process, with the elimination of paper and the exchange of electronic files. Successively, integrated databases were realised, applying the fundamental concept according to which: a piece of information must be generated only once, managed and guaranteed in an effective manner, without redundancy or useless duplication and must be made available to all of the users who need it in the form, place and manner most opportune for the user. All of this takes place because experience has taught us that the adoption of "open systems" facilitates integration of data along the entire line of the supplier – user, starting from the supplier of elementary components and from the provider of services, to the final user.

The manufacturer is called upon to transfer a great quantity of information, in the form of: data, technical documents, logistical support analysis, technical manuals, planning and control, etc. Additionally, he is required to guarantee the appropriateness of his processes of design, development, production and logistical support, which must be such as to permit the Customer access and use of the relative information.

Some time ago, several organisations adopted the technique of creating and exchanging data, using common interfaces, to ensure efficient use of the digital techniques in exchange. The CALS standard initially used tended to facilitate digital exchange of drawings, figures, technical manuals and engineering data, while the most recent ones focus on the complete definition of data and models of products and on their management in a distributed database.

The need to standardise is due to several considerations:

- the useful life of the data is greater than the systems or software;

- the data have several uses;
- sharing of data requires a common language;
- conversion/translation is costly and inefficient.

A policy to start a company CALS strategy is based essentially on a programme of revision of company processes, starting first of all from functional definition, and proceeding to define the relations between them and the various technical information that refers to them as well. It is therefore necessary and possible to harmonise and re-engineer company processes involved in the generation, management and processing of the various technical data. Setting up this strategy must be coherent and congruous with the needs and expectations of every customer, correlating internal actions of the industry to the definitions that characterise customers' policies on the subject. For example, various levels of updating of information structures must be implemented: starting from electronic mail systems, to systems for the integrated treatment of product information that use CALS standards.

US commissions that studied the matter quantified the benefits of this strategy, but said little about costs, in terms of investments; nevertheless, the judgement on the cost/benefit ratio is, overall positive. In particular, the benefits have spin-off prevalently on the traditional activities charged to the account of the user, while the costs are mostly in connection with engineering and organisational aspects, which the supplier must defray the initial phases of planning.

We can conclude by recapitulating the key message of CALS: information, of any kind, that is produced during the phases of purchase, design, production, operation and maintenance of a system, must be objectively defined and adequately managed.

3.3 Types of Breakdowns and Maintenance

Technology at the service of modern industry has led towards increasingly hard driven automation of productive processes. This phenomenon, which is in full development, has contributed to focusing the attention of many operators on problems related to maintenance. The *just in time* philosophy, which is now widespread in the West as well as the East, has placed even greater emphasis on the dependability and availability of the machinery necessary for production; consequently, maintenance strategies that provide more detailed indications for the correct scheduling of intervention have taken on great importance.

There is no doubt, therefore that in recent years, the level of awareness of operators has increased relative to the importance of maintenance, especially in consideration of the costs that it represents.[4].

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[4] “7% of the GNP is spent to repair damage caused by mechanical breakdowns" according to the Massachusetts Institute of Technology.

This collective increase in awareness has been accompanied by the simultaneous development of monitoring techniques and instruments that have contributed to changing the overall picture: many companies have understood that these problems are one of the few items of "controllable" cost in managing a plant. Not only this, but since the end of the Seventies, the market has begun to overcome the culture of *basic black*, which encouraged Henry Ford to say, in the Thirties: "every American can have an automobile of the colour he wants, as long as it's black!" More than ever before today, the final user privileges the factor of service in the process of purchasing goods: timely supplies, technical assistance, the level of quality, and customisation of the product, even beyond the price factor. In other words, needs change and consumers always require more *tailor made* products.

The answer of the factory to these market requirements is maximum flexibility, the flow of the productive process with a drastic reduction in cross-through time and care in the internal logistics process.

It is therefore necessary to make a deep revision of the organisational type and to perfect adequate operational mechanisms, and as a priority, an information management system and a plan for systematic intervention and inspections (continuously or at established intervals) to be developed with the assistance of appropriate equipment. It can be understood how, in this panorama, maintenance has become a highly critical function, for two fundamental reasons: the first, due to the high level of integration and therefore of complexity of productive systems; the second, due to the importance that the availability of production lines is taking on, accentuated by the casual breakdown, connected to a growing presence, in plants, of electronic components, equipment and systems.

The beginning of the process of valorisation of the maintenance function is situated, temporally, in the phase of passage from the industrial to the post-industrial company, in which great infrastructures exist, but where the need to maintain the system in a state of efficiency is beginning to prevail, rather than continue to develop and enlarge it. The central nature of maintenance for productivity in industrial processing, for the conservation of the environment, to improve the level of public services, has consequences on the organisational structure, operational mechanisms and, above all, on the professional maintenance figures and strategies.

Although it is true that breakdowns are always damaging, it must not be considered that they all have the same consequences. By definition, a breakdown is the impossibility of a material, structure or system to perform the task it was defined for in a safe and orderly manner, but there are different levels and characteristics in this situation. A classification of breakdowns is shown in Table 3.1

Table 3.1 Classification of breakdowns [Source: Fitch, 1992]

Type of breakdown	Description
Catastrophe breakdown	A condition of sudden and complete interruption of operations and total deterioration of functions.
Sudden breakdown	A condition of accelerated deterioration of both the material and perform-

	ance, which translates into a partial weakening of functions.
Imminent breakdown	A perceivable condition of deterioration of the material, in the presence of a serious deterioration of performance.
Incipient breakdown	A condition in which the use of appropriate means of detection permits the identification of the first signs of deterioration of the material, without the user being aware of any modification in the performance of the machine.
Conditional breakdown	A pre-alarm in which the deterioration has not yet occurred, either in the material or performance, but which is such that if the situation persists, a functional breakdown will inevitably occur.

The "primary causes of the breakdown" show up when there exist abnormal conditions that produce a situation of instability in the system. In the case of mechanical systems that use fluid, for example, it is possible to identify several typical causes:

- excessive contamination of the lubricating fluid;
- leakage of fluid;
- chemical instability in the fluid;
- physical instability in the fluid;
- cavitation;
- instability in the temperature of the fluid;
- severe conditions of wear and tear;
- deformation or fracture of the material.

If we start from the supposition that the producer has designed and built the machine correctly, a "conditional breakdown" will depend totally on the occurrence of one or more of these primary causes. Corresponding to this level of breakdown, as we shall see later, lacking identifiable symptoms of deterioration of the performance or material, the user can only identify and correct the primary cause of the breakdown through what is normally known as *proactive maintenance.*

When an incipient breakdown occurs, this means that the performance of the system is correct, but there is already a certain degree of deterioration of the material, which can be detected through monitoring of the *debris* from use, vibrations or noise. It is then a question of performing what is known as predictive maintenance. If a certain weakness in the performance of the system can then be seen, we are speaking of a situation of imminent breakdown, due to the fact that the user has not intervened in a timely manner to correct the conditions of irregularity that caused these problems. At this point the operator only has to programme preventive maintenance to avoid sudden breakdowns and machine down time.

Ignoring all of these signals of deterioration of the machine would inevitably lead to a phase of sudden breakdown, when the deterioration of the material takes on such proportions as to seriously weaken several machine functions. The machine will have to be repaired immediately and the damaged components must be replaced. In this sense, we speak of "reactive" maintenance, involving a breakdown that is already present – *breakdown maintenance.*

Finally, the catastrophe breakdown must be analysed. This is a condition in which normal operation of the mechanical system stops or becomes so problematic as to make it difficult for the operator to control. In this case, all of the broken elements must be removed, repaired and replaced, according to the strategy of the four R's *(Remove, Repair, Rebuild and/or Replace),* which for a long time was the only approach to maintenance.

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Chapter 4
Maintenance Policies and Strategies

4.1 Introduction

This chapter will analyse the various strategies we have referred to above, on the basis of an important premise: it is quite easy to have a certain degree of confusion in identifying the various approaches to maintenance, due to the fact that the diversities that authors attempt to bring to light are often fuzzy and difficult to render in a complete manner and, at times, through translations. In any case, the declared intention of this treatise is not to clarify possible shortfalls relative to terminology, but to provide an overview of the various possible approaches to maintenance, highlighting as much as possible the interrelations and stages that have marked its development.

The concept of maintenance subtends a vast set of problems, with innumerable operational implications, which makes it rather difficult to schematise the possible approaches in a general manner, which have marked development in this sector over the years. Nevertheless, the requirements of synthesis and clarity suggest at this point to provide an overall picture of the possible orientation of maintenance, followed by a detailed examination of the various criteria adopted.

One of the first aspects to bring to light is the distinction that can be inferred from the definitions provided previously, between maintenance policies and strategies: speaking in hierarchic terms, the latter comes to the fore in a second phase, characterised by an operational approach to maintenance problems, to be developed according to criteria provided by the maintenance policy adopted. Maintenance policy, on the other hand, indicates the overall attitude that a company assumes in relation to maintenance problems, which may then be clarified in the use (according to the departments, individual machine and economic convenience, etc.) of various strategies. This is the case, for example, of *total productive maintenance*, an approach to maintenance that was developed in Japan. The innovative aspects are primarily the acquisition and application of theories concerning the maintenance of failures, the dependability and feasibility of maintenance, the special attention dedicated to questions related to the economic efficiency of the project and, lastly, the introduction of an omni comprehensive system of maintenance, which involves the activity of all operators.

On the level of policy, but with a less "pervasive" approach with respect to TPM, the concept of Reliability Centred Maintenance (RCM) is situated.

It was at the beginning of the Sixties, when it was decided to perform an in-depth investigation on the efficiency of preventive maintenance, that the concrete possibility of evolution in the criteria that had been adopted up to that time in the prevention of failures began to take concrete shape. In fact, the approach to Preventive Maintenance was quite often applied dogmatically, programming revisions at established intervals of time, with no regard for possible comparison with the data derived from previous experience. RCM, on the other hand, had the objective of consolidating the intrinsic dependability of the project, with a complex analysis, which called for a certain number of meaningful phases (training of personnel, collection of information, identification and division of the system, strategy, inspection intervals, cost effectiveness) and led to the full assertion of Predictive Maintenance as the logical evolution of Preventive Maintenance.

In order to give an idea of the hierarchic and historical relationships between the various orientations, it was decided to insert a summary capable of providing a key of interpretation for the material that will be set forth fully in the following paragraphs. As can be inferred from the analysis of the aforementioned scheme (Figure 4.1), maintenance activity has been developing, for some time now, in three different directions, reconciling just as many categories of intervention:

- intervention that can be implemented only after the failure has occurred (Unprogrammed Maintenance);
- intervention born of logic and a predetermined, programmed plan (Programmed Maintenance);
- intervention centred on the attempt to engage in a process of continuous improvement in management of these problems (Maintenance for Improvement), starting from the operational procedures and continuing through to the progressive re-definition of critical situations, based on the experience acquired.

The behaviour upon failure of the property and the behaviour of the property in relation to the maintenance action performed are dynamic phenomena: improvement of the maintenance system permits continuous calibration between the system itself and the property maintained, optimising global management costs.

The possible variants of Programmed Maintenance are of particular importance:

- Preventive Maintenance, performed at predetermined intervals, on the basis of the number of operations, kilometres run, etc., based on the utilisation of reliability data (MTBF, Rate of Failure, etc.);
- Condition-Based Maintenance (CBM), maintenance performed on the basis of awareness of the effective condition of the system, gained thanks to the activity of Condition Monitoring. Actually, CMB represents a stage of considerable evolution with respect to preventive maintenance tout court, but can logically

be considered as a derivation of preventive maintenance, because it aims, in any case, to anticipate the failure, utilising the data provided by a system of monitoring, instead of reliability data.

CBM in turn is divided into two additional branches: Predictive Maintenance and Proactive Maintenance (capable of providing the necessary feedback to implement Maintenance for Improvement). Finally, the concept of Prognostics lies within the ambit of Maintenance for Improvement.

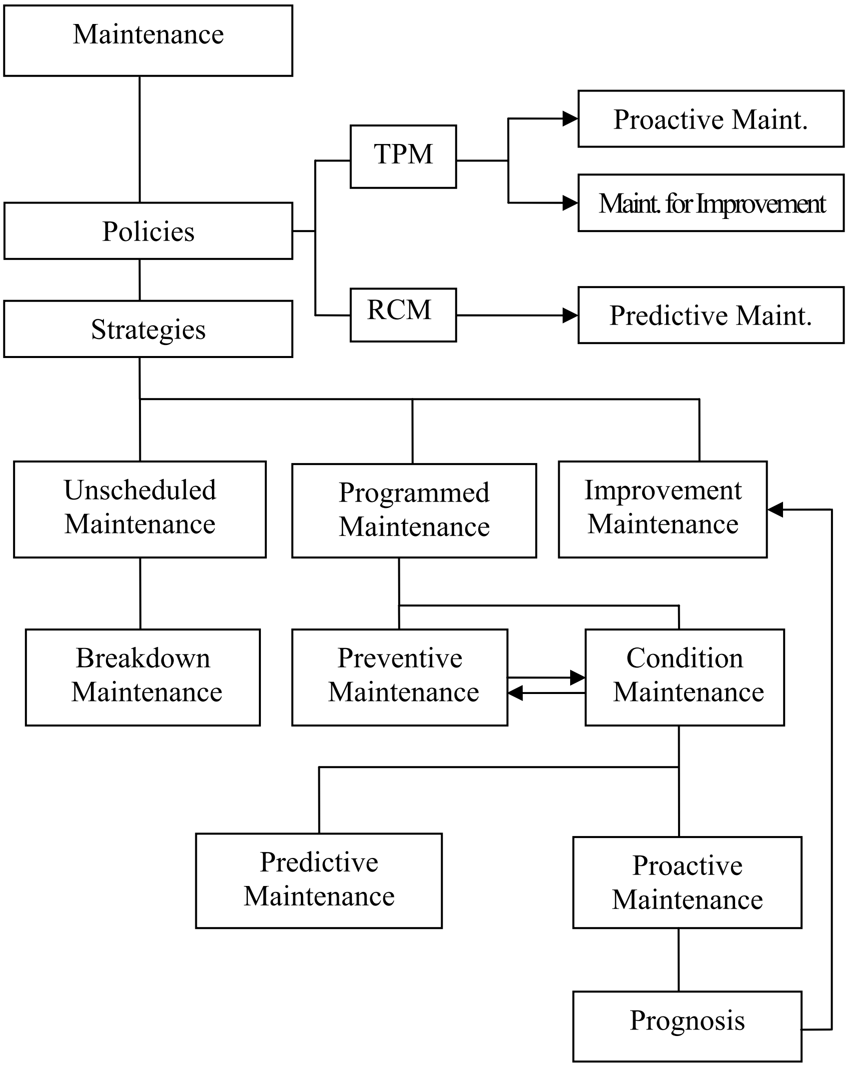

Fig. 4.1 Hierarchic relationships between the various forms of maintenance

4.2 Reliability Centred Maintenance (RCM)

The historical process that led towards the development of reliability themes began in the Forties, due to the operational needs of the Second World War: U.S. military and civilian organisations made an organisational effort, in several phases, which called for the creation of especially structured departments to study reliability, safety, maintenance feasibility and their interrelationships. We begin to speak of "maintenance feasibility" as the characteristic of a system and an engineering discipline at the beginning of the Fifties, with the precise objective of reducing maintenance costs.

No effort had been made until 1960 to perform an in-depth investigation on the efficiency of preventive maintenance, understood as a useful process to prevent breakdowns. Those who dealt with this type of maintenance approach seemed to be so sure of the correctness of their work that they completely failed to verify it, or even to perform a standardisation by way of induction, on the basis of the experience acquired. Around the end of the Fifties, the need to be able to manage fleets of jet aircraft increased the interest of airlines in improvement of efficiency of maintenance in air transportation.

Since it was widely believed that the dependability of a system diminished over a period of time, the first studies examined the relationship between dependability and age, through techniques previously utilised in the field of life insurance. The results of these studies seemed to refute several widespread certainties: in fact, a high number of cases of "infant mortality" were discovered, concerning a representative sample of the various categories of equipment; this appeared to be understandable in the case of electronic devices, but much less so in the case of mechanical systems.

In 1965 several studies made by airline companies showed that programmed replacement of complex systems, on the basis of the criteria of Preventive Maintenance, had no effect on dependability; these considerations led to the definition of a new approach to maintenance, which was developed in 1968. It was determined to apply, for this purpose, a logical tree of decisions, which permitted immediate highlighting of the importance of the impact of reliability on the various operations.

This technique was utilised the same year, when airline company representatives and industrialists constituted the *Maintenance Steering Group* (MSG), whose first act was to draw up a document, the MSG – 1 *Handbook: Maintenance Evaluation and Program Development, which contained the procedures necessary for the development of a Preventive Maintenance programme for the Boeing 747; similar methods were utilised for other aircraft (DC10, L 1011, Concorde and A 300). Successively, it was decided to update some details, making the document in question a useful instrument for the implementation of maintenance programmes for all new-concept aircraft; the result of this effort, published in 1970, is known as MSG – 2, Airline/Manufacturers Maintenance Program Planning Document.*

These methodologies were initially applied to Naval aircraft (P-3°, S-3°, F-4J) and were translated in a series of manuals, which culminated with the NAVAIR 00 – 25 – 400, a document that was utilised to redefine Preventive Maintenance specifications for most US Navy aircraft. Although many of the concepts expressed in the MSG – 2 had revolutionised procedures for the development of maintenance programmes, some aspects were not reported in the NAVAIR 00 – 25 – 400: for example, the procedures to define the frequency of inspections were not transcribed. In order to compensate for this type of shortfall and update the MSG – 2, the DoD requested the same authors of the aforementioned documents to write an overall report on these subjects: this report, *Reliability Centred Maintenance (RCM)* is dated 29 December 1978 and completely illustrates the purposes and procedures of the programme.

RCM was born of the attempt to find answers to questions that had until then been partially ignored:

- What does hardware do?
- What type of functional failures are possible?
- What are the probable consequences?
- What can be done to prevent them?

The approach to preventive maintenance was quite often applied dogmatically, programming revisions at established intervals of time, with no regard for possible comparison with the data derived from previous experience. The objective of RCM was to consolidate the intrinsic reliability of the project, rather than to focus attention directly on each sub-system, asking yourself what type of Preventive Maintenance could be performed; RCM starts from the beginning and is made up of the following phases:

- dividing the product into systems and sub-systems, to be analysed separately;
- identifying the important functional elements;
- determining maintenance requirements for each important element, on the basis of the analysis of its functions and possible failures;
- determining when and how each task must be performed and by who;
- utilising information gleaned from experience and the most suitable analytical techniques to improve the characteristics of each previous phase from one time to the next.

The entire Preventive Maintenance programme is taken into consideration, therefore, independently of the level of resources assigned to fulfil the specifications, evaluating all aspects. All of this requires an integrated and efficient organisational structure, which is completely responsible for the aspects of planning and management of maintenance.

4.3 The Principles and Phases of RCM

RCM is a methodology that aims to define a Preventive Maintenance programme for the entire system and, therefore, it is an error to focus attention on each level of sub-systems without first having understood how that level is interfaced with the remaining hardware, in performing a function whose usefulness is felt by the entire system.

It is a complex analysis, the most important phases of which may be indicated as:

- *Personnel training* The preparation of a maintenance programme based on RCM requires an initial period dedicated to learning the fundamental concepts of this methodology. It is also important for the analyst to have deep knowledge of the project, the operational characteristics and the operational experiences of the system under study; in this sense, it could be useful to have an approach that envisions a form of collaboration with supervisors in possession of the experience required on the manner of failure, so as to permit a good quality of analysis. It is not advisable to use pre-existent documentation concerning the maintenance programme for personnel training: what is required, instead, is an innovative approach, a creative research of the most suitable requirements and what should be done, rather than a re-examination of what has already been done.
- *Collection of information.* Technical information is required for every system and its components: descriptive information (project characteristics, system plans, drawings) and operational information (maintenance instructions, standards of performance, failure data).
- *Identification and division of the system.* One of the first things to do is to identify all of the sub-systems present and perform a logical division of them by drawing up a *System Work Breakdown Structure* (SWBS). This breakdown is performed for the entire system and not for each individual group of the SWBS. When we speak of the system, there are two possible interpretations: we are speaking of the grouping of similar elements or of an organic and functional unit. In general, the latter is the choice that guarantees greater simplicity in analysis, uniting the inputs and the outputs; the first approach could be to place the inputs in a system and the outputs in another. The important thing, in any case, is for the analyst and final technical reviewer to be in agreement on the structure to give the system.
- Analysis of the systems. RCM calls for an analysis of the maintenance requirements of the various sub-systems, which continues to a level that is a function of the complexity of the system and the experience of the analyst.
- *Strategy.* The strategy describes the method to follow when it is realised that we do not have enough information: the idea is that if a final decision cannot be made, it is in any case necessary to opt for the alternative that minimises risks, and then possibly update the entire system when new useful elements are obtained. The operational instrument that permits this procedure is the logical tree

of decisions, in which a series of questions are used (for which a yes or no answer can be given) to characterise the possible functional failures. The answers will allow the analyst to formulate a judgement on the critical nature of each manner of failure and on the possibility of identifying a maintenance requirement that permits effective control.

- *Periodical nature of inspections.* Advanced studies in this sector have shown that there is quite often no inverse correlation between time and Reliability: this does not mean that the individual components are not subject to wear and tear, but that the time frames within which the failures crop up are distributed in a manner that makes a Preventive Maintenance Programmed useless. As we shall see, such an approach may at most lead to an increase in the average rate of failure. In any case, if we opt for a series of revisions at fixed intervals, it is important to choose the frequency with which the maintenance activity is performed very carefully. In fact, the MTBF often does not constitute a meaningful piece of information in this sense, inasmuch as it provides no indications as to how Reliability varies over time, but only on the average age in which a failure occurs. In this light, it appears convenient to adopt an initial interval dictated by experience, hypothesizing a certain function of distribution of failures, and then modify it on the basis of knowledge acquired operationally on the hardware.
- *Cost effectiveness.* The problem of economics in the phase of planning, which is decisive in the commercial sector, is often overestimated in the military field, but the reduction of budgets that has characterised the last decade has brought this aspect forcefully back to the fore. We therefore speak of cost effectiveness, intending precisely the measure of efficiency achieved in utilising the resources to obtain certain results. In practice, it is necessary to evaluate the annual costs of performance of the individual maintenance activities and compare them with the direct annual costs of failures that each activity aims to prevent.

To summarise, RCM is a set of rules, methods and procedures for the economic design and management of maintenance, whose principles aim to rapidly increase and sustain growth in the availability and safety of plants. Substantially, RCM utilises the theory of reliability as its basis, namely, a model of analysis of the causes of failures, which permits maintenance personnel to define plans and procedures to manage intervention.

This is obtained by implementing RCM on three levels:

- stimulating evaluation of the consequences of failures to integrate decisions on safety, economic parameters and maintenance costs;
- developing research on models of behaviour upon failure of the complex systems, to define a new approach in the choice of the most opportune prevention policies, or in identifying alternative activities, in the event preventive maintenance is not applicable;
- combining these activities, in a process that guarantees the production of optimal choices.

4.4 Total Productive Maintenance

Total Productive Maintenance has been defined [Nakajima, 1984]: as "Productive Maintenance performed by all workers of the company, organised in small operational groups".

As with RCM, this is not an actual maintenance policy, but a set of rules and organisational behaviour, intended to achieve quality and efficiency in Maintenance in complex productive environments, where traditional procedures are no longer sufficient for the management of phenomena and it is necessary to involve and muster all company structures to achieve excellence.

In other words, “it is a global approach to factory problems, with a view to improving the performance of productive plants and equipment, which takes into account the Japanese matrix and applied experiences in industry”. Namely, the importance has been acknowledged of bringing some of the most important factors that determine success, on the operational level, under the sole responsibility of the person who coordinates a segment of production: primarily, on-line maintenance and quality control.

A new role has therefore emerged on the organisational level of the maintenance function, a role of service of qualified production, which tends towards continuous improvement of production efficiency and effectiveness. In a similar context, the party responsible for a plant can no longer say, “it’s the fault of maintenance”, because he is the one who decides upon the orientation and choices that determine the availability of the plant. This close functional relationship of maintenance with production requirements, together with a strong orientation towards continuous improvement and prevention through monitoring, are embodied in the concept of TPM.

“In this context, TPM recognises the existence, within the same company, of different maintenance situations, which may require different techniques to achieve an appropriate result: consequently, it uses different methodologies, which may differ from plant to plant or from machine to machine, providing they are demonstrated to be cost effective in a given situation. Many of the strategies utilised are definitely not new: what is innovative is the Japanese culture, the use of this culture calls for all employees to be involved and the use of small activity groups.

The most important contribution of TPM with respect to the theory of maintenance is the attempt to abate the artificial barrier or line of demarcation, if you will, which exists in a company, between maintenance and production departments. The implementation of TPM makes it necessary, in other words, to definitively abandon the mentality according to which “you break it, I fix it”, with the consequential increased efficiency in productivity.

A complete definition of TPM therefore includes [Nakajima, 1984]:

- the attempt to maximise the efficiency of productive plants and equipment in terms of economic efficiency and profitability;

- the concrete formation of a complex system of productive maintenance, which includes preventive maintenance and continuous improvement of maintenance feasibility for the entire life cycle of each component;
- the involvement of all company employees, from top management down, in the implementation of productive maintenance;
- the promotion of maintenance through small activity groups.

Productive maintenance involves widespread professional ability, which is oriented towards prevention, operation of the productive system and rapid absorption of down time. This is obtained by reorganising the responsibilities for management of the productive system in the field, not only concerning the traditional activities for which the production operator is responsible, but also responsibility for maintenance activities and the quality of the product.

Optimisation of the company maintenance policy should be pursued within the framework of improvement of company profitability and the service distributed and, in particular, the continuous improvement of the operational result. This continuous improvement is the expression of a close synergy between maintenance and production, which takes concrete form in productive maintenance.

4.5 Maintenance Strategies

Starting from an entirely general consideration, it can be asserted that the purpose of maintenance activity is to obtain a certain degree of continuity in the productive process; this objective, in the past, was pursued through operational and functional redundancy, by guaranteeing a calculated excess of productive capacity or, finally, by applying an aggressive programme of revision and replacement of critical systems.

All of these approaches have been demonstrated to be partially inefficient: redundant systems and excess capabilities immobilise capital that could be more profitably used for productive activities, while carrying forward a policy of excessively prudent revisions has been shown to be a rather costly method to obtain the standards required. So maintenance has been transformed, in terms of its mission, from a prevalently operational activity of repair to a complex management system, oriented more than anything else towards the prevention of failures. This is not an easy passage, as it implies a considerable cultural change in management in general and maintenance in particular.

4.5.1 Breakdown Maintenance

Breakdown Maintenance is definitely the oldest, most spontaneous and simplest manner of intervention, which envisions repair of the failure as the occasion upon which the professional competence of the maintenance personnel is fully asserted. This, in turn, is understood as promptness in organisational response and as the availability and ability of the operators.

It has already been seen how it is necessary to resort to this type of rather drastic approach in the case of sudden or catastrophic breakdowns, namely under conditions that a good maintenance activity should prevent a priori. It is based on the idea according to which, in the presence of non-critical systems that are easy to replace at low cost, it is convenient to wait for the failure to occur before intervening. It may occur, in effect, that the reduction of down time and the increase in availability is not such as to warrant the greater burdens that a more sophisticated strategy of intervention would entail.

It is therefore necessary to identify the component that has broken down (a task realised immediately by an expert maintenance technician) and take all the measures necessary to re-establish the operational integrity of the system.

Unfortunately this strategy has many aspects that are subject to discussion:

- machine down time occurs in a casual manner and often at the most inopportune time;
- the serious and unexpected failure of a component could have detrimental consequences on other elements of the system, compromising functional efficiency and provoking a consistent increase in costs;
- unprogrammed repairs often require longer time (to obtain spare parts, assign the right technician, etc.), hindering production and occupying technical personnel in an unprofitable manner.

4.5.2 Preventive Maintenance

All intervention performed on the basis of the conviction that the average life of some components can be determined and that it is possible to anticipate the failure of a complex system (machine or production line), defining in advance the time of intervention, generally consisting in replacement, as a function of the expected life cycle of the component, falls within the definition of the term *Preventive Maintenance*. This concept had great success in the Sixties and Seventies, because it responded to a need that was felt by maintenance personnel, to provide a "scientific" basis and to make their intervention programmable. This undoubtedly favoured cultural and organisational growth of the maintenance function, which had to equip itself with the first programming instruments. It didn’t take long, however, to realise that this generalise practice leavened costs in terms of the use of human resources and technical materials, without substantially affecting the availability of plants.

It is a form of maintenance that is just one step above the former one, because in this case the mechanical system still functions, but its performance has deteriorated to the point of determining an imminent failure, suggesting the performance of inspections, revisions and similar activities, which can be divided into three classes (Fitch, 1992):

- normal maintenance of correctly operating sub-systems and mechanisms that require some maintenance, through lubrication, cleaning, adjustment, changes, etc;
- trouble-shooting to find redundant components that have broken down and possible repair or replacement;
- revision or replacement of worn components.

There are two possible philosophies to follow to implement an activity of failure avoidance:

- depending upon the condition of the component: this is an attitude that reflects the strategy of "if it works, don't touch it", and promotes maintenance only when it is necessary to avoid the blockage of considerable capital to guarantee the spare parts necessary to cover every probability;
- according to a programme: maintenance performed at constant intervals (time-based maintenance), on established calendar dates (hard time maintenance) or on the basis of parameters of utilisation of the machinery (hours of operation or kilometres operated), to ensure the system retains a sufficient level of dependability, safety and performance.

The latter is precisely the approach followed by Preventive Maintenance, because at first sight, it would seem that replacing a machine according to an established programme, independently of being aware of the actual condition of the machinery, is the best way to prevent the costly consequences of a failure. If the analysis goes a bit deeper, however, the defects of this maintenance methodology are clear.[1].

Most mechanical systems present a development of the failure rate that determines the well known "*bathtub curve*", in which three regions can usually be distinguished: breakdown and infant mortality, causal breakdown and breakdown due to wear and tear, as shown in Figure 4.2.

Fig. 4.2 Bathtub curve

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[1] One out of three dollars spent for Preventive Maintenance is lost" (Forbes Magazine). "60% of the hydraulic pumps replaced had nothing wrong with them" (Hydraulics and Pneumatics Magazine).

In the first region there are new or newly refurbished systems (in the hypothesis of “non-memory”, which considers the system “like new” once it has been subjected to maintenance); in this phase, the probability of failure is rather high due to the presence of possible design or planning errors and due to the variables associated with production, assembly and installation of a new piece of equipment. Once the system has passed this critical period, it enters a phase (typical of electronic apparatus) characterised by a constant failure rate; at a certain point every mechanical system begins to feel the effects of wear and tear and enters the last phase, which has a growing rate of failure. If the machine is replaced on the basis of the preventive maintenance programme, it is removed from the casual failure area, where the rate of breakdown is minimal (compare figure 4.3), and taken back to the area of infant mortality, namely precisely where λ reaches the maximum value.

It can therefore be concluded that the maintenance programme of a mechanical system that follows the model of the bathtub curve leads to an increase in the overall probability of failure: this is therefore an extremely costly activity, which ends up lowering the reliability of the system and creates a conflict with the objective pursued by the company of increasing the average time between successive downtimes of the plant.

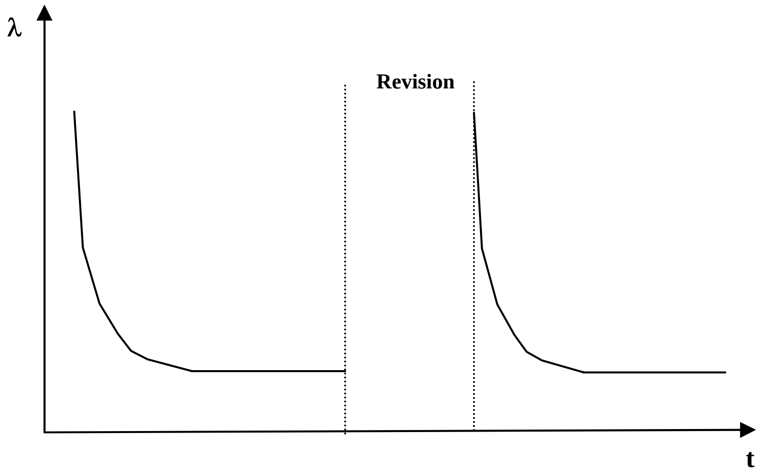

Fig. 4.3 The effect of Preventive maintenance on the curve of failure rate

4.5.3 Predictive Maintenance

A more modern vision of maintenance problems led to the use of non-destructive techniques to test systems and apparatus in order to identify, with consistent lead-time, the presence of failures, and programme a revision only when the condition of the machine determined the need. This approach is known as Predictive Maintenance, and has many advantages: it is an on – condition form of maintenance, which calls for real time programming of maintenance intervention, as a function of the machine condition and requirements to be respected, permitting the avoidance of unforeseen downtime or catastrophic chain reactions and improving the global reliability of the system at reduced costs.

It is a type of maintenance that aims to predict and identify incipient breakdowns, without altering the cycle of failure nor extending the MTBF value of the system, but punctually informing the maintenance personnel on the presence of problems that require programming of appropriate corrective action. From this point of view, this type of maintenance can be considered "reactive" maintenance. The initial assumption is that only rarely does a component actually break down suddenly; in the majority of cases (especially for mechanical, hydraulic and pneumatic systems) the failure constitutes the point of arrival of progressive deterioration.

Maintenance according to condition is defined on the basis of parameters, which permit understanding what the effective condition of the machine is, which are detected through a series of measures, visual inspections, non-destructive controls, operational or functional tests, without generally having to disassemble the components of the mechanical system. These actions, performed at regular defined intervals for each characteristic, permit the user to detect when the performance of a component starts to deteriorate and, on the basis of this information, to decide whether to perform intervention to make repairs or replace the component prior to the occurrence of a failure.

This maintenance practice is based upon the following techniques:

- *Visual monitoring:* in search of possible signs of fatigue, welding defects, misalignment, etc.;
- *Monitoring of correspondence to specifications:* verification of pressure, flow, temperature and speed take on values near the design values;
- *Monitoring of vibrations and noise;*
- *Monitoring of debris from use;*

This maintenance strategy does not use probability methods to perform a prognosis of failures, but uses the trend of parameters monitored to predict potential breakdowns. Maintenance according to the condition of the plant should therefore be understood as a diagnostic process, which provides indications on the state of health of the machinery, permitting the planning of intervention for revision, based on the actual condition of the components, rather than on the operating time.

This is a maintenance philosophy that has undoubted economic and operational advantages and also important implications for planning: in fact, in order to reduce passive times due to frequent inspections to a minimum, it is opportune for the mechanical system to be equipped with a whole series of accesses, necessary to determine the state of efficiency of the components. Identification of the parts to revise, identification of the meaningful parameters and definition of the frequency of inspections are all activities that must be developed, if possible, in parallel with advancement of the project.

The benefits that can be obtained are not only economic: the success of Condition-Based Maintenance (CBM) not only prevents breakdown and downtime of the machine, but also assists in increasing the safety of the plants and employees, and ensuring that the plant is effectively used, plus a series of other advantages of no small import, which are summarised in Table 4.1.

Table 4.1 Benefits of CBM

Benefits of CBM	How the benefits are produced
SAFETY	CBM response time permits machine downtime prior to reaching critical condition
Increased availability of the plant, lower maintenance costs	Intervals between two successive revisions may be increased Downtime may be reduced as resources are procured in advance
Greater plant efficiency and improved quality	Machine operating condition may vary to obtain a compromise between what must be produced and the condition of the machine
Greater possibilities to negotiate with producers	Since conditions are measured when the machine is new, it is possible to have data for comparison at the end of the period of guarantee and after revision
Improved customer relations	Advance awareness of imminent failure permits improved organisation of production
Opportunity to improve the design of future plants	Opportunely collected experience in historical files may serve this purpose
Increased satisfaction in work	The maintenance manager is capable of better planning the work of personnel in his service

4.5.4 Proactive Maintenance

The limit of Predictive Maintenance can be identified in its “failure-oriented” nature; it is more effective with respect to traditional approaches, but leaves ample space for improvement in terms of reliability and reduction of costs. This strategy has the purpose of providing the operator with an alert signal, with sufficient lead-time to permit him to programme the necessary repairs, thereby minimising downtime. This naturally depends on the monitoring programme and on the time necessary to obtain the results of the analyses; if deeper analyses are indispensable in the presence of controversial data, the incipient failure may worsen the condition of the machinery in the meantime and become quite a bit more worrisome. True benefits can be gained, on the other hand, through another type of "on condition" maintenance: Proactive or productive maintenance, where the term "proactive" is the opposite of "reactive", in the sense that it refers to actions performed prior to the occurrence of a critical event.

This is an activity of pre-alert, which is realised in expectation of any damage relative to the material or performance of the system, namely a series of actions aimed at correcting conditions that could lead to deterioration of the machine. Instead of analysing the alteration of the material or performance to evaluate the entity of the condition of incipient or imminent failure, Proactive Maintenance proposes to identify and correct the abnormal values of the primary causes of breakdown, which could lead to conditions of operational instability. The latter are the "root causes of the breakdown" and signal the initial level of malfunction, which was previously called "conditional failure". For example, the ball bearings of electric motors are often indicated as the true "cause" of failures, while, in effect, the actual cause is the dispersion of current across the rotating shaft which, by generating an electric arch, ends up provoking breakage of the bearing guides: in this case the primary cause of the breakdown are the parasite currents and not the defective bearings!

This maintenance practice constitutes the first line of defence against deterioration of the material (incipient failure) and the consequent weakening of performance (imminent failure) which inevitably leads to *breakdown*; it therefore succeeds in affecting the values of Failure Rates and MTBF of the system (figure 4.4), not to mention that intervening with such marked lead time allows the avoidance of both the functional deterioration preceding the *breakdown* and the occurrence of many secondary failures that could take place on the elements adjacent to the one incriminated (for example, the cause of vibrations induced by the latter).

In the initial phase the operator is required to perform an activity of monitoring of key parameters, which allows him to evaluate the critical nature and primary cause of the failure: if a condition of instability is identified, this means that there is a conditional failure; a phase of correction of the critical factors identified then follows.

All of this requires familiarity with the mechanical system under study by the maintenance personnel, who must possess a deep understanding of the operational principles and characteristics of the machine in order to correctly identify the roots of the failure.

In short, it can be asserted that Proactive Maintenance requires the following actions (Fitch, 1992):

- monitoring of key indicative parameters of machine health (namely, the operational conditions relative to primary causes of failure), for example, the level of contamination of lubricating fluid;

- definition of threshold values – namely, the maximum acceptable values for every parameter, for example the maximum level of contamination or the maximum temperature;
- recognition and interpretation of any abnormal values of these key parameters, which indicate a certain instability in the operational conditions of the machine, for example the level of contamination above the threshold limit;
- specification of the means and methods to apply to correct the primary causes of failure and restore the system to stability, for example to improve the filtering system and procedures of oil change.

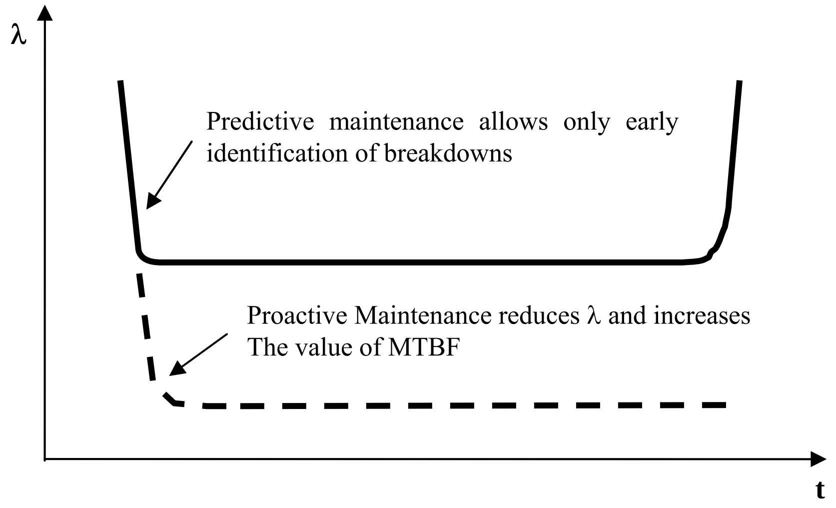

Fig. 4.4 Effect on λ of Proactive Maintenance

4.6 The Choice of the Most Opportune Strategy

The implementation of a company maintenance strategy requires maintenance planning criteria based on the logic of reducing the global cost (own and induced costs). This logic presides over all maintenance actions during the life cycle of the property and in respect of legislative limits within the ambit of safety and environment.

In order to get an idea of the spread of some maintenance strategies in Italy, it should be noted that currently, repair maintenance is still quite widespread and accounts for approximately 50% of the resources. The prevention of the statistical – opportunistic type accounts for around 20-30% of the resources, while the rest is conditional maintenance.

The latter, in its various forms, is in any case the strategy towards which all processing and manufacturing companies are striving.

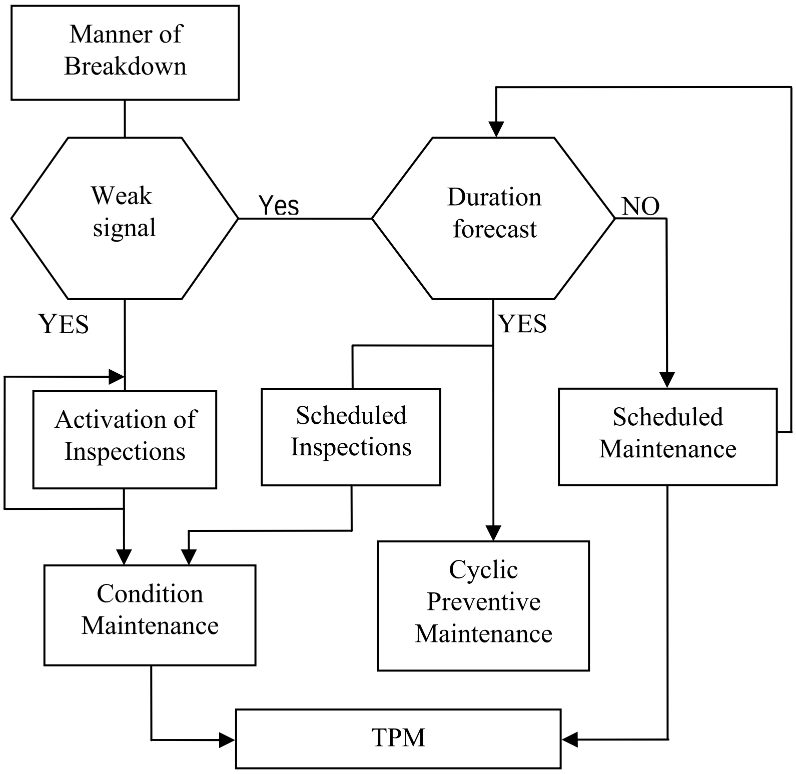

Fig. 4.5 Logic for definition of maintenance strategies

The scheme proposed (Figure 4.5) briefly summarises the logic upon which the choice of maintenance policies is based.

If we examine the first block, which identifies a precise manner of failure of a specific component; the question is posed alongside: “Is there a weak signal?” - in other words, does the progression of the failure show “signals” that are perceivable or measurable? If so, once the feasibility of control has been verified, monitoring is activated of the weak signal to understand the progression in time and perform the maintenance intervention at the most opportune time, realising the typical situation of maintenance according to condition. If the weak signal exists but cannot be monitored, a different question is asked: “Is there an estimate of the durability of the component?” If so, there are two possibilities:

- activate programmed inspections with instruments, according to the feasibility of inspection of the component, returning to maintenance according to condition;
- perform replacement in preset time frames, realising cyclic preventive maintenance.

Finally, when there is no signal that can be monitored and no estimate of the life of the component, only repair maintenance can be activated. Concerning the behaviour of the machine, there is an optimal mix of these policies, which constitute the basis of productive maintenance.

The choice of the various maintenance strategies is determined by the level of criticality of the property in the productive cycle of the company and also by the economic evaluation of the possible choices, while the principles of safety of persons and the environment remain valid. In this sense, it is extremely useful to employ methodologies such as analysis of cost effectiveness or analysis of costs and benefits. These methods presuppose the evaluation of the global cost of maintenance, which expresses both the cost that the company must sustain to perform a certain maintenance policy (own cost of maintenance) and a whole series of costs induced by the failure. The own cost of simple repair maintenance is expressed by: labour, materials and spare parts, equipment, general structure costs.

The following costs must be added to these:

- for cyclic preventive maintenance, the costs of preparation and programming work;
- for maintenance according to condition, the cost of preparation and programming, the costs of controls and inspections and costs relative to the instruments for monitoring of the property.

The costs induced by the type of policy of intervention are fixed costs for spare parts on hand (stock valued by rate of possession) which will be higher in proportion to the lower level of programming of work. The costs induced by the failure are:

- the cost of unavailability of the property and consequent interruption in production;
- the cost of fixed assets of stock of finished products or non-specific production, to deal with the variability of production due to the low level of reliability of the plants;
- the cost consequent to the disservice caused by the interruption in service.

To avoid confusion, it should be said that in every industrial reality, various maintenance strategies coexist, each of which is integrated with the others, without cancelling them and absorbing a percentage of the available resources: it is therefore possible to apply a mix of maintenance strategies, which, as a whole, constitutes the company policy. The choice must be made on the basis of the criticality of the components, an economic evaluation of the alternatives and any recommendations by the supplier.

It is therefore possible to outline a more complete scheme than the previous one, which takes into account the considerations reported above, as a model of decision making logic for a correct selection of the company maintenance policy (Figure 4.6).

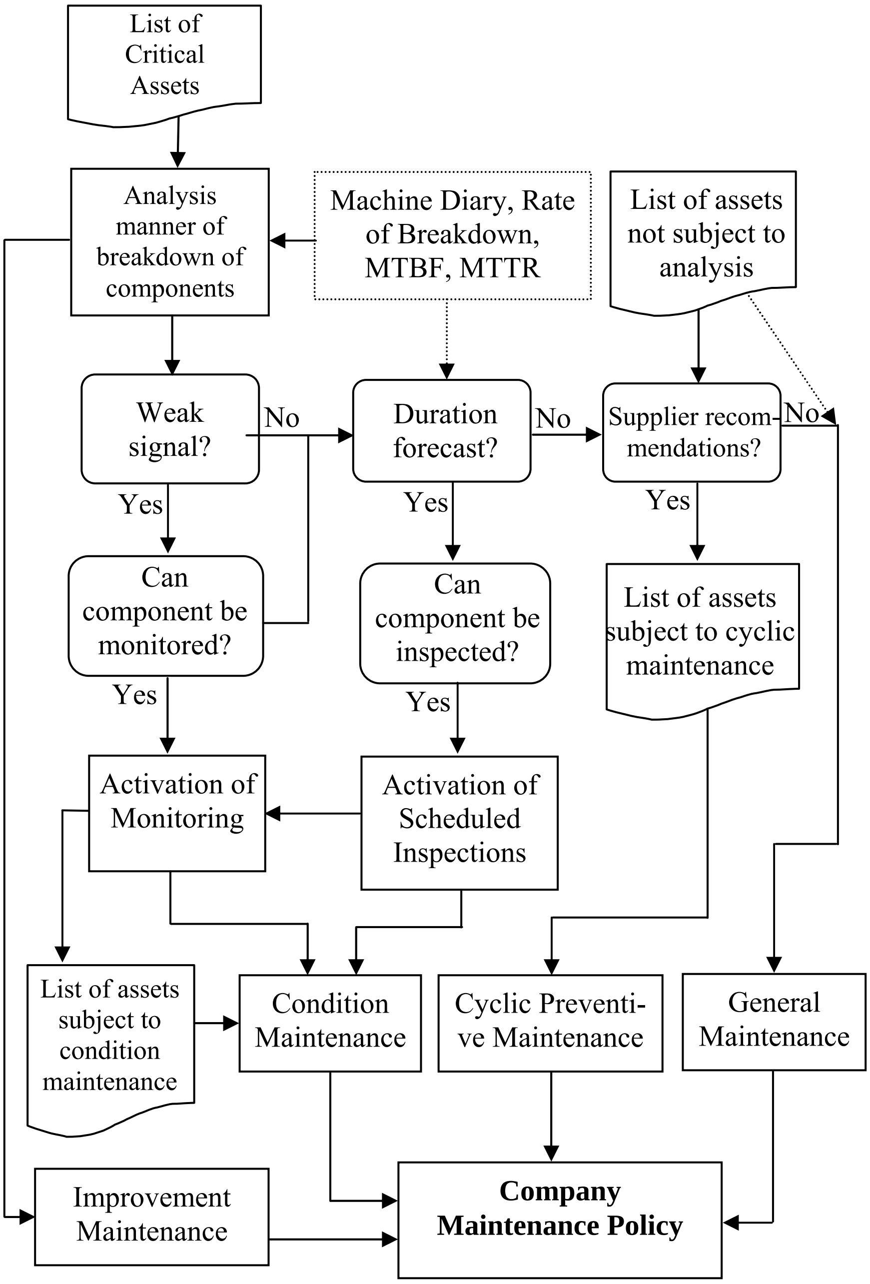

Fig. 4.6 Flow chart for definition of company maintenance policy

4.6 The Maintenance System

The company maintenance system may be divided into four fundamental subsystems:

- Management;
- Programming
- Performance;
- Engineering.

4.6.1 Maintenance management

The subsystem of management aims to achieve the technical and economic optimisation of management. It is a function that appears as such in maintenance structures of considerable size. It works as the staff of the maintenance chief and, synthetically stated, proposes to coordinate the following activities:

- forecast and control of management;
- preparation of forecast data and control of final values;
- quantification of work orders issued by other functions to implement proper preparation, taking into account operational limits;
- provide monthly reports to superior functions (data, graphs, tables, trends, etc), with the aid of information technology systems, on the progress of management of the maintenance service.

Good management should first of all be able to define the procedures and identify the costs that make up maintenance in the components of labour, materials and performance of third parties and their relative weight. The budget and control of this forecast must be provided with procedures and followed by all functions involved – namely, not only by Maintenance; these will take on different characteristics and forms according to the dimensions of the company and the individual facilities. Maintenance costs are no small share of a company’s turnover, even if their incidence per unit of product may vary according to the reference industrial reality. It is therefore easy to understand how strategically important it is to succeed in managing the costs and benefits of maintenance in a balanced and efficient manner.

Formulation of the Maintenance Budget is a highly qualifying moment for a company, where the forecasts made over a period of time, on the basis of concrete data, are set forth.

This document must possess features that cannot be foregone:

- it must be an appropriate instrument of operational, management and administrative control with which to formulate and pursue objectives;
- it must reflect the effective need for the services requested, over time, by users;

- drawing up of the budget and the relative control must be integrated in the process of Maintenance Management.

Management control, utilisation of Analytical (or Industrial) Accounting to specifically take into account every activity, in the attempt to bring to light a whole series of induced costs, which are therefore less immediately detectable, due to maintenance shortfalls. The purpose is to quantify Maintenance expenses, analyse them, eliminate useless costs, evaluate any more advantageous solutions together with technicians and control the results in economic terms at set dates. Obviously, this is not a question of wishing to achieve an unconditional reduction in the budget for expenditures, because the costs induced due to maintenance shortfalls as a result of such a strategy would definitely be greater than the pure cost of intervention.

Typical induced costs are due to:

- under utilisation of plants blocked due to breakdown, often characterised by extremely important investments on which it is necessary to obtain rapid returns;
- poor quality of productive processing, with the consequent increase in discards;
- loss of image with customers due to failure to respect delivery times;
- drops in productivity due to the interruption of the productive cycle.

In the phase of estimation, Maintenance costs are made up exclusively of the elementary components, such as:

- work performed by internal shops;
- outsourced services;
- materials (taken from the warehouse and charged to Maintenance at the time of use);
- services performed by third party specialists (technicians and/or consultants employed through assistance contracts on a time by time basis).

In order to foresee and control the total expenses imputable to maintenance appropriately, it is indispensable to divide the total volume of maintenance (made up of labour, materials and means) grouping the individual categories of expenditure.

- Operational assistance (works due not to behaviour of the machinery, but as a requirement of the productive cycle);
- conservative maintenance (works that do not fall into the previous category, but which are necessary to restore correct operation of the equipment);
- maintenance modifications (works to improve the operating conditions of the equipment, independently of the need to restore them to efficiency);
- construction of spare parts;
- fixed assets (non-Maintenance work performed at least in part by the Maintenance service).

For this purpose, it may be useful to divide accounting into cost centres: a “maintenance cost centre” is defined as an independent and homogeneous unit of specialisation (electric, hydraulic, mechanical) that absorbs all of its relative costs, against the parameter taken as a reference (for example maintenance labour), representative of a certain activity, in proportion to the time the centre has dedicated to the machinery to be repaired. In a structure of considerable dimensions, therefore, there are as many cost centres as there are detached maintenance sections.

The purpose of the Maintenance management system, however, must not be only aspects related strictly to the economics of maintenance, but also all of the information and data relative to each codifiable object for the duration of its life cycle. In other words, orderly archives must be obtained of the technical documentation available, in order to guarantee maintenance personnel have the possibility to be aware of the “maintenance history” of the machine, including data relative to reliability and maintenance feasibility, of intervention performed and resources used. It will also be opportune to establish procedures to permit technicians to create actual case jobs to record, collecting all the historical and statistical data necessary.

The first step is to draw up a work request on the basis of which the most important maintenance document is drawn up: the work order, which permits definition in writing of the detailed instructions necessary for performance of a job, together with the forecasts formulated through study of the workload and short-term programming. Finally, the procedure continues with delivery of the work to production, followed by periodical reports decided upon by the personnel during annual operation, essentially made up of the data supplied by the information system or collected manually (impressions, suggestions, etc.) to attach to the machine card.

4.6.2 Programming of Maintenance

The most important principles of this subsystem are:

- re-examination of work requests in order to identify the exact purpose, complete them with reference data necessary and with dates, and transforming of the work requests into work orders, providing comments and explanatory notes and verifying the availability of material;
- to define, together with the inspection department, the quality of all spare parts and materials and their optimum quantity;
- planning and programming maintenance work and plant downtime, ensuring the optimum use of available resources;
- updating procedures and sequences for preventive maintenance;
- promoting actions to ensure awareness of safety, enhancing the sensibility of personnel on this subject.

The Technical Office is responsible for this subsystem and performance of the following duties:

- applying norms, codes and standards in an unequivocal manner;

- studying plants and estimating costs of new works of modification;
- preparing the executive technical documentation (drawings, specifications, etc.) to permit the operational divisions to perform the works rapidly and in conditions of safety.

4.6.3 Performance of Maintenance

The subsystem of performance of maintenance is related to the objective of performance of the works. The activities in this subsystem are:

- maintenance and development of personnel motivation;
- optimisation of executive efficiency;
- quality control of performance to guarantee the required reliability.

The last point is supervised by a particular function, which is the function of inspection, whose main duties can be summarised as follows:

- to verify that plants and equipment are in good repair, through a clear programme of inspections, simultaneously investigating the cause of breakdowns and the requirements relative to repairs;
- promoting maintenance intervention;
- inspecting and testing plants and equipment prior to acceptance from suppliers;
- collecting all the necessary data for preparation of the maintenance budget according to condition.

Finally, the subsystem of performance refers to the shop area; among the most important objectives are:

- performance of all maintenance works;
- coordination of personnel of external companies,
- guaranteeing the best performance of work from the technical and organisational points of view;
- collaborating with staff functions to study technical problems, proposing possible solutions;
- drawing up the annual shop budget.

4.6.4 Maintenance Engineering

The subsystem of Maintenance Engineering has the objective of research and improvement. It therefore includes the activities of:

- improvement of design;
- improvement of operating plant availability;

- improvement and adjustment of instruments and procedures of the management system, guaranteeing continuous adaptation to new socio-economic realities;
- improvement of techniques of intervention;
- improvement of human resources, through the development of specific training and education plans;
- definition of a programme of studies, with objectives agreed upon between production and maintenance;
- examination of the procedures of performance of intervention and study to achieve technical and methodological improvement.

The three subsystems cited above make up the backbone of the Maintenance System; the organisational structure will therefore be built around them. The articulation and ramification that these subsystems assume in the various company realities is another matter. Various factors come into play here: the weight the company attributes to individual objectives, the dimensions of the factory, the problems of parcelling and polyvalence, internal and external resources, etc.

Progress is therefore made from a primitive organisational structure, in which the three subsystems will be substantially embodied in one (systems with less than 30 employees) to sophisticated structures in which only the three subsystems are well identified, but each of them will be ramified into various functions with objectives or even *business*es that are different and coexistent (such is the case of large integrated companies).

4.7 The Movement of Maintenance Management towards the Services Economy

In recent years, the connotations of the offer of companies working within the ambit of the services sector, in relation to resources given over to them for their operational ability and competitiveness, have modified. The search for technical and organisational solutions capable of ensuring the following features are becoming increasingly important:

- structural flexibility;
- high professionalism of the company;
- innovation of processes and services, performed in respect of containment of costs and satisfaction of the needs of service users.

This trend has led to the definition of management techniques that take the name of outsourcing (entrusting services to external companies), aimed at efficient reorganisation of activities of management, to satisfy requirements for managerial innovation (often connected with the achievement of positions in the marketplace), in the declared attempt to achieve advantages of an economic nature.

The market orientation is present in various types of externalised services, performed to implement specific strategies of external integration. The most meaningful are:

- subcontracting;
- the constitution of ad hoc companies;
- outsourcing.

4.7.1 Subcontracting

Subcontracting consists of a "contractual relationship according to which the purchaser entrusts to a sub-supplier the total or partial realisation of a part or component, which constitutes one or more phases of his productive process in a general sense and which will then be input once again to complete the product". On the basis of this contractual relationship, therefore, the buyer identifies a service he cannot perform at a lower cost and which he deems more convenient to purchase externally; successively the parties define the characteristics that the service must possess at a given price.

Substantially, subcontracting rests on the normal process of negotiation, for which the mechanism of regulation of these exchanges can only be the market price of the component of service subject to the transaction.

4.7.2 The Establishment of External Companies

The second manner of externalisation is the founding of external business units with juridical autonomy, which provide services to the founding company under a preferential contract.

This services company may, according to needs, operate exclusively for the parent company, or (as it often happens) on the free market, being able to utilise the external know-how and excess productive capacity with respect to the reference customer's requirements.

This process of externalisation from a parent company, which capitalises on previous internal staff experience, aims to achieve:

- scale economies;
- experience effect;
- improved operational efficiency.

These factors, in the last analysis, translate into lower costs for distribution of the service and therefore in acquiring a competitive advantage that can be defended in the sector.

The benefits that can be achieved from this operation are connected with the possibility to purchase services in appropriate quantity and quality for the parent company and with a lower need for capital outlay, as a consequence of the process of disinvestment.

4.7.3 Outsourcing

The object of this model is the alienation not of individual services, but of entire areas of activity, creating a relationship of partnership between the alienating company and the existing enterprise on the market, as a specialist. The company thus seeks a partner with whom to initiate joint investments, planning and production of services, in order to acquire advantages, not only on the level of containing costs, but also in terms of continuous improvement of the outsourced services.

This is a veritable relationship of cooperation and close interaction between the outsourcer, the external unit that distributes the services, and the outsourcee, or the purchaser of the services subject to the transactions; in fact, although on one hand the customer recognises the professional superiority of the supplier, on the other he must benefit from the fact of collaborating with a company the does business successfully on the market and possesses a strategic vision of outsourcing. This requires the employment of mechanisms of regulation, which partially substitute and partially integrate those traditionally in use in market and hierarchical relationships (price, programmed plans, budgets, etc.).

The competitive advantages are closely tied to the occurrence of the following conditions, which are typical of *outsourcing* processes:

- persons with routine duties and unimportant activities from the strategic point of view are freed, creating the conditions to enable the management and company resources to be concentrated on activities that are instrumental to developing and enhancing the company's core competencies;
- alliances are made to acquire externally the competence of high-level professional specialists with a high level of technological innovation, thereby guaranteeing over a period of time the improved performance of the possible services.

Let us briefly examine the principle aspect to take into account in the phase of starting up a relationship of *outsourcing*:

- *Decide what activity to be alienated.* The company management identifies the architecture of the activities, analysing the competence that the company possesses, distinguishing between basic and support activities: the former contribute significantly to the advantages that the customer identifies in the product or service and which are difficult to imitate; the second, on the contrary, have no impact on the value created by the company and serve only as a support to the development and consolidation of the basic competencies. Among the support activities, the ones to be subject to externalisation must be identified.

- *Identification of the partner.* The choice of the partner is made by jointly evaluating:
  - his financial solvency;
  - his technical – organisational ability.
- *Establish the contractual aspects.* This entails defining the formal mechanism of regulation of the relations of exchange between the parties.
- *Analysing the advantages and risks relative to the choice of outsourcing.* The primary risks one is exposed to in *outsourcing* are:
  - difficulties between the parties in building a sufficiently solid relationship of trust;
  - problems of identity of the role of those who work in positions of responsibility in the areas subject to outsourcing;
  - difficulties relative to norms concerning labour and union rights relative to transmigration, when the contract between the parties envisions it, of outsourcee personnel moving to the organisation of the outsourcer;
  - the high degree of irreversibility of the process.

4.8 Facility Management

Facility Management (FM) is a recent market for Europe. In fact, this market developed in the Fifties in the United States and landed in the United Kingdom in the Eighties, from where it spread to northern Europe, promoting the formation of new companies and professional figures. The activity of Facility Management, according to the definition coined in the Anglo-Saxon world, is “the practice of coordinating the organisation of persons and activities in a specific physical location (*facility*)”, or, in other terms, it can be defined as “a strategy of company and asset management (industrial and non-industrial) which deals with all service activities that do not have an institutional nature, for a property, organisation or company, as it may be, and which do not fall within the *core business* (namely, the main content of the entrepreneurial activity)”. Namely, this deals with a discipline that is concerned with the optimisation of the management of maintenance services and the so-called “general” services of support to the main activities of an organisation, which may be performed either internally or externally to the company itself. At this time we are interested in analysing the aspects concerning the integration of the various services and entrusting them to external sources in *outsourcing*, with the relative advantages.

At the base of the great success that this practice is experiencing in Europe is the principle of efficiency and cost reduction. Facilities services – according to the experience gained by the Centre of Facility Management of Glasgow – annually affect the balance sheets of companies to an extent between 18% and 29% of the overall costs and are normally managed in a non-specialised manner by organisational structures within companies.

In the countries where the culture of FM has developed most, a “specialised” approach to the management of support services has permitted savings on the order of 20% - 35% on costs relative to the management of *facilities*, or 4% - 10% on total company costs, creating a decided improvement in the level of quality of the services distributed.

4.9 The Global Service of Maintenance

The search for new organisational solutions, capable of realising a form of maintenance that offers a good level of service quality, together with economic advantages, clashes with evidently contrasting requirements, which find a viable road, however, in the movement towards the tertiary economy and of maintenance activities performed according to the Global Maintenance Service formula. This is a multidisciplinary maintenance services contract, in which the distributor is called upon to plan, manage and distribute the activities of maintenance with full responsibility for achievement of the commonly agreed upon objectives between the parties and within a clearly measurable timeframe. This may also include a plurality of services in substitution of normal maintenance actions, such as planning, management and performance of Maintenance with the supply of structures, operational resources, materials and all necessary elements to preserve the patrimony and make it available.

In exchange, the internal organisation must be reorganised for the correct management of the relations with a services provider who is, at the same time, a partner of the company: The tertiary economy requires innumerable elements of management and technical knowledge, with reference to the company and the territory surrounding the factory. This makes it necessary to have a permanent internal structure of maintenance engineering, charged with:

- evaluating adherence of the service to supply specifications;
- measuring the level of quality of the service;
- performing Audits on the correct maintenance of the company patrimony.

This evolutionary development is born of the need of the companies to be freed from the incumbencies that are not strictly related to operation of the plants, attempting, moreover, to reduce fixed costs of the maintenance service, to the advantage of variable ones. The phases to overcome in arriving at this approach are:

- *Strategic feasibility:* this analysis permits the purchaser to decide which activities to maintain inside the company, inasmuch as they determine a competitive advantage and a distinctive competency on the market;
- *Technical-organisational feasibility:* the technical feasibility of the activity that may be managed in outsourcing must be evaluated, along with their impact on

the process of maintenance, favouring, in the choice of the supplier, the aspects of technical competence and economic advantage;
- *Distribution of the service:* this phase is characterised, with respect to internal maintenance, by a system of relationships and relations, even formal relations such as reporting, work requests, total activity performed, auditing of maintenance of the patrimony.

The advantages that can be obtained by correct implementation of this approach are typically the result of the following factors:

- the unique nature of the objectives between the purchaser and contractor;
- the acceptance of global responsibility by the company;
- the reduction of fixed company costs following downsizing of its structure (manpower) and of warehouse stock (materials);
- the net distinction between the roles of enterprise and purchaser;
- rationalisation of intervention and limiting waste;
- concentration of the company on its own core business;
- guarantee of maintenance and service standards;
- greater flexibility with respect to the company's internal structure;
- greater control of expenditures.

A last distinction is necessary to avoid confusion between *Global Service* and Multi-service: the latter is a contract for a plurality of services, which does not envision, however, the responsibility for the overall result, as occurs in *Global Service*, defined as the supply of a service of maintenance in an entrepreneurial context, complete with total responsibility, even from the legislative point of view, for the contractual result relative to the availability to production and conservation of the property subject to the contract.

To summarize:

- the evaluation of whether to move towards the tertiary economy or not with maintenance services must be carefully examined with respect to all of its technical and economic implications, to ensure that the objectives of functional efficiency, reliability, maintenance feasibility, safety and efficiency of plants are adequately guaranteed;
- the choice of the type of Service, whether total or partial, will be influenced by the company policy and by market certainties, in particular relative to induced turnover;
- it is not possible to forego a minimum of company structure and some strategic functions (for example, management, engineering, programming of work) and it is often also necessary to maintain an operational shop for prompt intervention;
- a correct critical attitude of the internal maintenance structure must allow the optimal use of an internal service, avoiding impoverishment of the technical and technological knowledge of the plants, to the sole advantage of third parties.

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PART II
ADVANCED MAINTENANCE

Chapter 5

From Basic Maintenance to Advanced Maintenance

5.1 Introduction

Condition Monitoring is the activity of evaluating the current condition of a plant or apparatus, obtained through techniques that range from the use of complex computerised instruments to the exploitation of human sensitiveness, for the purpose of preventing breakdowns and implementing maintenance only in the presence of a potential breakdown and when it is most convenient on the basis of the production schedule (Williams, Davies, Drake, 1994).

In other words, it is a question of performing comparative, periodical or continuous measurement of parameters that are considered to represent the condition of the component or system subject to analysis, thereby permitting evaluation of the current situation and future performance or possible deterioration. Among the various possible techniques of monitoring, the ones that are currently enjoying the greatest popularity in industry are the monitoring of vibrations and the analysis of lubricants.

The former is well supported by easily obtainable and relatively inexpensive devices and has the advantage of being considerably flexible in application; it is quite simple to interpret the signals recorded by the sensors and the results are fairly dependable.

The second method, on the other hand, is particularly indicated for hydraulic systems or, in any case, for machines that have internal circulation of lubricants: specifically, it is useful to monitor the state of health of components such as ball bearings, cams, pistons, gears, etc. Concerning the analysis of the vibrations, this technique is capable of providing quite clear indications on the probable cause of a breakdown, with the additional advantage of performing a measurement that provides results that are independent from the operational speed of the machine; it is more difficult, however, to implement an *on-line* or continuous version.

One last paragraph is dedicated to more recent developments in the field of *Condition monitoring,* which rightfully justify the expression of "advanced maintenance".

5.2 Condition Monitoring

The concept of "condition monitoring" was born around the Seventies, when the usefulness of this process of continuous recording of operational data became apparent, subsequent to dependability analyses, to obtain information on the total population of components in service, on the basis of which to undertake possible modifications of the system or maintenance programme. The most widely used techniques of monitoring for mechanical systems can be classified in the following types:

- visual monitoring;
- performance monitoring;
- monitoring of noise and vibrations;
- monitoring of wear debris;
- monitoring of heat.

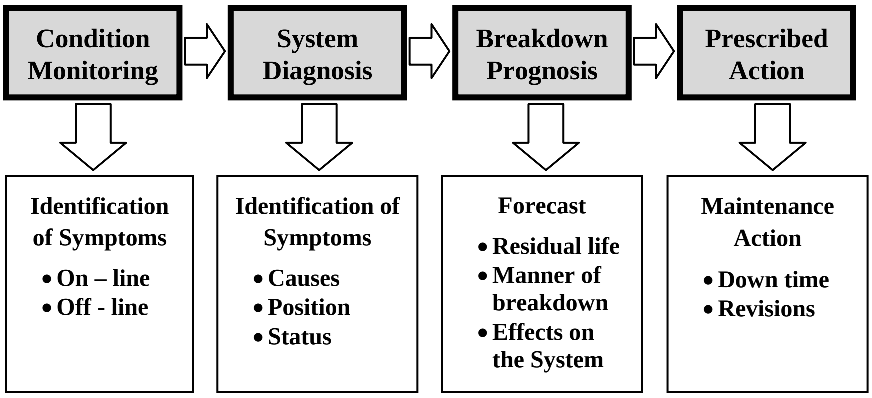

Fig. 5.1 Characteristic phases of the maintenance approach

All of these techniques will be briefly described below, after which we shall dedicate greater attention to two techniques that are in widespread use in industry: monitoring of vibrations and, above all, monitoring of lubricant oil.

5.2.1 Visual Monitoring

An initial form of monitoring, which is effective in its simplicity, is performed by operators on line, who are capable of identifying the most evident symptoms of deterioration. This is simply a question of observing the system, seeking any cracks, excess dust, welding defects, filter malfunctions, etc.; personnel is assisted in this by appropriate instruments, which may include:

- mirrors;
- comparators;
- optical fibres (sufficiently flexible to be used to illuminate hidden areas and obtain an image through the use of a scanner);
- closed circuit television.

5.2.2 Performance Monitoring

When the deterioration of the material has reached an advanced stage, we proceed to the status of "incipient breakdown" and "imminent breakdown". In a mechanical system that circulates fluid, this is the phase in which several parameters that are indicative of a certain worsening in performance are normally monitored, such as the pressure of the fluid, the flow, the temperature, the speed of rotation and the efficiency of thermal exchanges.

In applying these techniques, maintenance personnel can evaluate the correspondence of the performance of the machine to design specifications (by measuring the response of the machine when subjected to a standard load, for example) and succeed in drawing a correlation between the results obtained and specific anomalies. It is thus possible to bring out slippage of joints or gears, variations in the trim of cylinders, internal leaks of liquid, etc., to forecast the start of a breakdown situation in a timely manner.

5.2.3 Monitoring of Vibrations and Noise

All machine parts tend to vibrate due to the imperfections in the surfaces that come into contact, alignments and balancing of parts, etc. These vibrations also end up involving the particles of air next to the surfaces, which produces a variation in the atmospheric pressure in the area; this variation is perceived by our eardrums and translated into a sensation that we call "sound". The intensity of the sound varies with the level of (sound) pressure and the frequency of its variation.

This said, an operator might obviously analyse both the vibrations and the noise to investigate malfunction of a system. In particular, the mechanical components produce excess noise due to misalignment of the guidance systems, imbalance in rotating parts, defective bearings, and frameworks that are not rigid. When there is an involute fluid in the system, the noise may also be produced by variations in flow or pressure: insufficient suction pressure, in particular, can cause rather loud phenomena of cavitation. A general operator can therefore measure noises originating in the structure with an accelerometer, noises caused by fluid with a pressure transducer and noises originating from the movement of particles of air with a microphone, thereby bringing out possible abnormal values.

The development of noise over a period of time is caused by the emission of energy at certain frequencies, consequently the intensity of the noise is a function of both time and frequency; by breaking down the overall level of noise into the various frequencies, an acoustic spectrum can be obtained. The spectrum is modified when a component suffers an anomaly, so it is sufficient to compare it with the one relative to a system that is known to function correctly in order to bring out every small variation. The fact that the level of noise is above normal should not be underestimated and it should be promptly reported, even because of the negative effects that it may produce on the operators themselves: damage to hearing, fatigue, stress and a general disturbance of physical and mental capabilities of the individual.

The case is analogous for vibrations: this type of phenomenon is naturally related to the operational activity, but if vibrations exceed the standard values provided by experience, they become unequivocal symptoms of anomalies. From this point of view, the most expressive parameter is probably speed: in many cases, a level of vibrations of 8 mm/sec, for example, is already indicative of a certain irregularity in the surfaces that come into contact with each other: the operator must inspect the machine to verify the presence of elements that are not balanced, couplings that are not aligned and so forth; between 8 and 10 mm/sec, it is advisable to programme intervention for more thorough revision of the machine. Over 10 mm/sec indicates a high level of wear and tear, which suggests that it would be opportune to replace the piece.

5.2.4 Monitoring of Wear Debris

Analysis of the particles generated by wear and tear, which are dispersed in the lubricating oil of a machine, are useful in interpreting the severity of wear that a normally lubricated mechanical system is subject to.

This type of analysis makes this evaluation possible, providing the following conditions are present:

- there is a functional relationship between the concentration of debris and the rate of wear and tear, obtained through opportune tests of sensitiveness to the particles of the various components of the system being studied;
- the availability of representative samples of the fluid on the basis of standards;
- the ability to extract and measure the debris in the oil with available techniques (spectrometry, ferrography, particle count);
- interpretation of the results through the functional relationships mentioned above.

By studying the chemical-physical characteristics of the particles, their concentration, dimensional and morphological distribution, and drawing a correlation between this data and the data from previous measurements, the analyst will be able to formulate reliable hypotheses on the state of health of the machine.

As a general rule, the following could be a possible chronology of the monitoring activity:

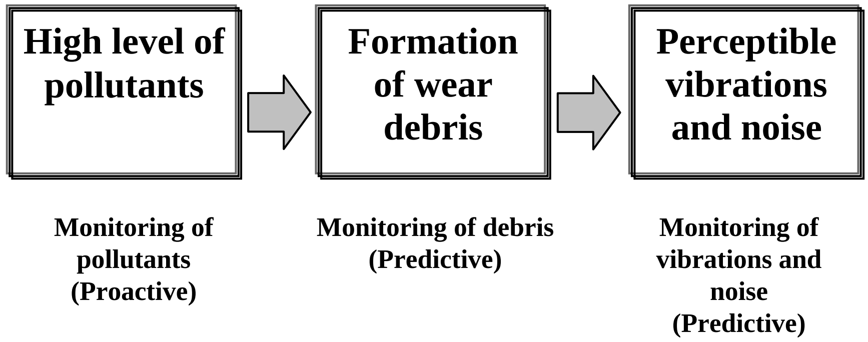

Fig. 5.2 Chronology of monitoring activities

5.2.5 Heat Monitoring

When surfaces are subject to excessive stress, the material is subject to flexion; the force of friction (and the load on the bearings), increasing the phenomena of surface wear and tear (adhesion, abrasion) accelerates. Under such conditions, the production of excess heat (thermal energy) translates into a localised increase in temperature, which can be measured with appropriate instruments.

Two techniques can be identified from this point of view:

1. *Calorimetry* This is a technique of measurement of the heat absorbed and released by a system, which uses temperature sensors of a thermo electric or resistive type. In particular, these include:
   - Thermocouples – these are transducers that provide an electric output signal proportional to the difference in temperature between the joint of the thermocouple and the reference values of the two materials.
   - Optical pyrometer – this instrument operates on the basis of a comparison that the observer must make between the brightness of the heated body and the brightness of a reference filament. If the temperature of the filament is greater than the object being monitored, the object will be darker; otherwise the filament will appear as a dark spot against the background of the body. By varying the intensity of the current passing through the filament, it will take on the same degree of luminosity (and therefore the same temperature) as the object, making it possible to measure the temperature.

  - Resistive thermometer – this is an instrument that uses a conducting or semi-conducting material, exploiting the fact that a variation in temperature produces a proportional variation in the electrical resistance of the material, which can be measured.
  - Radiation pyrometer – this is an instrument capable of measuring thermal radiations (and therefore irradiation) and of directly providing the output of the temperature value of the body emitting the radiations, or a value that can be immediately converted to it.

2. *Thermography*. One of the most frequently used radiation sensors is the thermography: this instrument is capable of measuring the temperature of a great variety of objects placed at a certain distance, without contact. This interesting result is obtained by detecting the infrared energy irradiated by any body above absolute zero and converting it to an equivalent value of the surface temperature. This technique is particularly useful when the bodies to be studied are quite far away, excessively hot, in movement or fragile. A special telecamera is used that is sensitive to the infrared range of radiations in the spectrum.

With a view to maintenance, measurement of the temperature of a machine is particularly important: any device that generates, conducts or consumes power, in fact, emits heat as a consequence of the loss of energy of the system.

Generally speaking, decreased efficiency of a component corresponds to an increase in emitted heat, therefore the temperature of a device susceptible to failure will increase rapidly as a symptom of an incipient breakdown. In particular, this type of detection is suitable for mechanical systems more than for electrical or chemical ones; there are a great variety of possible applications on a series of components whose "normal operation" can be evaluated with this technique: couplings for power transmission, bearings, gearboxes, reducers, cooling circuits, etc. The source of excess heat can thus be identified, simultaneously evaluating the consequent increase in temperature.

5.3 Two important CM techniques: Analysis of Vibrations and Lubricating Oil

5.3.1 Analysis of Vibrations

The concrete use of *condition monitoring* consists in succeeding in solving the problem of determining the effective condition or state of health of the machine, in some way: one of the most successful methods in this sense is based on the measurement and analysis of the vibrations produced by the machine.

Vibrations are understood as the oscillating movement of a machine or machine part, with respect to its position at rest. There are many different causes for this phenomenon (Table 5.1), which almost always refer to mechanical defects. The most common of these are: imbalance in rotating parts, misalignment of bearings and rolling of joints, friction due to wear between the teeth of gears, defective transmission belts due to the presence of unevenness, defective clamping in connections between the components of a mechanical system, deviated shafts, phenomena of resonance, etc. More in general, it can be stated that construction tolerances vary due to the initial effect of wear, with the consequent eccentricity of rotating parts and dynamic imbalance. This in turn produces vibrations that increase wear, producing a cumulative effect of the phenomenon.

A machine vibrates when the mass of its carcass is subject to periodical stress due to:

- solid components of the body (i.e. Windings in electric machines);
- reaction forces (i.e. Explosions in internal combustion engines);
- forces transmitted to the body by the rotor through the supports, which may be centrifugal (due to imbalance) or with impulses (due to gear couplings or fluid that comes into contact with the rotor blades).

Table 5.1 Types of vibration phenomena

Causes	Extent	Frequency	Considerations
Imbalance	Larger in the radial direction	1 x rpm	One of the most frequent causes
Misalignment of bearings	Great in the axial direction	Normally 1 x rpm	The most evident cause of axial vibration
Bearings in poor condition	Unstable	Extremely high	The damaged bearing is the one that vibrates the most at high frequencies
Gears in poor condition	Low.	Extremely high	The maximum vibration is measured at the centre of the toothed wheel
Defective transmission belt	Irregular or pulsating	1 – 4 x rpm of the belt	The stroboscope is used for visual control
Electric	Not high	1 or 2 times the synchronous frequency	If s = 0 when the current is cut off, the cause is electric

A vibration is generally a periodical movement, which is repeated in an identical manner at constant intervals, called *periods.* The law according to which the movement of the vibrating mass is implemented with respect to the point of equilibrium (corresponding to the case of the absence of vibrations) is almost always complex. When this law is sinusoidal, the movement is said to be harmonic.

As stated, there is generally more than one cause of vibration in a machine, each of which is characterised by a specific frequency: we therefore speak of complex vibrations and:

- *Predominant frequency:* the frequency of vibration having the greatest amplitude;
- *Fundamental frequency:* the first (lowest) frequency, normally associated with a particular problem;
- *Harmonic frequency:* the frequency that is exactly equal to a whole number of times of the fundamental frequency.

5.3.1.1 Strategies in Measuring Vibrations

Some general considerations can be made concerning the choice of the unit of measure of vibrations, points of measurement and testing conditions. First of all, it is correct to state that speed and frequency are the two parameters utilised most often by analysts to evaluate the condition of machines in terms of vibrations.

Speed allows immediate evaluation of the amplitude of the vibrations, which may be compared with data concerning past situations of the machine, providing useful elements for a perspective study on future variations. But the frequency study is what guarantees the possibility to identify the component responsible for the vibration: the amplitude and speed of the vibration provide a measurement of the seriousness of the phenomenon, but is sometimes insufficient to determine the cause. The maximum value of the frequency, in fact, is generally equal to a multiple of the angular speed of the machine being studied, and it is often used to determine the type of anomaly that has occurred due to a vibration outside the set limits. In other words, and without going into detail, the analysis is performed by correlating the frequency of the vibration with the fundamental frequency of the component: the maximum amplitude of the vibration of a certain component will be identified in correspondence with the fundamental frequency or the successive harmonic frequencies; this is generally sufficient to identify the defect.

Measuring the amplitude of the vibration is preferable to examine individual machines and parts, for the inspection of the status of a vibration over a period of time, to compare between identical machines, for machines in which the quality of the product may depend on the vibrations and for comparison of different machines at low rotation speed.

Measuring the speed of vibration is preferable, on the other hand, if you have to compare completely different machines and when other vibrations with different frequencies are superimposed upon the fundamental; normally this parameter is used for frequencies from 100 to 1000 Hz (60,000 c/min.). Measurements of the acceleration of the vibration are performed only in special cases, or for extremely high frequencies (> 1000 Hz).

A vibrational phenomenon can be studied visualising the waveform on a Cartesian coordinate plane, which presents the value of amplitude of the vibration on the ordinates and the time or the frequency on the abscissa (in this case we would speak of *Signature* or Spectrum).

The device used for the measurement is normally placed on two supports of the machine to be controlled; other points may be the casing, the feet and the flanges. The measurements must be performed according to three directions orthogonal to each other in order to make an accurate evaluation: horizontal, vertical and axial.

No machine should operate in service with rotation speeds near its critical speed or the frequency of its supports and framework, and precisely within a range of –20% to +20% of the speed of resonance: it is a well-known fact, of course, that the conditions of resonance considerably increase the effects of all phenomena, which produce vibrations within the limits of tolerance under normal conditions.

5.3.1.2 The Critical Level of Vibration

As we have already stated, every machine vibrates, independently from the care with which it has been designed and assembled.

Industrial practice has suggested the existence of a strong correlation between the characteristic vibrations of the machines and their relative condition; in fact, it has been seen that in over 90% of the cases, the breakdown of a machine is preceded by an increase in the level of vibrations. The problem resides in the difficulty encountered when it is desired to establish a threshold value for the intensity of vibrations, which indicates that the machine is in poor operating condition when it exceeds the value.

Many authors, based on empirical data, have advanced proposals in this sense, but the values obtained have rarely been obtained from accurate scientific analysis. The characteristic magnitudes most frequently used are the amplitude and velocity; the purpose of the following graph is to calculate one magnitude from another. The graph was drawn up on the basis of the relationship:

$$v = 0{,}1046 \cdot s \cdot n \tag{5.1}$$

Where:

v measured in mm/s
s measured in µm
n measured in cycles/s

This relationship, which is rigorous for harmonic vibrations, is conventionally considered valid for complex vibrations as well, namely, vibrations that are made up of several sinusoidal vibrations of different frequencies and amplitudes, considering n as the characteristic frequency (for example, the speed of rotation of the most important rotating organ of the machine).

It should be noted that taking the amplitude into consideration, it is also necessary to consider the frequency. Evidently, in fact, a certain amplitude of vibration represents a modest value, which is therefore acceptable if the frequency is low, but which can become a very high value and therefore a dangerous one, if the frequency is greater. Measurement of the speed of the vibration, on the other hand, permits us to express a valid and definitive judgement, even if we are not aware of the frequency. This is therefore very useful when we want to examine a machine where several vibrations with different frequencies are present simultaneously.

One practical method of judgement of the severity of vibrations is to establish a characteristic value *(signature)* for a piece of equipment that is known to be in good operating condition (not necessarily new), recording departures that crop up over time. It has been seen, for example, that in many cases an increase in the level of vibrations begins to take on importance only when the initial value is doubled.

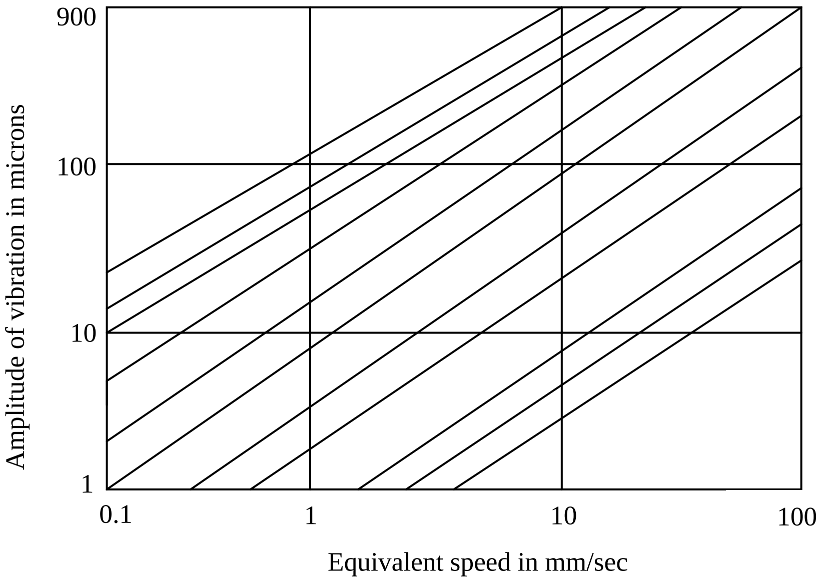

Fig. 5.3 Limits of acceptability for vibrations

In any case, the rate of variation is more important than the absolute value of variation, since the level of the characteristic vibration of a mechanical component, expressed as a function of time, can be represented as a line with a slight positive inclination, for 75% of the useful life, following which there is an exponential growth until breakdown.

Some authors (Rathbone, Yates) have based their evaluations on the opinions of experts as well as on results obtained through direct methods of measurement on rotating machinery at less than 5000 rpm (subsequently succeeding in extrapolating superior speed curves) and have compiled vibration severity cards. These have been applied to some extent in industry when it is not desired to entrust evaluations to experience alone. The cards generally advise not to exceed the value considered as normal by more than one and a half times.

In any case, it should be born in mind that vibration levels considered acceptable for machines may not be acceptable for the operator: in this sense, in the field of low frequencies, from 1 to 6 Hz, the maximum movement (in inches) admissible is of two, divided by the cubic frequency ($2/f^3$); for a frequency between 6 and 20 Hz, the limit of movement is $1/3f^2$ and for a frequency between 20 and 60 Hz, the maximum movement admissible is 1/60f.

5.3.1.3 Techniques of Vibration Monitoring

An initial large subdivision (Davies, 1998) concerns techniques of vibration analysis based on time, on one hand, and techniques that use the frequency as a significant parameter, on the other. Both groups are shown synthetically in Table 5.2

Table 5.2 Division of Techniques of Vibration Analysis

Significant Parameter	Technique
Time	Root Mean Square
	Peak Level
	Shock pulse Method
	Peak Energy
	Shape of wave in time
Frequency	Spectrum analysis
	Waterfall plot
	Cepstrum analysis
	Spectrum differences

- Techniques based on the parameter of time

  – *Measurement of the global level (Root Mean Square, R.M.S.)*
  This is the most used method, especially because of its simplicity and low cost: this is simply the measurement of the average amplitude of vibration as a function of time. It is based on comparison with special cards that

indicate acceptable levels; there are some consistent limitations to this, however. In effect, this is a technique that is not very sensitive and, therefore, in the presence of small defects, detection may be late. Problems arise in particular in identifying peaks of short duration or impulses, which often occur for vibrations produced by gears or ball bearings. Ball bearings, in fact, produce vibrations of short impulses, which are generated whenever one of the rotating elements (spheres, rollers) passes over a defect.

  - *Detecting peak levels.*
    Alternatively to the RMS method, there is a particularly useful method to detect deterioration of a damaged bearing, for example, but it is not very dependable, because the increase in the peak level of a signal may also be due to other causes.

  - *Shock Pulse Method (SPM)*
    This technique permits identification of the development of a wave due to mechanical shock from a damaged bearing, and consists in a measurement of the frequency of resonance of the bearing. In other words, since it may be difficult to identify a defective bearing with a simple spectrum analysis, if its contribution to the overall vibration is small, the SPM measures the wave of pressure generated by the impact of the rotating elements of a bearing, through an accelerometer. If the outgoing signal from the instrument is filtered at the frequency of resonance, a shock pulse is obtained.
    This is widely used, but it has been seen that in the presence of a breakdown that is already in an advanced state, it may not be entirely dependable (for example, phenomena of turbulence or cavitation may affect the reading).

  - *Peak energy*
    This method is based on a study of the maximum acceleration at high frequencies, using a circuit that rejects vibrations provoked by sources characterised by low frequency, bringing out the peak level caused by excitation of the machine in resonance.

  - *Waveform in time*
    Through a simple instrument such as the oscilloscope, it is possible to visualise the shape of the vibration wave. Taken by itself, this technique does not provide a great deal of information, but represents a useful instrument if it is used in conjunction with other methods.

- Techniques based on the parameter of frequency
  - *Spectrum analysis*

The spectrum is derived from the shape of the vibration wave, through the use of the Fourier transformation; namely, the amplitude of the vibration is studied as a function of the frequency. Direct analysis of the spectrum or the indexes that are derived from it is one of the best methods of monitoring the condition of a mechanical system. In fact, it is possible to draw a correlation between the peaks of the spectrum and the individual components of the machine, exploiting the fact that the measured frequency is directly proportional to the speed of rotation of the machine.

Clearly, the vibrational characteristics of each machine are unique and depend on the method of assembly, mounting and installation of the machine; consequently it is possible to obtain a reference spectrum (signature spectrum), obtained under normal operating conditions, to use as a comparison for successive analyses, to correctly bring out frequencies where an increase in the level of vibrations has occurred.

It is opportune to bear in mind the fact that the overall spectrum is often characterised by a few predominant vibrating components, which are important to monitor, but which may mask those of lower amplitude, produced by other machine elements that must be kept under control. One way of solving this problem consists in dividing the spectrum into various frequencies, to be able to clearly observe the less evident components as well, immediately identifying the vibrations on each frequency, long before the effects become sufficiently ample to be visible on the global spectrum.

- *Waterfall plot*

  This is a three-dimensional representation of the spectrum, where the third dimension is generally time, which permits immediate identification of each temporal variation of the spectrum.

- *Cepstrum analysis*

  The cepstrum is the spectrum of the logarithm of the power spectrum (which is understood as the amplitude with respect to the frequency); its purpose is to bring out any periodical forms in the spectrum, precisely in the same manner that the spectrum brings out periodical changes in the shape of the wave with respect to Time. Consequently, several harmonics in a spectrum are added up in a single peak in the cepstrum, permitting a more precise determination of the specific frequencies of the breakdown.

- *Spectrum differences*

  By mathematically subtracting one spectrum from another, any differences in level can be brought out, which then permits analysis of the breakdown frequency to place the frequencies in relation with the various machine components.

5.3.1.4 Vibration Analysis Instruments

The operation of transducers for the measurement of vibrations may be based on electromagnetic, electro dynamic, capacitive or piezo electric properties. Almost all of them are characterised by a probe that transforms the mechanical signal into an electric one.

In recent years, piezoelectric accelerometers have been more widely used, which may be designed to avoid the phenomenon of resonance for a wide range of frequencies, thanks to their interesting characteristics of reduced size and weight; these instruments are quite stable, not very sensitive to stress, temperature variations, magnetic fields and background noise, and are hard to damage.

- **Accelerometers**
  Accelerometers are often used for *"condition monitoring"* and substantially consist of a certain number of piezoelectric disks, upon which a relatively heavy mass has been placed; this is mounted on a base upon which a rigid spring acts and is closed inside a metal casing. If it is subject to vibration, the mass exerts force against the disks, which generate an electric signal that is directly proportional to the force applied and, therefore, tot he acceleration of the mass. By using special circuits, the signal can be integrated and visualised in terms of speed or movement. The *range* of frequencies that can be used is, for many accelerometers, within 10 – 40 kHz (Collacott, 1977) and is strongly influenced by the manner in which the sensor is joined to the machine. The best method seems to be the use of a steel pin for connection with a rigid part of the machine; the use of composite cements, special or magnetic glues, in fact, lowers the upper limit of admissible frequencies.
  The most widely used piezoelectric materials are zircon titanate or, for special applications, lead niobate and lithium. Finally, the sensitivity of the accelerometer is measured taking as the unit of intensity the output signal from the circuit in millivolts, in the presence of an acceleration equal to the acceleration of gravity.

- **Speed transducers**
  Speed transducers essentially consist of a probe, namely a permanent magnet that surrounds a mobile winding; the vibrations of the machine cause the relative movement of the winding with respect tot he magnet, producing an electric signal proportional to the vibration speed (and therefore to the movement, once the signal is amplified and integrated).
  These transducers may be point or seismic: in point transducers, the detector is attached t a fixed element, while the rod is in contact with the vibrating part; a relative measurement between the two parts is thus obtained. In seismic systems the case of the detector is attached to the vibrating part, while inside the detector there is a part (winding or other) that is seismically suspended; in

this case there is a measurement that is defined as absolute. The field of frequencies that can be used is from 10 – 1000 Hz.

It must be born in mind that each of these means, whose purpose is to transmit the vibration to the probe, has a natural frequency of vibration that can alter the measurement.

It always preferable, therefore, to use the probe without any appendix and, where it is necessary, it is always opportune to repeat the measurement in the same point and in the same manner, so that the data can be compared in any case.

- **The stroboscope**

  An evaluation for a wide spectrum of vibration frequencies can be performed with a stroboscope examination; the stroboscope allows us to see the rotating objects (animated by alternating motion) in an intermittent manner, producing an optical effect that makes the movement appear to slow down or entirely stop. For example, an electric fan, rotating at 1800 rpm, will appear immobile if it is observed with a light that flashes 1800 times per minute; with 1799 flashes per minute, the fan will appear to rotate at 1 rpm, etc. The amplitude of a vibration can thus be evaluated when a recognisable mark is placed on the vibrating part (this instrument is often used for elbow shafts).

- **Magnetic tape recorder**

  Tape recording allows signals to be stored, reproduced and analysed later, with the possible expansion or compression of the scale of times, thereby creating the possibility to maintain time and phase relationships between a certain number of recordings.

  Direct recording is the most convenient technique if you want to analyse every signal individually, in a field of frequencies between 30 and 10 kHz. But if the signals to be analysed have lower frequencies, or the study of the relationships between several simultaneous signals is particularly important, recording with frequency modulation may be used.

- **The laser holograph method**

  The holograph is a technique through which the phase and amplitude of a wave source diffused by an object illuminated by a coherent light (for example a gas laser) are recorded in the form of a model of interference on a photographic plate. The original wave can be reconstructed by illuminating the photographic plate with a coherent light, to obtain a complete three-dimensional image of the object.

- **Multi-channel deviation monitoring**

  It is possible to identify any deviations from the normal intensity of the vibrations by monitoring that does not require continuous memorisation of the information and which activates the output device only when the deviations exceed a pre-determined value. A schematic layout could be as shown in Figure 5.4

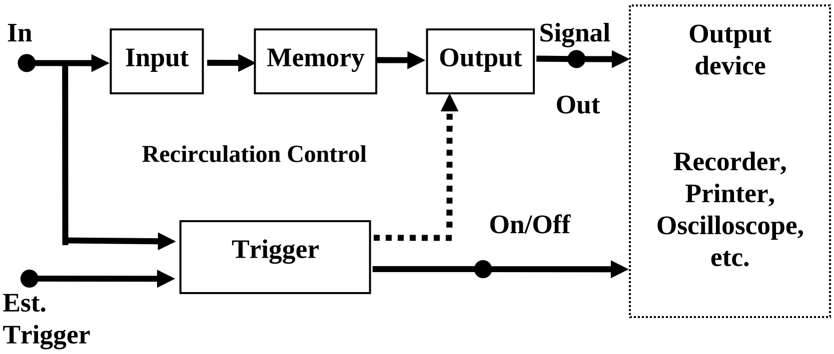

Fig. 5.4 Block diagram of multi-channel monitoring [Source: Collacott, 1977]

The input unit translates the incoming signal, digitalising it in numerical form, which is more suitable for recording in the computer memory. The number of channels to monitor varies from 1 to 16 and the frequency of the sample necessary to reproduce the signal with proper accuracy should be 3 or 4 times that of the signal being studied. The Trigger analyses the incoming signal in search of any deviations form the norm, monitoring several channels at a time if necessary and using a pre-established threshold as a comparison, which may concern the frequency, amplitude, rate of variation, etc. when the memory stores new information, it cancels the old information, therefore its dimensions determines how long the data can be saved. Finally, the output unit represents the signal in a form suitable for the output device (printer or other device).

5.3.2 Analysis of Lubricating Oil

In most mechanical and hydraulic systems a lubricating fluid circulates during the operational phase. The reason for this is generally to reduce friction between two surfaces that slide against each other. The use of these fluids, in fact, permits the friction between the two dry surfaces to be substituted with the friction inside the fluid, which is much less. This practice permits considerable reduction of the amount of energy lost in the form of friction in the machine and of the damage provoked by wear and tear, namely by the removal of particles from the surfaces during the reciprocal sliding movement. In particular, phenomena of mechanical wear (with the release of metallic particles of the same material that the worn piece is made of) or chemical wear (in the presence of a reaction, oxides, salts, phosphates, etc. are generated).

In general, this is a complex process that is influenced by various factors. The lubricant, the material that makes up the surfaces, the characteristics of the lubricated organ (geometric conformation, level of finishing of the surfaces, play), the conditions of operation (sliding speed, load, environmental conditions). Fairly recently, it was seen that the importance of lubrication lies not only in the aspects cited above, but also in the quantity of information that a well programmed activity of diagnosis can glean from studying lubricating oils. In fact, the analysis of the oil, like the blood in the physiology of the human body, is capable of revealing defects or malfunction relative to the "state of health" of the machinery being examined.

Extended, in depth investigation conducted in recent decades on the particles of wear produced during the tribological deterioration of variously interacting couplings, has permitted the identification and quantification of several peculiar traits of the particles, which are fundamental in interpreting the tribological processes. Substantially, it was possible to demonstrate that the particles of wear conserve typical elements of the mechanisms that produced them. In particular, the following can be identified:

- quantitative traits (quantity and dimensional distribution of the particles);
- qualitative traits (nature of product fragments).

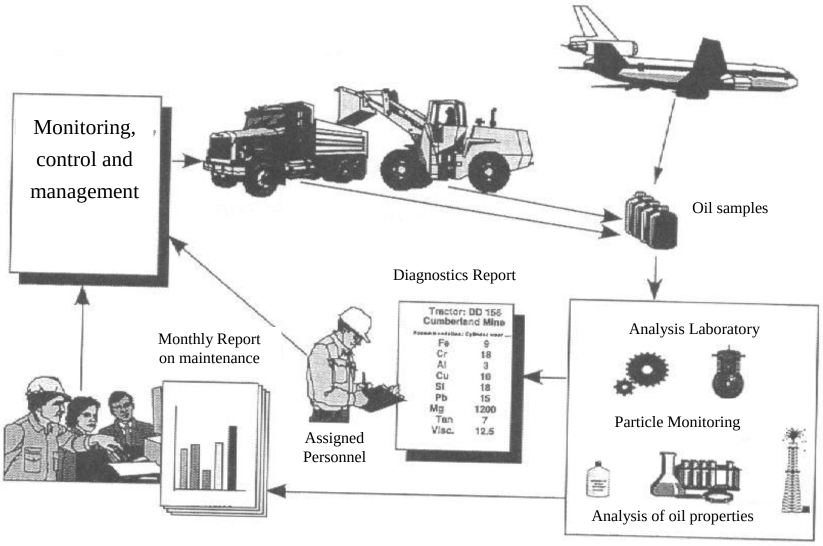

Fig. 5.5 Flow chart of an oil analysis programme

For example, it was seen that the presence of spherical particles is a symptom of mechanical fatigue, due especially to rotating contact.

In the evolution of these phenomena from one manner of wear to another, and from one level of wear to another, the characteristics mentioned undergo substantial variations which, appropriately detected and quantified through various techniques of analysis, offer an effective method of diagnosis of operating systems. More precisely, it can be held that the processes of wear and tear are distinguished by four fundamental elements:

- quantitative level correlated to the total volume of particles of wear produced and representative of the entity of wear in the area of contact;
- level of severity, correlated with the dimensional distribution of the particles produced;
- morphological distribution of the significant fragments, which shows, with a fair degree of precision, the mechanisms of wear and tear underway (adhesion, abrasion, delamination...) that are responsible for the damage;
- nature of the fragments, correlated with the materials they are made of, which permits identification of the source of the particles produced.

As an image and by way of example, it can be stated that all of modern industry is resting on a film of lubricating oil no thicker than 10 μm: the disappearance of this protective film is a source of serious damage. One of the most common causes of phenomena of wear and tear and breakdown of a machine is the impoverishment of the lubricating fluid, due to the presence of polluting particles or humidity.

Often, a breakdown provoked by alteration of the lubricant is attributed to "normal wear and tear". The Canadian Research Council has determined that a good 82% of all breakdowns registered in a vast sample of industries, were imputable to this type of defect (Troyer, 1996). The particles from dirt, dust or other pollutants slowly erode the critical surfaces of the machine, until the geometric conformation of the play is modified, making the replacement of the piece or revision of the entire apparatus necessary. Similarly, humidity compromises the quality of the lubricant, causing irregular contact between the relative moving parts.

Monitoring this type of phenomena through a strategy of *Proactive Maintenance* therefore constitutes a good opportunity to reduce maintenance costs.

In order to do this, it is necessary to pass through three phases to ensure the achievement of the desired benefits.

Since, by definition, this type of maintenance strategy is based on continuous monitoring and control of possible causes of breakdown, the first thing to do is to set an objective, or a standard, associated with each cause. In the case of oil analysis, the most important causes consist of contamination of the fluid (particles, humidity, heat, coolant liquid) or in deterioration of the additives. In any case, the process of definition of the standards is only the first step. It is necessary to verify that these normal levels are acquired and maintained by the fluid, possibly by using improved filtering systems or separators.

The third phase is just as important and consists in managing the return of information from analysis of the oil. When "attention" thresholds are exceeded, corrections must be implemented in a timely manner, in order to develop a disciplined activity of monitoring and control of the quality of the lubricant, instead of a simple exercise of forecasting the level of pollutants present.

Standards must be set taking into account the sensitiveness of the machine to clean oil, the severity of the consequences of a breakdown and the environment in which the apparatus is used. Once defined, however, these limits must also be respected. The use of filters is not sufficient, because extracting a particle when it has already been introduced into the lubricant costs ten times more than the procedures necessary to keep it away from the machine.

Controls must be implemented from the time the supply of oil is received. The new fluid, in fact, is rarely clean enough to be placed immediately in service. The logistical processes related to transportation of the lubricant from the refinery to the supplier and to the plant involve a risk of contamination that cannot be disregarded. In this sense, a great deal of attention must also be dedicated to the manner in which the machinery is replenished, during the phases of changing or topping off oil, and the procedure of storage. To limit contamination of the oil by foreign particles, it is necessary, in a word, to make an organisational effort to define specific and detailed procedures for the correct treatment of the lubricant, from the time of delivery to the time of its replacement.

In conclusion, *when the punctual warning signals of incipient breakdown are received, which are the result of prudent Predictive Maintenance, they provide the advantage of being able to achieve a prolonged useful life of the machine, thanks to effective Proactive Maintenance, and the user is certain of having implemented a complete programme of On Condition Maintenance.*

This is made possible by two complementary strategies. While the objective of Proactive Maintenance is the identification and control of the first causes of breakdown, Predictive Maintenance aims to determine incipient anomalies, relative to the properties of the fluid and the machine components. Both of these types of maintenance contribute in a proportional manner to the good condition of the plant. For motor oil, for example:

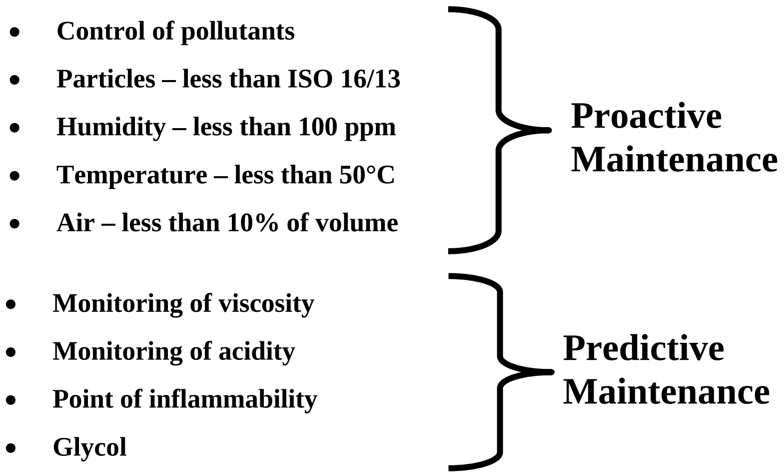

Fig. 5.6 Division of maintenance duties for an internal combustion engine.

5.3.3 Advantages and Applications

Research conducted in the United States to quantify the value of an activity of lubricant analysis established that the return on the initial investment may be in the neighbourhood of 250% (Leugner, 1998). This result is a consequence of the fact that an organisational effort such as the one described in the previous paragraph provides information in two different areas:

- the physical properties of the lubricating oil, such as viscosity, the level of contamination, etc.;
- the condition of the component or system from which the oil was taken.

It is therefore possible to succeed in keeping possible inconveniences under control, before they develop into more serious problems[1]. For the person in charge of Maintenance, this means having the possibility to programme machine down time for efficiently, guaranteeing reduced time for repairs and making continuous improvement possible (calculating, for example, the optimal interval for replacement of the filters).

In motors, for example, this type of analysis can provide information on the state of health of the air intake system, through monitoring of the level of silicon (a pollutant). If the level increases, the air filters must be replaced and the oil needs to be changed. Similarly, the presence of combustion residue in the

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[1] In this sense, oil analysis often provides more timely indications than can be obtained through analysis of vibrations, inasmuch as the symptoms subject to monitoring occur before the symptoms detected from vibrations.

lubricant could mean that the intake system is too narrow, that the oil filter is ineffective, or combustion is incomplete; a certain percentage of iron or aluminium, on the other hand, indicates damage of the cylinder walls. The level of wear and tear of bearings can also be measured before the elbow shaft feels the effects, or any infiltration of water or antifreeze liquid in the oil can be detected before it reaches a level that could be cause for concern. For example, the presence of boron in many liquid cooling systems indicates leakage of the coolant, which combines with the products of combustion if timely intervention is lacking, forming powerful acids that attack the metal.

This type of analysis can also be programmed for hydraulic systems, transmissions, gearboxes, differential, etc., where a process of combustion does not take place. A high level of aluminium, for example, indicates the potential breakdown of a pump or transformer.

An increase in the content of silver and nickel in certain types of diesel engines for railroad applications is a symptom of high wear and tear on bearings. If performed in time, this analysis enables the user to simply replace a bearing, rather than repair the shaft, and therefore to sensibly reduce costs.

The cleanliness of the oil, which evolves in a hydraulic system, is particularly important, given the characteristically narrow tolerances of pumps, control valves and the play between the pistons and the cylinder walls. It is a well known fact that about 25% of the breakdowns of these systems are caused by the presence of detritus, dust or humidity in the lubricating oil.

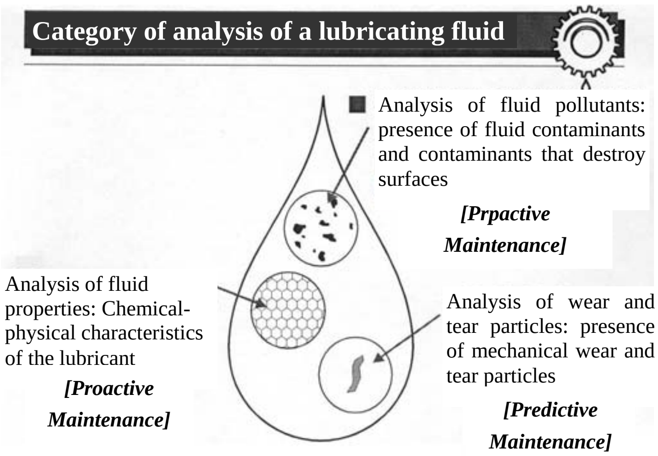

Fig. 5.7 Category of analysis of a lubricating fluid

Nevertheless, there is still a certain mistrust in this type of analysis and, in condition maintenance in general, due to the fact that a "proactive" approach, by nature, envisions an economic return that his hard to quantify and is not readily usable, against a definite and immediate investment. Additionally, if you consider the approximate manner in which the savings due to a breakdown of essential machinery that has been avoided are often calculated, sometimes accompanied by a superficial imputation of costs, it is easy to explain the obstructionism that certain modern maintenance methods encounter.

Stated more clearly: if the expenditures for *condition monitoring* are accounted for under the item of "maintenance" and then the greater receipts due to accelerated production are imputed exclusively to the ability of the director of production, the fact that part of those earnings were made possible by the reduction of machine down time obtained through maintenance on condition is not taken into due consideration.[2].

Figure 5.8 shows a graph that brings out the potential of this type of analysis and may explain this aspect more effectively than words.

It provides an indication of the total number of samples of oil analysed, in 1991, by the various government organisations, within the ambit of the Italian Air Force Spectrometric Oil Analysis Program (IAF SOAP).

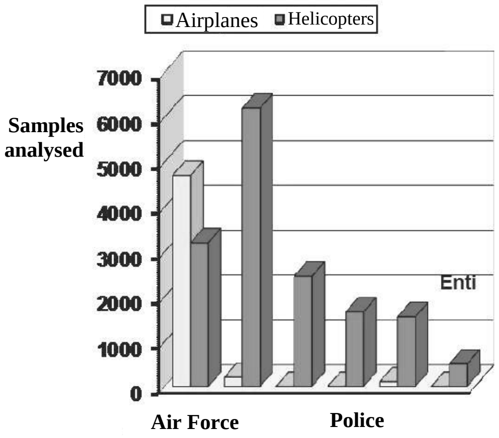

Fig. 5.8 Programme of spectrographic analysis for government agencies

Figure 5.9, on the other hand, shows the percentage of abnormal situations signalled through the analysis, relative to several of the essential components of the aircraft and helicopters monitored. In the worst scenario, breakdowns would have occurred in 6.6% of the aircraft, unless the piece had been replaced on the basis of other maintenance logic (such as cyclic preventive maintenance, for example). A priori, it would be difficult to determine the consequences of this, even in terms of the risk of loss of human life.

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[2] In the case of military aircraft, for example, it is sufficient to succeed in avoiding a breakdown every ten years, to justify the expense sustained for monitoring".

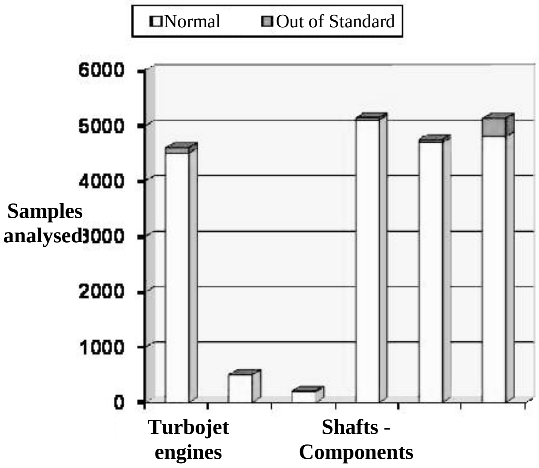

Fig. 5.9 Anomalies detected in analyses relative to 1991

5.3.4 The Parameters Monitored

In a machine that is in good condition, lubricant tests provide an almost constant rate of growth in contamination of the oil. A sudden increase could be a symptom of incipient breakdown. Therefore a single measurement is not particularly meaningful. It is much more interesting to make a comparison between different results, obtained over a period of time, from analysis of the same machine.

To succeed in identifying an anomaly, it is first necessary to understand what is meant by "normal conditions of operation". This is possible through the use of opportune information technology systems, capable of managing a database on the results relative to a group of similar machines, thereby permitting the development of a perspective analysis, capable of generating dependable forecasts on the condition of the machinery and lubricating fluid. The most important tests in this sense aim to quantify:

- Viscosity;
- The presence of insoluble material;
- Acidity (TAN);
- Basicity (TBN);
- The presence of solid or liquid pollutants (water, fuel, glycol).

Other factors to determine may be the level of exhaustion of the additives in the oil, the rate of production and shape of particles of wear that may be present in the lubricant, the presence of chlorides (very corrosive, typical of the naval industry) and fuel in the oil (which produces a decrease in viscosity).

Table 5.3 Cause and effect relationships brought out by CM

Cause	Effect
Topping off with excessively viscose oil	Increased consumption of fuel, low lubricating fluid, accelerated wear and tear
Topping off with low viscosity oil	High temperatures, oxidation, accelerated wear and tear
Damaged shaft	Presence of particles of iron
Damaged bearings	Presence of particles of bronze
TAN too high	Corrosion of pistons and bearings
Low content of additives	Polluting agents deposited on the metal, oxidation of the metal
Presence of insolubles (combustion debris, residue from depletion of additives, etc.)	Gelatinisation of the oil
Presence of insoluble abrasives (dust, particles introduced during maintenance or oil changes)	Increased viscosity and gelatinisation of the oil

A good programme of *Condition monitoring* must therefore be able to establish the physical properties of the oil, reporting every sudden deviation from normal conditions promptly, which may be imputable to the most disparate causes. Several examples of this that can be gleaned from careful analysis of the machine condition are shown in Table 5.3.

The presence of external pollutants is particularly dangerous.

The level of dangerousness depends on the dimensions and hardness of the particles. Hard particles such as sand, due to a "dirty" fusion of the metal, can cause serious wear and tear on bearing surfaces, for example, modifying the play and interfering with the efficiency of other parts of the system.

In the most sensitive hydraulic systems (such as the ones used in aeronautics), even a small percentage of insoluble material in the oil can cause breakdowns and malfunction. In this case particularly severe standards must be defined. Polluting substances in these systems include slime, containing solid particles of various chemical compositions, with an infinite array of shapes, dimensions and hardness. In order to avoid problems, these particles must pass through the play of the parts in movement; if this does not take place, they act on the surfaces of the various components, levigating them and thereby adding other damaging detritus to the solution, creating a process known as a "chain reaction of wear and tear".

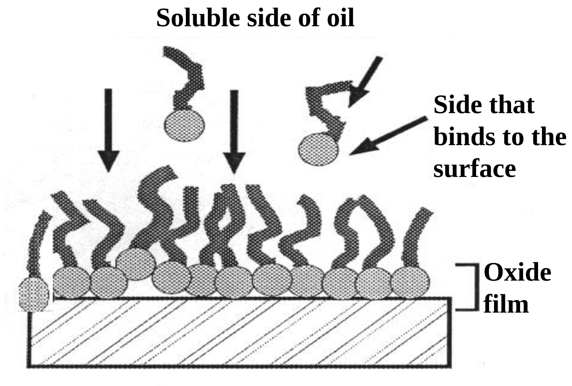

Fig. 5.10 The protective function of additives

Table 5.4 Types of additives and their functions

Types of additives and their functions	
Diesel engines	Anti-oxidant, corrosion inhibitors, Dispersing Detergents, Anti-wear, Anti-foam, Additives that fight acidification of the oil
Steam turbine – compressor	Anti-oxidants, Corrosion inhibitors, Anti-emulsifying agents
Gears	Anti-wear, Anti-oxidants, Anti-foam, sometimes Corrosion inhibitors, Additives for extreme pressure
Gears – worm gears	Anti-oxidants, Corrosion inhibitors, Additives for extreme pressure
Hydraulic systems	Anti-wear, Anti-oxidants, Anti-foam, Corrosion inhibitors, Additives that lower the freezing point, additives that increase the index of Viscosity

One of the possible monitoring systems for the distribution of particles in a hydraulic system requires extraction of 100 ml samples of oil from the system, each of which will be filtered through a membrane, where the detritus to be studied under the microscope are deposited. Once this procedure is applied to a high number of systems, it is possible to define the classes of contamination that express the maximum number of particles larger than the size specified, contained in a 100 ml sample, as illustrated in Figure 5.11

But then in order to correctly express the levels of contamination in fluids, the various standards that have been developed over time can be used.

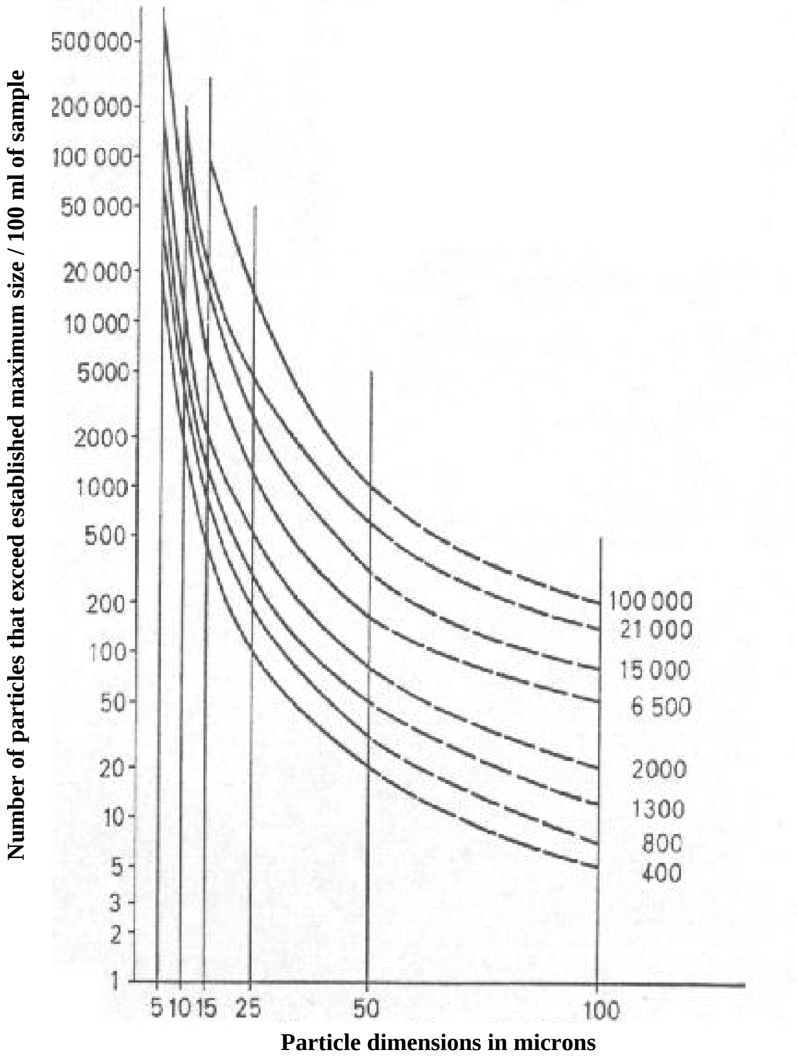

Fig. 5.11 Possible levels of contamination [Source: Collacott, 1977]

In particular, there is a norm for solid pollutants that provides the standard of representation illustrated in Table 5.6.

Table 5.5 The most important standardized representations of levels of contamination

ISO Code	**Particles per ml >10µm**	**Gravito-metrical Level mg/L**	**MIL STD 1246A (1967)**	**NAS Code 1638 (1964)**	**SAE Class 749**
26/23	140000	1000			
25/23	85000		1000		
23/20	14000	100	700		
21/18	4500			12	
20/18	2400		500		
20/17	2300			11	
20/16	1400	10			
19/16	1200			10	
18/15	580			9	6
17/14	280		300	8	5
16/13	140	1		7	4
15/12	70			6	3
14/12	40		200		
14/11	35			5	2
13/10	14	0.1		4	1
12/9	9			3	0
11/8	5			2	
10/8	3		100		
10/7	2.3			1	
10/6	1.4	0.01			
9/6	1.2			0	
8/5	0.6			00	
7/5	0.3		50		
6/3	0.14	0.001			
5/2	0.04		25		
2/0.8	0.01		10		

Table 5.6 Code of Solid Pollutants approved by ISO 16/13

Number of particles per ml		
Greater than	**Less than or equal to**	**R=Range Number**
80000	160000	24
40000	80000	23
20000	40000	22
10000	20000	21
5000	10000	20
2500	5000	19
1300	2500	18
640	1300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1

$\mathbf{R_{5micron} / R_{15micron}}$

For example:

400 Particles >5 micron/ml
65 Particles >15micron/ml

ISO code = 16/13

The presence of water in the lubricant is equally damaging, because it reduces the effectiveness of the additives, accelerating the process of oxidation of the oil and corrosion, reducing the useful life of the lubricant. Immediate corrective action is often necessary, or even replacement of the oil.

The limits to be respected for the presence of the aforementioned pollutants are established by the companies that produce lubricants and by the *American Society for Testing and Materials* (ASTM), and vary according to the system. It is important for there to be a programme of acquisition and recording of data, which envisions reporting whenever the limits are reached, through the use of appropriate software.

5.3.5 The definition of Alarm Thresholds and Oil Sampling Methods

In the past, most users of lubricant analysis techniques used external laboratories, to which they also delegated the determination of the most opportune threshold values for the parameters used. This approach does not permit the best exploitation of the potential of modern *on condition* Maintenance programmes, because it does not take into account the fact that it is difficult for an external laboratory to formulate completely valid proposals, due to the inevitable approximations that take place when information relative to an unknown apparatus must be interpreted.

Obviously, external analysts do not know the environment where the lubricating fluid is used, which the on line operator knows well, on the other hand. It is more suitable, in this sense, for the on line operator, to perform the necessary tests and to be equipped with the necessary tools. Another need of the customer that a laboratory cannot satisfy is to have immediate results. Results may be available from a laboratory only three weeks after the sample of oil was taken from the machine, with costs that cannot be disregarded.

In recent years, with the commercialisation of sophisticated systems that permit users to perform this type of monitoring themselves, many workers in the sector and industry operators have understood the need to set attention thresholds on the basis of their knowledge of the machinery, lubricant and historical data, leaving to the laboratory the task of obtaining complete and punctual results, without expressing evaluations of any kind.

One of the principle benefits obtained by using software for the analysis of the oil inside the works consists of being able to obtain an accurate selection of data from the outset, so that the data relative to failure to respect standards are subject to reporting. All other data will be acquired in a database that will be useful in analysing trends. The data relative to some parameters are characterised by the presence of only upper limits (for example, the measurement of polluting particles present in the oil or the level of debris from wear). In other cases, only a lower limit is set (TBN, additive elements, point of inflammability). Finally, there are parameters that use both limit values (in the case of important chemical and physical properties of the oil, such as viscosity).

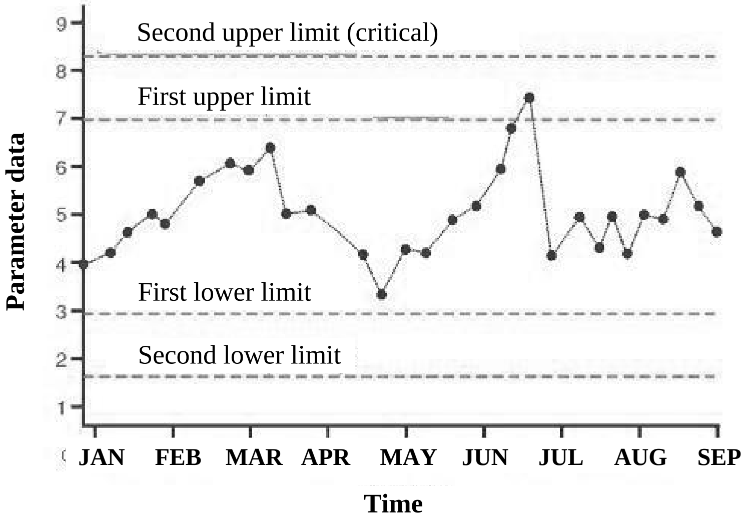

Fig. 5.12 Upper and lower limits applicable in oil analyses

It is possible to identify three principle limit categories. (Fitch, 1998)

- *Proactive limits.* These are limits set according to a "Proactive" strategy, which are used to advise the user of a machine anomaly, related to the cause that produced the anomaly, in terms of decreased performance of the machine or lubricant. These limits are functional to the philosophy of *Proactive Maintenance* and must be managed as such. The condition of the lubricant are therefore controlled as a function of the threshold levels, which are continuously updated and increased in absolute value whenever experience makes it possible. Every limit is the fruit of an improvement, suggested by practice and the threshold level in force up to that time. For example, if a quantity of foreign particles in the lubricant is used as a parameter to monitor, it will be necessary to choose the minimum level of cleanliness, which will consist of perfecting the one in use.

  This type of approach leads to the definition of "goal-based" limits, and can also be used to define the maximum acceptable limits of humidity, acidity, glycol and fuel present in the oil.

  Alternatively, so-called "aging limits" can be determined – namely, the threshold values that concern the primary physical-chemical properties of the oil. These limits have a natural tendency to deteriorate in time, with respect to the moment the lubricant is placed in service, when there is a sudden acceleration in the process of degeneration, which indicates that correct maintenance action is necessary.

Particular care must be taken in measuring the properties of new oil, because it is a sort of "signature" of recognition of the lubricant, which will be used as a point of comparison for future measurements, which will be performed taking care to use the same instruments and the same procedure used to make the initial measurement. This type of limit can be effectively used to study parameters such as TAN, TBN, viscosity and the dielectric constant.

- *Predictive limits* The limits described follow the philosophy of "Proactive Maintenance" and are therefore useful in determining the initial causes of breakdowns; it is also possible to use a different approach, based on a typical strategy of Predictive Maintenance, whose purpose is to report the presence of symptoms of incipient breakdown with reasonable advance notice. The use of these predictive limits, if correctly applied, enables the user to forecast future damaging events for the machine with an appropriate degree of approximation. The limit set for the rate of variation of a parameter can be used by way of example. Suppose that in a given machine it is normal to expect that the concentration of iron in the lubricating oil will grow at a rate of approximately 5 ppm per month. The first month after changing the oil, the expected level of 5 ppm is recorded. The second month, the growth remains stable, presenting 10 ppm of iron and the same trend continues in the third month, when there are 15 ppm of iron. At the end of the fourth month, however, the analyses provide a result of 50 ppm. The software reports this as a critical situation, not because the concentration is abnormal in itself (it is, on the contrary, quite common in industrial practice), but because the rate of variation in the presence of iron went suddenly from 5 ppm to 35 ppm, an unequivocal sign of accelerated wear, which would not have been detected if the limits specified had not been used. In addition to detecting the debris from wear, these limits are indicted for the calculation of polluting particles and the TAN.

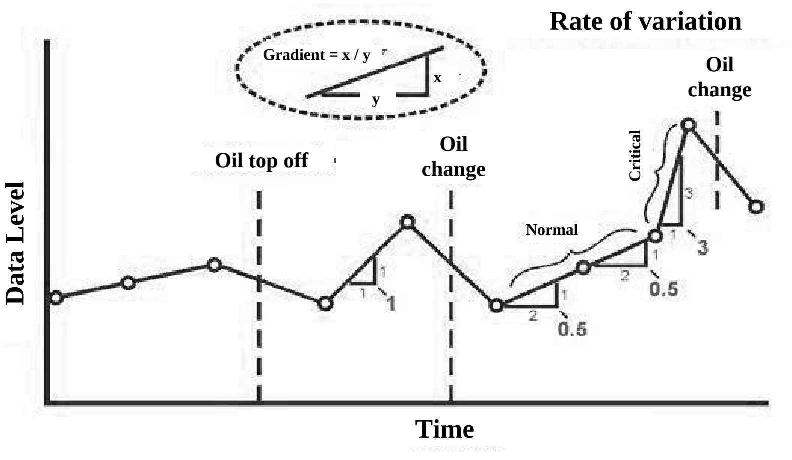

Fig. 5.13 Limits in the rate of variation for a trend analysis [Fitch, 1998]

- *Statistical limits* Statistical limits have been used successfully for a long time in the analysis of oil, again within the ambit of a Predictive Maintenance approach. The availability of a certain number of historical data is necessary relative to the parameters being studies. It is therefore possible to determine a probable distribution and therefore to calculate the standard deviation σ on the basis of which to set the upper limits. The data are available at many laboratories and concern many different models of machinery. This permits easy calculation of the average national values and the consequent standard deviations. When the σ value is exceeded, it means that the result of the test exceeded the historical data values by 68%; 2σ corresponds to 95%, while exceeding the level of 3σ is the equivalent of 99.7% of the database. Many analysts position the level of attention at the value of 2σ. The most frequent applications for this type of limit concern the elementary analysis of metallic particles from wear and the analysis of the density of iron.

Three precautions can be taken to guarantee a valid procedure for the extraction of samples necessary for analyses from the lubricating fluid:

1. *Selection of an optimal sampling point.* In circulating oil systems, the best area to draw off a sample is up line from the filters, where there is a greater concentration of detritus from wear; generally, this means performing the sample on the line of drainage or, in the case where oil drips into the cups without using a special line (for example in diesel engines), by exploiting the pressure in the line between the pump and filters. Areas where the oil sits stagnant should be avoided; on the other hand (tanks, drop tanks), while for spray or immersion type lubricating components, it is advisable to use opportune drip points for sample.

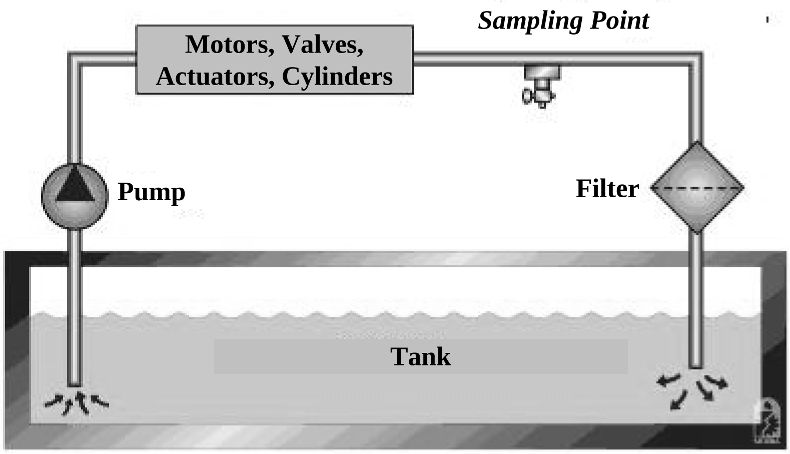

Fig. 5.14 Sampling of fluid for routine analysis in a hydraulic system

2. *Collecting samples correctly.* Once the most suitable point has been selected, it is necessary to proceed with extraction of the sample without invalidating the data. The oil must be hot and well mixed in order to guarantee a representative concentration of particles, humidity and other pollutants. This can be obtained by sampling in turbulent areas, such as in correspondence to an elbow in tubing. It is also necessary for the machine to be analysed to be in its typical operational environment, possibly operating at full speed, with average load values and work cycle. Appropriate valves are often used, which are inserted in the lubricant conduit, permitting extraction of a sample without stopping the machine or losing great quantities of oil. These points must be washed carefully with a violent jet before use and the oil extracted must be placed in laboratory bottles, which are filled up to three quarters of their capacity and closed hermetically to avoid contact with polluting atmospheric agents. In many systems, the only possibility is to take static samples, through special apertures, for example or, alternatively, through vacuum pumps operated manually or by extracting samples from the oil dripping into the cup, following complete changing of the oil. All of the devices mentioned must be rinsed scrupulously after every sample, to avoid contamination and mixing of fluids.

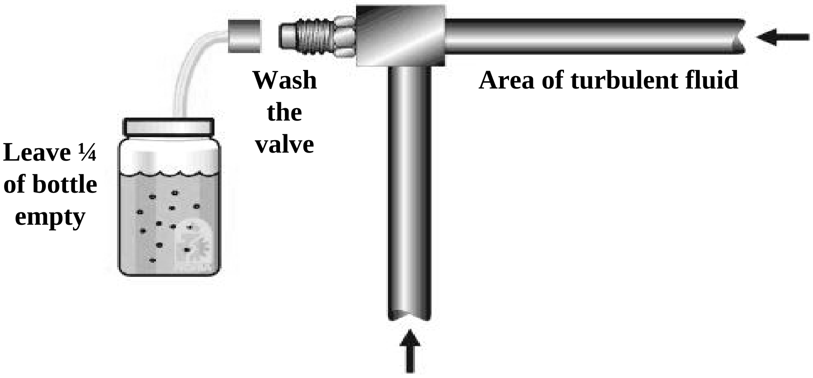

Fig. 5.15 Sampling in a turbulent area

3. *Minimizing contamination of data.* Monitoring the level of pollutants is not sufficient. It is necessary to ensure that the sample does not come into contact with polluting atmospheric agents. Additionally, it is necessary to carefully programme the frequency of sampling. Experience suggests variable intervals, in relation to the critical nature of the machine, its age, workload and in consideration of safety.

Table 5.7 Example of sampling intervals

Machine	Interval in hours
Diesel engine	150
Transmissions, differentials	300
Hydraulic systems	200
Industrial gas turbines	500
Ball bearings	500
Gearboxes	300

5.3.6 Oil Analysis Techniques

Many techniques for the monitoring of tribological systems have been developed, taking into consideration the varied and complex phenomena in the process of deterioration from wear, such as the study of variations in the coefficient of friction, which induce variations in temperature in areas of contact, variations in play, which induce vibrations of variable intensity and frequency, the variation in shape and dimensions of mechanical organs and, finally, analysis of particles produced by wear. Each of these techniques permits us to control a specific aspect of the tribological phenomenon and is therefore used as an alert signal.

In order to achieve true efficiency, a programme of oil analysis must include the following three categories of analysis:

1. *Analysis of fluid properties.* This is an essential investigation to ensure the lubricant has a good level of quality. Its characteristics are cyclically compared with the traits of a new oil, especially with reference to viscosity, TAN, TBN and the point of inflammability;
2. *Analysis of pollutants.* It is important to perform tests such as the calculation of particles, the analysis of humidity, the glycol test (to signal possible leaks of the coolant fluid), control of fuel present;
3. *Analysis of debris from wear.* This is the type of analysis that can be most directly correlated to the state of health of the machine.

The most widely used techniques are explained in the following paragraphs.

5.3.6.1 Ferrography

Ferrography, developed in the Seventies, has attained a high degree of dependability in use in the last decade, as a result of continuous improvement in machinery, methods of use, procedures of sampling and analysis of samples and interpretation of the results. This technique offers the following opportunities:

- Collection of particles from wear, dispersed and deposited in the lubricating fluid as a mass on a transparent substrate (ferrogram);
- Selection and separation of large particles (greater than 10 μm – severe wear) and small particles (approximately 5 μm – normal wear) in two groups, with localisation in different areas of the substrate;
- Determination of the concentration of large and small particles with a densitometric reader;
- Study of the significant particles for the definition of the morphological properties and nature of the materials.

The principle advantage of the ferrography with respect to other techniques is the ability to deposit and anchor particles of wear on the ferrogram according to the mass. In fact, this facilitates the user in conducting various precise analyses, which would otherwise be difficult to realise, in order to determine the characteristics of the fragments. Additionally, the ferrography is more sensitive to the initial symptoms of wear for motors, when the particles remain in the oil in the form of stable colloids. Additionally, it guarantees the identification of particles with variable dimensions ranging from less than 1 μm to about 250 μm, which is impossible for the spectrometry.

To summarize: the ferrography is a technique that permits identification of particles of consistent dimensions, and identification of the manner of wear that caused them. It has the disadvantage of being slow and costly and requires specialised personnel.

5.3.6.2 Spectrometry

The spectrometry is the most commonly applied technique to analyse debris from wear. It is able to show parts per million (ppm) of concentrations of at least 20 different elements, including metallic elements (iron, aluminium, chrome, copper, tin, lead, etc.) and additives (calcium, barium, magnesium, zinc, phosphorous, boron and molybdenum). This is clearly a great advantage for the operator, who can limit the phase of inspection only to the components made of aluminium and iron, if the analysis shows a growth n the percentage of these two metals.

There are four fundamental Spectrometric Oil Analysis Procedures (SOAP):

1. Taking of oil samples
2. Spectrometric analysis
3. Diagnosis – interpretation of the data
4. Validation of the diagnosis

We have already spoken of sampling procedures in previous paragraphs. The analysis is based on the knowledge of several principles of atomic physics concerning the phenomena related to energy exchanges between atoms. In this context, the exchanges of energy caused by the transitions of electrons take on particular importance. In fact, these phenomena, caused by the absorption or emission of light in correspondence to the ultraviolet and visible region of the spectrum, namely for the wavelength between 2000 and 8000 Angstroms (Å), where 1 Å = 10^{-8} cm, in relation to a specific chemical element. The spectrometer is an instrument designed to identify and measure radiations in this interval. Table 5.8 lists several typical wavelengths.

Table 5.8 Wavelengths of the most common elements

Chemical elements	Wavelength (Å)
Copper	3247
Iron	3270
Chrome	3579
Nickel	3415
Lead	2833
Aluminium	3092
Magnesium	2852
Silver	3281

The process of evaluation may be manual or computerised. It is based on the use of special guidelines for the debris from wear, but also takes into account a considerable number of variables. These include the operating conditions of the equipment (during the running in period, for example, a high concentration of metals due to wear would be a reason for concern), the environmental characteristics, the machine hours since the last oil change. If a machine is left idle for a long period of time. It will be normal to encounter the presence of rust; the age of the machine must also be taken into consideration, as well as variations that have taken place in the stress it is subject to.

5.3.6.3 Instruments of Analysis

The ferrography uses the following fundamental equipment:

- ***The Direct Reading (DR) instrument***
  The need to have a reading of the tribological situation of operating systems placed in various locations in a timely manner has determined the need to develop a Direct Reading (DR) instrument, which is easily placeable and allows simple and rapid determination of the quantitative parameters, in terms of concentration and dimensional distribution of the particles.
  A sample of oil of 1 ml containing wear debris, taken from the lubricating circuit of the tribological system it is desired to monitor, is opportunely diluted

and made to flow through a capillary of calibrated glass, placed between the poles of a static magnet. The magnet is the heart of the equipment and is equipped with a high gradient of flow in the direction in which the oil flows in the capillary. Large magnetic particles (>10 μm) precipitate in correspondence with the first optical fibre, while the smaller ones (approximately 5 μm) precipitate in correspondence to the second one, placed 6 mm down line. Following a phase of washing of the particles, obtained by causing an appropriate solvent to flow through the capillary to remove every residual trace of oil or substances that cause opaqueness, a luminous monochromatic ray of appropriate width is passed through the capillary, whose intensity is read by photo resistors. The density of the large particles of debris DL and the small particles DS are detected as an attenuation of the luminous rays produced by the percentage of surface area occupied by the particles.

The DL and DS values provide a quantitative index, representative of the total volume of particles produced:

$$Q = DL + DS \tag{5.2}$$

The difference between DL and DS provides an index of severity, representative of the intensity of the phenomena of wear.

$$S = DL - DS \tag{5.3}$$

In order to keep the various wear phenomena under control, especially processes of corrosion that produce large quantities of very small particles, provoking a reduction of S, the index of wear was adopted (Maciga, 1989), defined by:

$$I_s = Q \cdot S = \left(DL + DS\right) \cdot \left(DL - DS\right) = DL^2 - DS^2 \tag{5.4}$$

This index represents a particularly sensitive parameter in detecting modest variations in the density of large and small particles, therefore, the early occurrence of abnormal states of wear. The DR is essentially used as an alert sensor and to develop the "Trend Analysis", whose purpose is to monitor operating systems.

- ***The analysing instrument***

  The basic analysing instrument of the ferrography is the only one capable of efficiently collecting the particles of wear and distributing them in order of mass on a transparent substrate called the ferrogram. The functional scheme is shown in Figure 5.16:

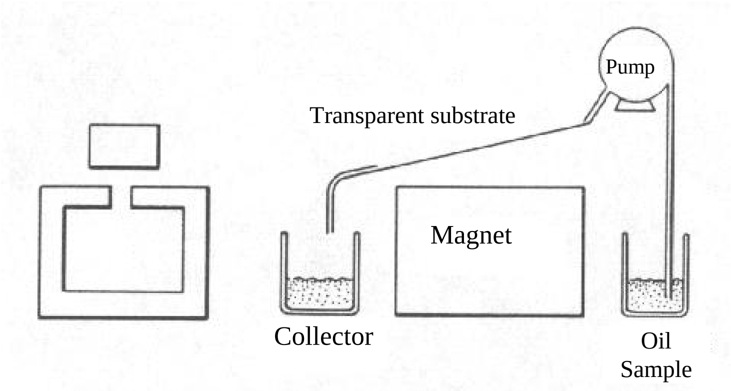

Fig. 5.16 Analysing instrument [Source: Collacott, 1977]

A volume of oil of 3 ml containing wear debris is appropriately diluted and made to flow with a peristaltic pump on the ferrogram, placed in a slightly inclined position between the poles of a static magnet with a high flow gradient (which reaches the maximum at one extreme of the ferrogram), analogous to the one used for the DR. The substrate, which is 60 mm long, is treated to resist without deteriorating, at temperatures of over 600°C. In the central area of the ferrogram a U-shaped barrier is produced with a special wax, which facilitates the flow of the oil towards the exit. A typical ferrogram is shown in Figure 5.20.

The fragments are gradually precipitated magnetically as the lubricant flows on the ferrogram. Particles with dimensions greater than 10 μm are deposited in the area of entry onto the slide, while those with smaller dimensions are deposited about 6 mm down line; following a washing cycle with appropriate solvents, the particles adhere perfectly to the ferrogram and can easily be studied under the microscope.

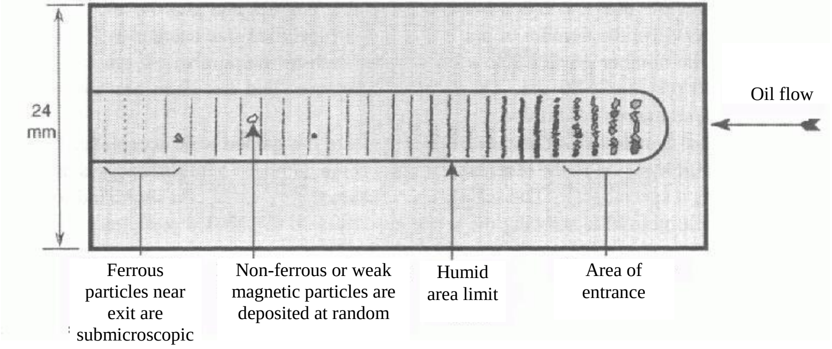

Fig. 5.17 Example of a ferrogram

This all takes place through extremely simple and codified operations and the time required is on the order of ten minutes, without counting that from analysis under the microscope, the manner of wear that generated the fragments can be determined. Nevertheless, specialised personnel are required in order to formulate a correct diagnosis through study of the slide and the process takes about 20 minutes.

- ***The ferroscope***

  The ferroscope is used to study the morphology and nature of the particles deposited on ferrograms. This instrument is designed to offer the best possible support in the qualitative analysis of fragments of debris from wear.

  It consists of a dichromatic microscope connected with a video camera and high-resolution monitor. The microscope allows illumination of the ferrogram with two luminous monochromatic rays of different colours at the same time, focused on the particles of wear debris. Generally, the ray that illuminates by reflection is red, while the one that illuminates by transmission is green. While the quantitative analysis of the particles is not difficult from the operational point of view, because the DR proceeds automatically for a correct and precise reading of DL and DS, in the case of the qualitative analysis with the ferroscope, the preparation of the operator is decisive in achieving an accurate result. In order to facilitate this task, techniques of observation of the particles with the ferroscope have been developed that are extremely simple, but sufficient to provide the necessary elements for a precise diagnosis. Extremely complete catalogues of particles have also been realised, which permits grouping of particles as a function of the operational condition of the systems. Analogously, in order to determine the materials the fragments are made of, procedures of observation and treatment of the particles are available that enable the operator to group them in classes of materials.

  Specific alloys can be distinguished in every class of materials, using the Technique of Selective Oxidation (TSO). The TSO consists of heating the ferrograms at room temperature to specific temperatures and for controlled periods of time. Under these conditions, the surface of the particles is covered with a micro stratum of oxide, whose thickness is a function of the temperature, time and characteristics of reactivity of the materials making up the fragments. For different thickness of the layer of oxide, the particles take on different colours if they are observed under the ferroscope. The most important correlations between temperature, time, colour and material are shown in Table 5.9.

  The ferroscope can also be equipped with a ferrogram reader (FR) made up of a photoelectric cell, which uses the illumination of the microscope to enable the operator to determine the density of the particles at any point of the ferrogram. While the DR may detect the density in two distinct areas of the substrate, corresponding to severe and normal wear, the FR may read along the entire dimensional spectrum of the particles, up to values of less than a micron (typical of fragments that precipitate in the area of exit from the ferrogram).

The use of the FR allows us to accurately monitor atypical process of wear and tear, such as corrosive elements present in lubricated operating systems.

Table 5.9 TSO characteristics for several materials

Material	**Heating Time (secs)**	**Colour at various Temperatures**			
		330°C	400°C	480°C	540°C
Bearing Steel	90	Blue-grey	Greyish-yellow	-	-
Quenched steels	90	Blue	Grey	-	-
Cemented steels	90	Greyish white	Yellowish white	-	-
Cast iron	90	Bronze	Bluish bronze	-	-
Nickel Alloys	90	Unvaried	Unvaried	Bluish bronze	Blue
Stainless steel	90	Unvaried	Yellow	Bronze	Bluish bronze
Lead Alloys	90	Unvaried	Unvaried	-	-

The spectrometry fundamentally uses a single instrument of analysis: the spectrometer.
Nevertheless, several types of spectrometer used, each of which has advantages and disadvantages.

- ***Emission spectrometer***
  By directly exciting the metallic impurities in the sample of oil at high voltage (15000 V), they emit radiations with characteristic wavelengths for the metal, which can be analysed with the spectrometer. The instrument consists of an opening, followed by a prism, which is necessary to separate the radiations into the various wavelengths making them up, after they have gone through the opening, and a photoelectric system that identifies and measures the various radiations.
  There are two types of emission spectrometers:

  1. RDE (Rotating Disk Electrode)
  2. ICP (Inductively Coupled Plasma).

In the first type, a rotating disk electrode drags the sample of oil continuously in the area between the disk and the other fixed electrode, made up of a bar of graphite; the electric arc is then shot so that the electrons in every atom of the sample are initially moved to more external unstable orbits, to then return to their normal orbit, emitting radiant energy.

The main disadvantage of this technique, as seen in the table below, consists in the limited precision due to the differences between the return signals, if several different derivatives of petroleum are used, due to a phenomenon known as the "matrix effect".

Table 5.10 Advantages and disadvantages of the RDE technique

Advantages	**Disadvantages**
Simple to use	Matrix effect
Without preparation of the sample	Only with samples of oil
Robustness	Inefficient for particles > 10μm
No liquid or refrigerating gas	
Little maintenance	

In the second type of spectrometer, on the other hand, a plasma is used that has been created without the assistance of electrodes, but through a flow of inert gas (argon), which acts as the secondary enclosure of a transformer, reaching extremely high temperatures (8,000 – 10,000° C) and ionising. The sample of oil is aspired into the plasma, causing the disassociation and excitation of the atoms.

Table 5.11 Advantages and disadvantages of the ICP technique

Advantages	**Disadvantages**
Performance	Requires preparation of the sample
Limited Matrix effect	Requires specialised personnel
Flexibility	Inefficient for particles > 5μm
Automation	Need for gas (argon)

In both cases an optical fibre is used to channel and focus the radiant energy onto a concave grid that divides the beam into various lines of spectrum associated with the elements present; successively, the photo multiplier

channels translate the energy emitted into an electric signal, whose intensity provides a measurement of the concentration of elements present.
Thanks to the presence of separate photo sensors for each element and teleprinter output, this technique guarantees immediate availability of the results of the analysis.

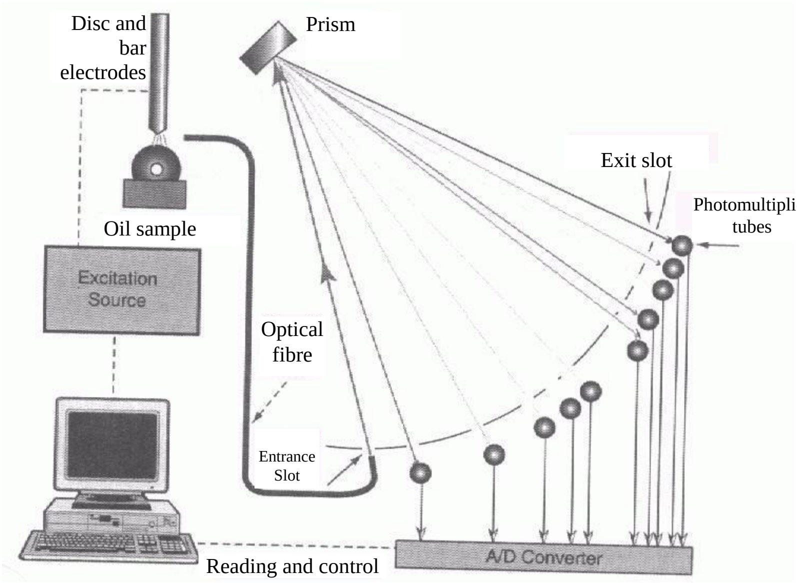

Fig. 5.18 Flowchart of an emission spectrometer

- ***Atomic Absorption Spectrometer (AAS)***
  Five elements are required in order to perform this type of analysis:
  - A source of energy that emits the characteristic light of the element it is desired to determine the presence of (an electro luminescent cathode);
  - A source of energy to transform the metallic elements present into atomic vapour (generally a nitrous oxide – acetylene flame);
  - A wavelength selector, to select the proper wavelength for the measurement light (generally a prism with a lens and fissure system);
  - An instrument that converts luminous energy into an electric signal (a photo multiplier tube with an attached amplifying circuit);
  - A reading device to measure the quantitative intensity of the electric signal, such as a printer.

  The arrangement of these instruments is shown schematically in Figure 5.23.

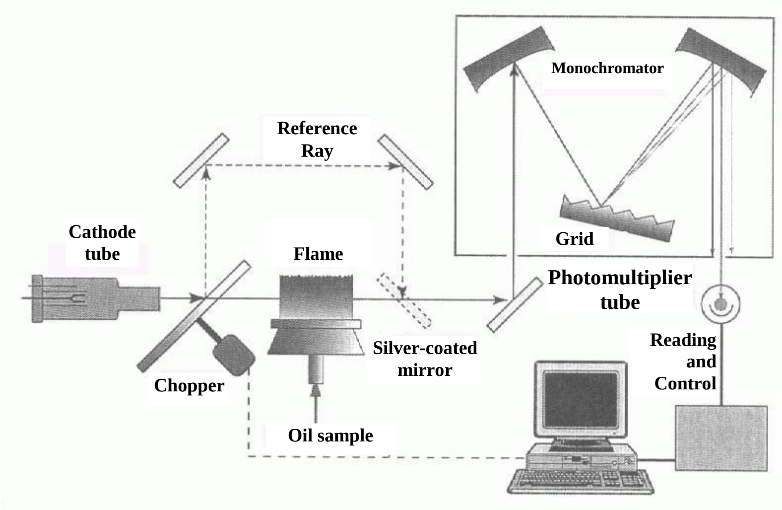

Fig. 5.19 Scheme of an Atomic Absorption Spectrometer (AAS)

The flame vaporises the sample of oil and takes the atoms to a higher level of energy, which makes them suitable to absorb the light emitted by the cathode. The cathode emits a luminous beam with the specific wavelength of the element to be analysed, on the basis of which the monochromator is adjusted, which simultaneously receives the reference signal from the cathode, thanks to the chopper. In this manner, the portion of luminous energy absorbed can be placed in relationship, through algorithms implemented on the computer, with the concentration of elements present in the oil.

The advantages and disadvantages of this technique are summarised in Table 5.12.

Table 5.12 Advantages and disadvantages of the AAS technique

Advantages	Disadvantages
Simple to use	Slow, one element at a time
Analytical approach	Requires preparation of sample
Virtually devoid of interference	Inefficient for particles > 5μm
Low purchase price	Requires a luminous source

The emission method is the most widely used, despite the high level of investment required, thanks to the speed of the test (40 samples/hour for 20 different elements), while the Atomic Absorption Spectrometry has the advantage of being more reproducible for low concentrations of particles.

- ***X-ray Spectrometer (XRF)***
  By bombarding the sample of oil with X-rays, the atoms of the particles of wear debris, pollutants and additives expel electrons, remaining in the state of ions. At this point the most external electrons, characterised by weak connections, occupy the vacancies left by the expelled electrons, losing energy in the form of fluorescence – namely, emitting a second band of X-rays, whose spectrum is typical of the element and whose intensity is proportional to the concentration of the element itself. This technique has a retention capacity of ' – 55o p.p.m., an accuracy of ± 6 p.p.m. and a temperature range from room temperature to 400°F.

Table 5.13 Advantages and disadvantages of the XRF technique

Advantages	**Disadvantages**
Analysis of several elements	Low sensitivity
No Preparation of Sample:	Only for atomic number > 10
Non-destructive	High cost
Analysis of large particles	

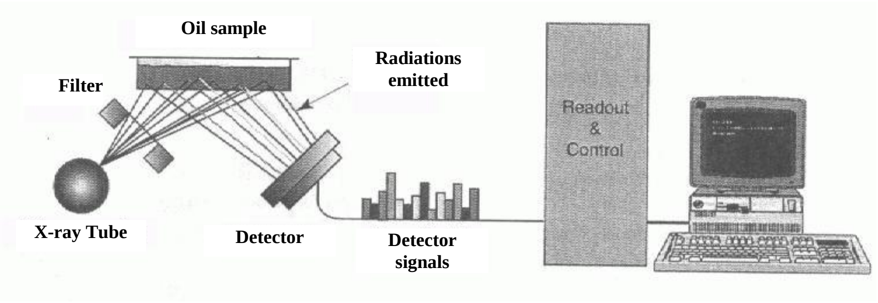

Fig. 5.20 X-ray spectrometer scheme [Booser, 1997]

- **Fourier Transform – Infrared Spectroscopy (FT – IR)**
  Lastly, this type of spectrometry analysis does not refer to research on wear debris, but to the measurement of several characteristics of the oil, which are useful in establishing the remaining life, as illustrated in Table 5.14.

Table 5.14 Physical properties determined by the analysis

1	Level of oxidation
2	Level of nitration
3	Combustion residue
4	Level of sulphates
5	Presence of water
6	Contamination from fuel
7	Glycol
8	Additives

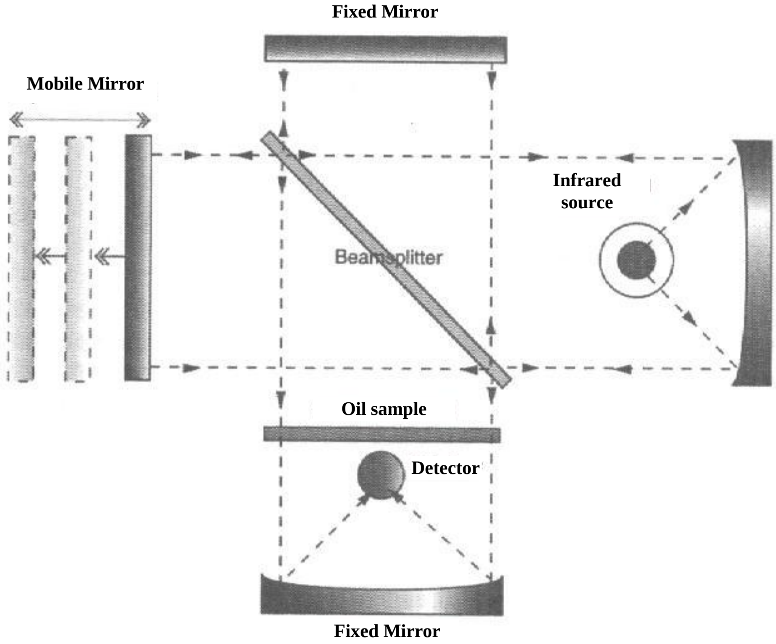

Fig. 5.21 Scheme of an FT – IR spectrometer

This spectrometer measures the energy in the infrared region of the spectrum and consists of three components: a source, a Michelson interferometer and a detector.

The interferometer, in turn, consists of a beam splitter, a fixed mirror and a mobile mirror. A wide beam of infrared light from the source is split by the beam splitter into two beams of equal energy, one of which is reflected by the fixed mirror and the other by the mobile mirror, reuniting on the splitter. A constructive or destructive interference thus takes place, depending on the relative position between the two mirrors; thus, the infrared beam can then be addressed towards the sample to be examined, which will absorb the wavelength corresponding tot he chemical elements contained. The intensity of the portion of the infrared ray that succeeds in crossing through the sample is detected by the detector and sent to the computer, which uses algorithms based on the Fourier transformation to convert the time/intensity values into frequency/intensity, from which the software is then able to glean the required information.

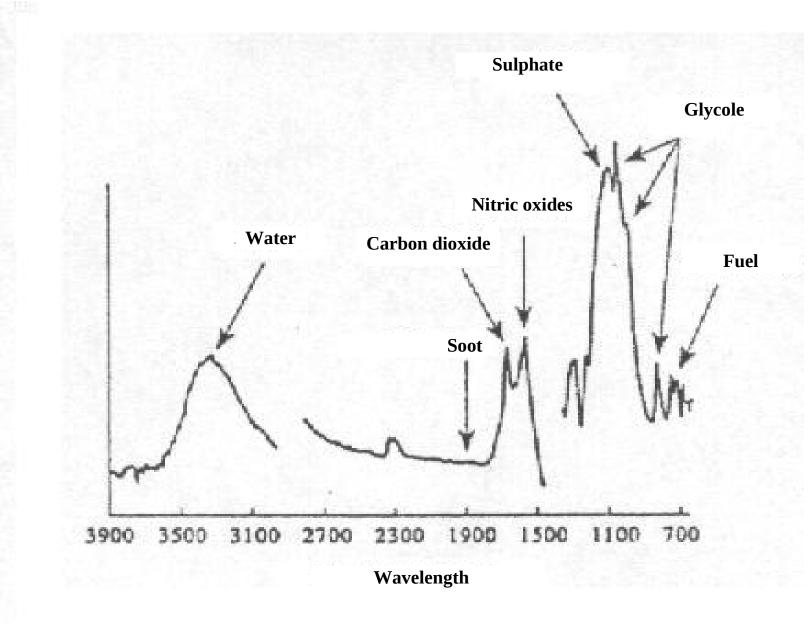

Fig. 5.22 Each peak on the diagram corresponds to an element, whose presence can thus be shown

By way of summary, Spectrometry is therefore the most widely used and complete technique to analyse oil lubricants, but also has three important limitations:

1. The instrument is complex and costly; its use is therefore generally limited to specialised laboratories, with the inevitable delays this entails;
2. This technique measures only small particles of six – seven microns, due to the impossibility to atomise larger particles: this is a serious defect, if you consider that fragments of greater size are a symptom of sever wear and tear;
3. Spectrometry does not distinguish between metallic particles, oxides and salts: in the presence of rust, this can lead to errors in evaluation.

5.3.6.4 Other Techniques for the Analysis of Particles

Many other less used but advantageous techniques are available under specific testing conditions, to perform analyses on oils. This refers to:

- Magnetic detector;
- Used oil absorption test;
- Thin layer chromatography
- Microscope analysis;
- Televised microscope;
- Monitoring of the distribution of particles;
- On line monitoring.

The most important characteristics of these are discussed below.

Magnetic detector

This is a technique that is complementary to the SOAP method. The SOAP method aims to identify suspended fine metallic particles, like the ones caused by wear and tear of bearings or keys, while this system allows detection of metal flakes like the ones typical of breakage due to fatigue. The method consists in capturing these particles from the ferrous nucleus, utilising a magnet. A detector, in fact, consists of a structure mounted on the lubricating system and a magnetic probe inserted so that it is exposed to the lubricant, in a position that permits maximum effectiveness (for example, outside an elbow in a conduit, where centrifugal force pushes the particles onto the magnet). An automatic closure valve permits replacement of the used probe with a new one without a loss of oil, at regular intervals (generally every 25 machine hours), in order to perform the analysis of the flakes captured up to the time of substitution.

Used oil absorption test

A drop of oil is deposited on filter paper, so that the largest polluting particles remain on the surface, forming a circular crown with a small radius. The oil then filters through the paper, leaving well defined circular areas, where the particles carried by the lubricant are deposited, arranged by increasing size. After about 24 hours, which are necessary for the complete absorption of the oil, a photometric analysis is performed on the particles, arranging the paper on a slide illuminated from below, to better bring out the characteristics of the particles.

Thin layer chromatography

In general, chromatographies are based on the fact that the components of a mixture may have different levels of affinity for an absorbent: in this particular application, a thin layer of selected absorbent is placed on an inert support, having a thickness of 0.25 mm. The structure is placed vertically in a vat containing the solvent. When it rises due to capillarity, it also transports the components of the lubricant sample, which is placed at the beginning of the test on the bottom of the recipient. The various components can thus be identified on the basis of the level reached or through a selective colour analysis.

Microscope analysis

When the particles have been extracted from the oil by evaporation or absorption, they can be studied under the optical microscope or, if necessary, under the electronic microscope, after having agitated them with ether and deposited a drop on the film to be analysed. The film allows us to obtain a good dispersion of the particles. The study is based on a numerical classification that takes into account the characteristic properties of the particles, as suggested by a special Atlantis. The numerical system utilised is of a binary type, where "0" indicates presence and "1" indicates the absence of each of the six characteristics shown in Table 5.15.

Table 5.15 Binary system for microscope analysis

Characteristics	Meaning of the digit for each characteristic
Transparency	The particle is opaque
Colour	The particle is coloured
Anisotropy	The particle is anisotropic
Refraction index	Used for an index greater than 1662
Dimensions	A dimension is a quarter or less than each of the other two
Shape	It is a needle, namely with a dimension at least equal to four times the other two

The analysis provides a six-digit figure, which unequivocally identifies the particle or group of particles.

Televised microscope

With this instrument, the time is reduced for analysis with respect to a normal microscope, inasmuch as it provides an instant reading of the number and shape of particles contained in a certain sector. The image is projected by a telecamera onto a monitor and is transmitted to an electronic sensor, which signals the variations read during scansion; the data is then processed by a computer that is capable of performing a division of the fragments based on their size.

Monitoring of the distribution of particles
This is a technique that was recently developed by the United States Navy, which takes into account the luminous attenuation due to a chemical and thermal degradation of the oil. When a luminous ray directed towards the outgoing flow of oil from a container is interrupted by the presence of particles, a photocell sends a signal to an automatic counter, which, on the basis of the entity of the signal, is capable of supplying a division of the particles on the basis of the dimensions of the individual fragments. All of the data is fed into a computer, which permits correlation of the trend observed with the possibility of an incipient breakdown.

On line monitoring
There are portable devices today that make it possible to perform an initial analysis of the oil, in search of particles due to wear or other particles, to identify first of all the samples that need to be taken to perform an accurate study in a specialised laboratory. These devices are based on phenomena of magnetism and permeability and their limited sensitiveness limits their use to systems characterised by accelerated wear and tear or by a high concentration of particles (for example, gearboxes or transmission organs).

5.3.7 Monitoring of Lubricant Properties

The second part of a programme of analysis of the oils, as stated, aims to evaluate the deterioration of the chemical and physical properties of the lubricant. Many of these characteristics can be measured with the FT – IR Spectrometer described above; the others are described below, along with the relative instruments of evaluation.

- Viscosity
  The most widely used test is identified with the abbreviation ASTM D 445 and consists of connecting a bottle containing the sample to be studied to a capillary tube, previously cleaned, at a temperature of 40° C. The oil is made to flow inside the tube and the time necessary to cross a reference tract of the tube is measured; the computer provides the output of the value of viscosity in centistokes (cSt), as a function of the time measured and the factor of calibration of the tube. The set of equipment described makes up a viscosimeter.

- TAN –TBN
  The test to calculate the TAN is identified with the abbreviation ASTM D 974 and simply implies an evaluation of the colour of the sample, after a solution of

potassium hydroxide has been added to it (KOH), which provides an accuracy of 15%. A similar system is used to calculate the TBN, with the ASTM D 2896 test; it is performed with instruments called "Titling Instruments", which are capable of performing the test in an almost completely automatic manner.

- Insolubles
  This type of measurement takes place through the deposit of a drop of oil on a special filtering paper and successive visual evaluation of the stain left. This is obviously a method that leaves a great deal to individual interpretation. The ASTM D 893 is a codified test, where the sample of oil is mixed with pentane and placed in a centrifuge; the precipitate is then dried and weighed to measure the content of insolubles, on the basis of the percentile increase of weight of the membrane used for filtering.

5.4 Information Technology Systems in support of CM

Computers play a very important role in the activity of *Condition monitoring:* they guarantee greater efficiency

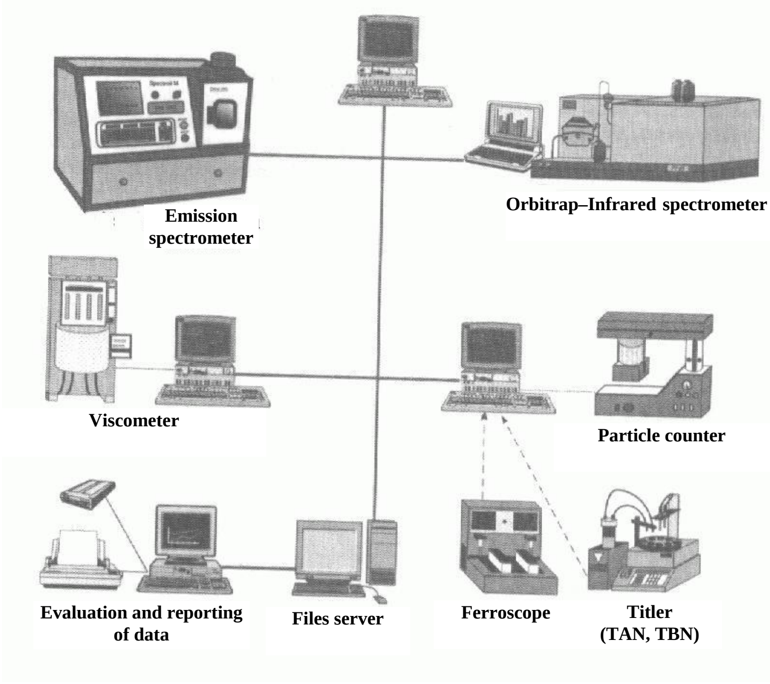

Fig. 5.23 Complete instrumentation in a laboratory equipped for used oil analysis

in the collection of results from measurements, which translate into time gained and therefore into the possibility, for the operator, of performing several tests on several machines. The structure of a computerised system of monitoring, which includes various types of analysis, can be schematized as shown in Figure 5.24.

Many different systems of this type are available on the market, which are capable of satisfying the most disparate requirements. The systems available range from the simple, capable of performing and permanently recording the initial analysis of the data supplied by the user, to complex, designed to perform more in-depth research, with the assistance of flexible techniques of information storage. In the latter case, we are dealing with sophisticated *multi-channel* monitoring systems, which perform spectrum analyses, performance analyses (electricity consumption, efficiency of thermal exchanges, etc.), expert analyses of data to identify the specific conditions of breakdown and evaluate the severity of the malfunction.

Lately, it has been noted that many of these on-line systems, instead of using the current processing information to evaluate machine conditions, are limited to acceptance of the data that are supplied by a *Programmable Logic Controller* (PLC), which indicates that the machine is in a condition to operate at full regimen. But if the mechanical system is subjected to stress at regimen (namely at a full load) only occasionally, the trend analysis based on periodical readings provide misleading results in the presence of a wide range of operational states. For this reason, expert integrated systems have been developed with systems of data processing, capable of performing an accurate evaluation of the health of the machine, succeeding in providing a prognosis relative to the remaining useful life of the apparatus, under changing conditions of operation.

An example of this type is provided by the system for the CMB developed by Honeywell Corporation in collaboration with Predict/DLI for the United States Navy, called *Machine Prognostics/Diagnostics System* (MPROS). This system uses Micro Elector Mechanical Systems (MEMS) of conventional sensors, placed on the machinery, intelligent units for processing of the signals called *Data Concentrators* (DCs) and a central subsystem called the *Prognostics, Diagnostics, Monitoring Engine* (PDME) This MPROS collects data continuously from the sensors, relative to vibrations, temperature, pressure, voltage, etc. The consequent flow of information is integrated first by the DCs, to permit *data fusion,* and then by the PDME. At this point the results of the various algorithms of Diagnostics and Prognostics come together to produce the most complete analysis possible.

A common need of all of the most powerful software packages is to configure the layout of the database correctly. This refers to the portion of the information system memory used for storage and management of the results provided by the measurements performed. Substantially, it is necessary to design the database to be able to manage all of the machines that it has been decided to monitor.

Additionally, it is in this phase that the system must be provided with useful indications to establish how often the measurements must be performed, what the alarm thresholds are, how the instruments must be set before every measurement, also providing details on the nature of the machine (parameters of bearings, characteristics of gears) in order to identify, through the study of the breakdown frequencies, which component requires repairs.

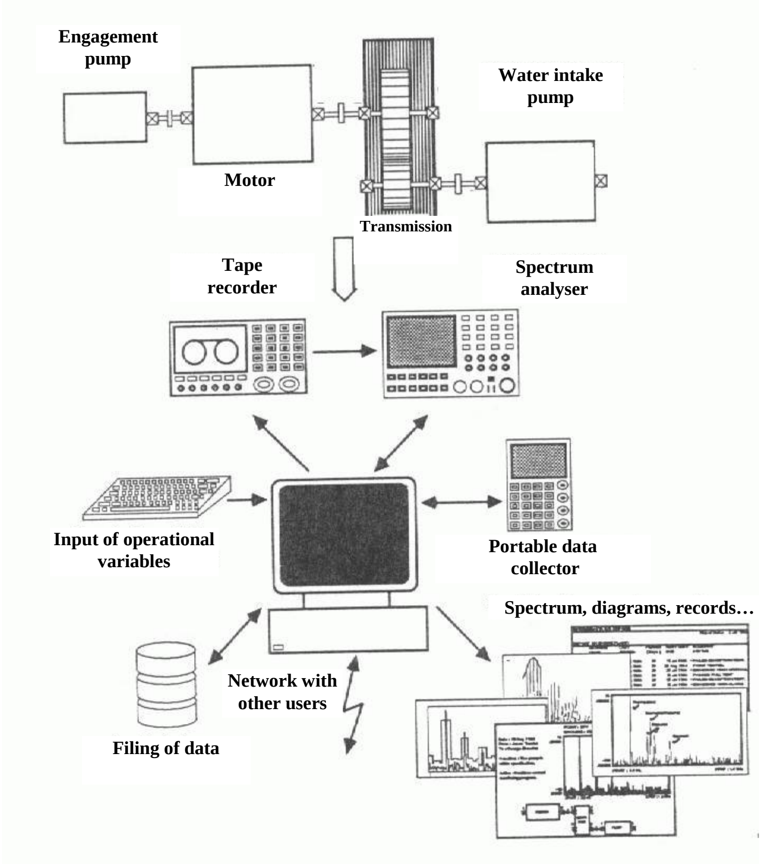

Fig. 5.24 Structure of a computerised monitoring system [Source: Tranter, 1990]

Once this is done, the system practically does everything by itself, making only rare intervention necessary in future. In the analysis performed, it is important to make it possible to compare the trend values relative to the same machine and also between different machines, and also to compare data of different kinds (for example vibrations and oil contamination). The comparison could be graphical or statistical, providing it brings to light existing correlations. In this manner, the operator will be called upon to perform an extensive analysis only in the event the threshold of attention has been exceeded.

5.4.1 Future Developments in Condition Monitoring

Currently, progress in the field of *Information Technology* (IT) [3] allows acquisition of data "in real time" and analysis of the information, simultaneously with the productive process, thereby permitting implementation of *Condition Monitoring* techniques that have heretofore been only theoretical. At the same time, this technology makes it possible to design advanced production systems, which use "intelligent machines" to guarantee a greater level of automation. In a word, IT "makes it possible to identify, decipher, transmit, receive, store and interpret information and to consequently promote appropriate action on the system" (Davies, 1998). Theoretically, all of these activities should be performed automatically, on the basis of the knowledge of the current condition, in real time: *Real Time Actual Condition Knowledge* (RTAK). This implies the use of information technology processes in real time, rapid interpretation of the data and an automatic logical – decision-making process.

In this scenario, Maintenance must evolve in an efficient organisation, which uses the capabilities of Information Technology to place them at the service of extremely complex and highly technological industrial systems. Today, the state of the art is such that it is possible to implement these concepts on machine tools with *Computerised Numerical Control* (CNC) and on *Flexible Manufacturing Systems* (FMS), through methods of adaptive control, with a consequent increase in the rate of utilisation of machinery, in the quality of the components and the life of the system, and a reduction in the cost of labour and space required.

Adaptive Control (AC) is *"a technique that permits a system equipped with sensors to identify a change in the environment and, if the variation is unfavourable, to automatically undertake corrective action, in order to optimise the system under control according to a given criterion"* (Williams, Davies, Drake, 1994). On the basis of this definition, it is possible to classify systems of adaptive control in two groups:

1. *Technological Adaptive Control* (TAC), which in turn contains two distinct types of systems:
2. *Adaptive Control of Constraints* (ACC), a technique that aims to obtain the performance of system operations in safety, in respect of certain physical limitations correlated to the machine and is the only one of the three that has already been consistently applied commercially;
3. *Adaptive Control of Optimisation* (ACO), a technique that aims to optimise the economy of production criteria;
4. *Geometrical Adaptive Control* (GAC). This is a product oriented system, whose purpose is to perfect the conformity of components with specifications, through continual adjustment of the position of the tools being operated, and of their progressive wear, for example.

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[3] With a simple definition, it could be stated that IT is "the manner in which we collect, record, process and use information" (Davies, 1998).

Recent developments in the technology of integrated circuits and optoelectronics have reached the point of making it possible to assimilate the functions of several sensors in a single unit. Additionally, information from different sources of data can be combined to produce what could be called an "intelligent sensor". These sensors also have the ability to evaluate, to a certain degree, the incoming data, in order, for example, to amplify the signal above the background noise, filter it or combine it with other signals from different sources. It is already possible to build prototypes with these characteristics and, thanks to the use of microelectronics; they can also be incorporated into an integrated system of sensors. Successive research in this sense aims to obtain fast sensors, which are accurate and have the ability to perform self-diagnosis, with a simple design if possible and preferably dependable, not intrusive and such as not to alter the complexity of the system.

The methods of optoelectronic measurement seem to respect these specifications quite well, and could soon be used in interesting industrial applications. The use of this type of sensor in an automatic system would enable the user to:

- reduce the frequency of defective products;
- eliminate the possibility of a casual process of error due to uncontrollable environmental parameters;
- provide information relative to the product and process that is useful in forecasting breakdowns, assuring quality, control and diagnostics.

5.5 Soft Computing Technologies applicable to support CM

Among the prognostics technologies it is possible to apply, great interest has recently developed with respect to soft computing type information processing systems. This term is indicated among the methodologies for the treatment of data based on algorithms that are not limited simply to the processing of the information received, but which create other algorithms and procedures suitable for this task. In practice, in a very simplistic vision of the subject, which is suitable however to mention the concept of soft computing, we may speak of meta-algorithms, capable of generating the algorithms necessary for the treatment of the data submitted to them.

Soft computing is rightfully considered a branch of the extremely interesting field of research that deals with artificial intelligence and there are four primary branches of this type that can be delved into:

- Fuzzy logic;
- Genetic Algorithms
- Expert Systems
- Neural Networks.

Fuzzy Logic is an extension of classical logic. While in classical logic an element can only belong or not belong to a set, in *Fuzzy Logic* a degree of belonging of an element to a set is introduced, therefore it is possible to find assertions of the type: "Element x possesses an 0.34 degree of belonging to class A and a degree of 0.56 of belonging to class B". In this logic, the concepts of intersection and union of sets are therefore amplified, to the point of seeing all theorems of classical logic in this key and drawing up new ones. The objective is to draw relationships between data that possesses a fundamental uncertainty and to extract, in any case, the information they contain.

Genetic Algorithms are used for optimisation. A parametered algorithm is created to find the optimum of a function and various strings of casual parameters. The algorithm is applied with the parameters of each of the strings and the strings are selected that have reached the greatest results, eliminating the others. At this point the winning strings are reproduced with a genetic *cross over* (which is the reason for the name). That is to say, a new set of strings is created, obtained by mixing the elements of the winning strings together with a modest quantity of casual strings. The strings that reach the best result are then selected and new ones are created through "coupling" them. The process is repeated until an "evolutionally suitable" string is fund to solve the problem.

Expert Systems are systems that follow a definition of the type:

> *An expert system is a program that possesses a large base of knowledge on a restricted dominion, and which uses complex inferential reasoning to accomplish activities that could be performed by a human expert.*

In practical terms, one of the most important features of an expert system is the ability to explain. In the same manner that a human expert is able to explain his conclusions and the reasoning followed, an expert system should be able to provide a concise or detailed explanation.

Neural Networks are adaptive systems that learn to solve a problem posed after an adequate period of training. These systems have been developed in step with research in the field of the physiology of the human brain. The first Neural Networks were mathematical models of behaviour, on the level of synaptic activity, and therefore of transmission of information on the par to biological neurons. Research on neural networks was then freed from investigation in the field of physiology and began to gain interest in a wider ambit of industrial applications, with such encouraging results as to be considered a new instrument today, on the same standing as traditional systems of data processing.

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Chapter 6
Testability and Prognostics

6.1 Introduction

With a view to maintenance, the concept of system testability is understood as the "intrinsic characteristic of a system or apparatus to permit means of internal self-diagnosis, or appropriate external instrumentation, to verify the functional efficiency and diagnose breakdowns". This logistical parameter has been a matter of concern for some time now and many figures of merit have been defined for it in order to evaluate the quality of a system of self-diagnosis or to estimate how testable an apparatus is from outside.

The concepts that are the subject of our investigation were developed within the ambit of testability (Figure 6.1). Overall, these concepts can be catalogued as prognostics. Stated synthetically, it can be said that prognostics consists of the activity of early diagnosis of breakdowns (predictive maintenance = incipient breakdown) or of limitation of conditions favourable to breakdowns (proactive maintenance = conditional breakdown), whose purpose is to transfer part of the energy and resources lavished in corrective maintenance to preventive maintenance. The purpose of testability (understood as diagnostics) is to report a breakdown that has occurred, while prognostics, on the other hand, reports an incipient or conditional breakdown.

This chapter describes the characteristics and advantages of prognostics, in terms of availability, and the relationship between prognostics and other logistical parameters (safety, dependability, etc.). It was also deemed necessary to define the figures of merit (FOM) that establish the "quality" of a system of prognostics and therefore of the primary system to which it is applied, inasmuch as performance depends on both and on their reciprocal adequacy. This need arises from the awareness that while there are publications that define the FOM applicable to testability (RADC – TR – 79 – 309), the same cannot be said for FOM applicable to prognostics, which have never been dealt with in an organic manner as a whole, and whose values were provided in an inhomogeneous and partial manner by the various authors and organisations that have dealt with the subject.

6.2 Testability

The intrinsic testability of a system or apparatus, which considerably influences the time necessary to restore operational conditions, is one of the fundamental parameters that determine the average cost of maintenance. Customers try to have maximum visibility of all phases of design, in order to ensure that it complies with the criteria of testability required and to avoid needles redesigning, which raises the cost and makes the product inhomogeneous.

It has become increasingly pressing to satisfy the requirements in question in recent years. These requirements are differentiated according to the equipment, but have several parameters in common, whose purpose is to evaluate the correspondence of the testing devices to contractual requirements. These parameters are *Figures of Merit* (FOM), whose value can be estimated through detailed logistical analyses, which start from the design data and lead, through methods that have been perfectly defined by norms, to the determination of the required parameter.

Before listing the most commonly and contractually requested FOM, it is opportune to clarify the meaning of several terms that will be referred to below.

- *Built – In – Test* (BIT): the internal ability of a system or apparatus to identify and isolate a breakdown; this includes *Built – In – Test – Equipment* (BITE), software programs, testing circuits, maintenance panels, indicators, etc. BITE, in particular, is an internal diagnostics system made up of many different sensors, whose purpose is to report any failures [1].
- *External – Test – Equipment* (ETE): this includes Automatic Test Equipment (ATE), consisting of devices external to the apparatus or system (i.e. testing benches) designed to identify and isolate failures.

6.2.1 Testability Figures of Merit

Several figures of merit have been defined in order to evaluate the quality of a system of self-diagnosis or to estimate how testable an apparatus is from outside. The most meaningful are listed below:

- Coverage;
- Accuracy;
- Rapidity;
- Immediacy;
- Immunity to false alarms;

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[1] NOTE: These are go – no-go systems, which do not provide indications on the deterioration of peformance of the system in question, but only detect a fault that has already occurred: such is the case of luminous indicator lights (LED), which indicate the malfunction of a headlight. These systems are inexpensive and applicable even to non-essential components, whose breakdown will not involve a loss of the most important functions.

- Immunity to false indications;
- Self-diagnosis capabilities;
- Dependability;
- Expandability.

A short description is provided below for comparison with the equivalent figures of merit of prognostics.

Coverage (Fraction of Faults Detected)
The fraction of faults detected or detectable (through BITE or ETE) with respect to all of the faults possible in the apparatus. For Bite – on – line, values above 85% of detected faults are typical; for critical faults the coverage required is generally 100%.

Accuracy (Fraction of Faults Isolated)
This refers to the fraction of faults detected and isolated for replacement of items relative to a definite level. In other words, knowing that a pump is broken is not sufficient; it is also interesting to know the component that is broken, which needs to be replaced (filter, gasket, etc.). Since isolation (or location) of the fault may also be somewhat ambiguous, Fault Isolation Resolution is defined as the fraction of faults isolated up to a certain level of indefiniteness. Typically, definite isolation must be above 60%; isolation with an indefinite factor of two must lead to the identification of 90% of the faults and must reach 95% with a factor of three. Such stringent values require great coordination on the level of design in order to obtain a high level of testability for the apparatus.

Rapidity (Mean Fault Detection Time)
This is the time of latency, or the average time between the occurrence of a fault and its detection and reporting; it must be less than the magnitude of apparatus reaction time. It should be born in time that BITE must not give priority to operating parts (which have already been verified to some degree through operational functions), but must primarily test precisely the non operational components, to detect dormant defect that do not show up as contingent operation.

Immediacy
This parameter refers to the "readability" of the indications provided to the operator by the BITE or ETE, thereby establishing the quality of the man-machine interface, as far as diagnostics is concerned. There are no typical values associated with this figure of merit. Clearly, in any case, the result of the test (especially of BITE) must not be interpreted, but must give the operator the immediate sensation of the type of fault and the functions lost or degraded.

Immunity to false alarms (Fraction of False Alarms)

This refers to the fraction of faults reported by the BITE or ETE that are not due to the presence of actual faults. It is indicated as the maximum percentage of false alarms with respect to true alarms. The typical values range from one to five false alarms per hundred true alarms. Since false alarms are due by definition to a concomitance of exceptional and unfavourable situations (the presence of false impulses, induced currents, etc.), false alarms cannot be protracted in time. This characteristic enables us to take action in three ways to favour the reduction of false alarms:

- "Strengthening" alarm thresholds;
- Extending tested parameter sampling time in order t perform more "integrated" measurements;
- Repeating tests on parameters detected out of tolerance one or more times before signalling the alarm.

Immunity to false indications (Fraction of False Indications)

This is the fraction of erroneous fault indications (a fault is indicated on an item, while the faulty item is actually a different one). False indications are particularly deplorable, because they can be avoided with a more accurate diagnostics design and, at the same time, they provoke a great loss of image and lengthen maintenance time considerably.

Self-diagnosis capabilities

This term indicates the ability of a diagnostics system (especially the BITE) to distinguish faults of components relative to the primary system from those relative to the diagnostics circuitry. When required, the self-diagnosis of BITE is one of the most difficult FOM to realise. It is not possible to test or make all devices dedicated to the BITE redundant. Self-diagnosis must therefore be limited to the less dependable and more easily testable components. This is in any case quite costly to realise and we often prefer to speak of self-diagnosis only for ETE.

Dependability

This is the percentile decrease in dependability of a system due to the introduction of the circuitry dedicated to the BITE. An attempt is made to ensure that the rate of total faults does not increase by more than 5%.

Expandability

Expandability is the potential of a diagnostics system to improve its performance without entirely redesigning it. This parameter is insured by the modular nature and standardisation of the BITE. The system must therefore be designed from the outset to permit possible future improvements (for example, we are speaking of using x-rays or radioactive substances to detect cracks, etc.).

It should not be surprising that some of the figures of merit overlap, in the sense that, in the current state of the art, improvement of one almost always entails worsening of another (i.e. accuracy and rapidity), giving rise to the need to make a thorough evaluation of the requirements during the contractual phase.

Table 6.1 Table summarising Testability FOM

TESTABILITY FOM	**BITE / ETE VALUES**
Coverage	$\text{Detention \%} = \dfrac{\text{Faults detected}}{\text{Total failures}} \times 100$
Accuracy	$\text{Isolation \%} = \dfrac{\text{Faults isolated}}{\text{Faults detected}} \times 100$
Rapidity	$\text{Time of latency} = \dfrac{\sum \text{Detection times}}{\text{Faults detected}}$
Immediacy	There are no representative parameters for this FOM.
Immunity to false alarms	$\text{FFA} = \dfrac{\text{False alarms}}{\text{Faults detected}}$
Immunity to false indications	$\text{FFSI} = \dfrac{\text{False alarms or not reported}}{\text{False or missing}}$
Self-diagnosis capabilities	There are no representative parameters for this FOM.
Dependability	$MTBF = \sum \lambda^{-1}$
Expandability	There are no representative parameters for this FOM.

6.2.2 Management of Testability

When the FOMS that define the testability of an apparatus or system have already been expressed by the requirements, agreed upon with the customer and included in the specifications, the activity of *allocation* begins, which consists in determining the maintenance feasibility specifications of the components of the apparatus. This activity therefore consists in distributing the requirements of testability of the system or apparatus in a logical manner, on the basis of healthy criteria of economic and technological feasibility. Testability allocation, in any case, must be preceded by the allocation of dependability and by an analysis of the functions, in order to assign greater diagnostics resources to the most probable and most critical faults.

Another aspect to bear in mind is that several logistical analyses, specified in a *Data Requirement List* (DRL), are now required in all new designs, which is an indication of the growing interest of customers in this type of problem.

In particular, the following reports are extremely important for the purposes of testability:

- *Testability Analysis.* Analysis of the capability of built-in (BITE) and external (ATE) diagnostics systems, in terms of the various FOM defined in the previous paragraph; the interdependencies and limitations of the various means of diagnosis on different levels are brought to light, in particular.
- *BITE Analysis.* This analysis is similar to the one indicated above, but envisions greater details concerning the evaluation of devices and the relative algorithms of the various FOM.
- *Fault Means and Effects Analysis (FMEA)* This is the analysis of the effects, classified on the basis of the various ways in which faults can occur on every component, in order to determine the probability that certain categories of failures could occur, especially the category of critical faults (we are speaking in this case of *Fault Means and Effects Criticality Analysis* (FMECA). This is a *bottom-up* analysis, which starts from the components and their manner of failure, in order to analyse, at the end of the chain, the effects on the functions of the system, permitting the prevention and limitation of phenomena of propagation of the faults.
- *Fault Tree Analysis (FTA)* This is a top-down analysis, which starts from the primary functions that the system is required to perform, and permits the construction of a tree of physical items, which are interconnected through the signals generated and contribute to performance of the primary function being examined. The FTA is a more immediate, albeit less analytical instrument than the FMEA, of which it may be a corollary;
- *Fault Catalogue* This is a basic document that lists at least 95% of all possible manners of failure (short circuit, out of tolerance, intermittent contact, absence of signal, etc.) and the probability of their occurrence. This document does not provide a true analysis, but is the basis for the determination of the various FOM (which, as has been seen, refer precisely to the number of "possible faults") and therefore must be approved beforehand by the customer, especially if he requests demonstrations;
- *Demonstrations.* In addition to the analyses "on paper" described up to this point, the customer generally requires two additional categories of tests relative to the correspondence of the system or apparatus to the FOM of Testability required.

  - Demonstrations during acceptance;
  - Demonstrations during the phase of service.

- The former are performed on the basis of simulated faults and, if values below the threshold of acceptance are detected, the supplier is required to make the necessary variations and to repeat the tests when the modifications have been completed (at his own expense), and to provide hard copy evidence of the improvement made.
- Demonstrations in the field are even more penalising. The actual FOM are calculated and if out of specification values are detected in the apparatus, modification for improvement is imposed, ensuring that the customer has the availability of analogous equipment during the time required for the modifications (again at the expense of the supplier).

6.3 Prognostics

As mentioned earlier, prognosis (Figure 6.2) consists of an activity of early fault diagnosis (incipient or conditional), whose purpose is to transfer part of the energy and resources spend in corrective maintenance to preventive maintenance. The purpose of testability is to report a breakdown that has occurred, while prognostics, on the other hand, reports an incipient or conditional breakdown.

It is opportune to stress immediately that we are not speaking of scheduled maintenance, but of preventive maintenance. This science, then, is addressed to components that have a limited life span, which are characterised by a rate of breakdown with a trend like the one shown in Figure 6.1:

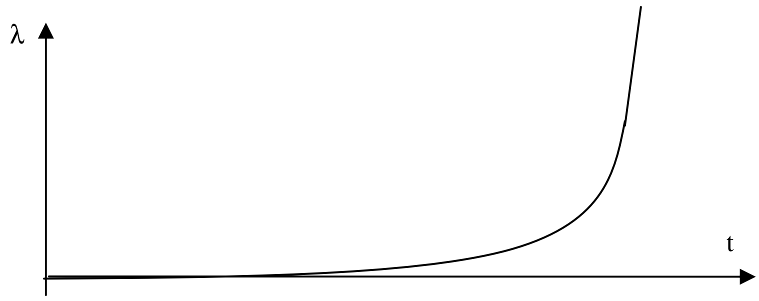

Fig. 6.1 Growing rate of fault

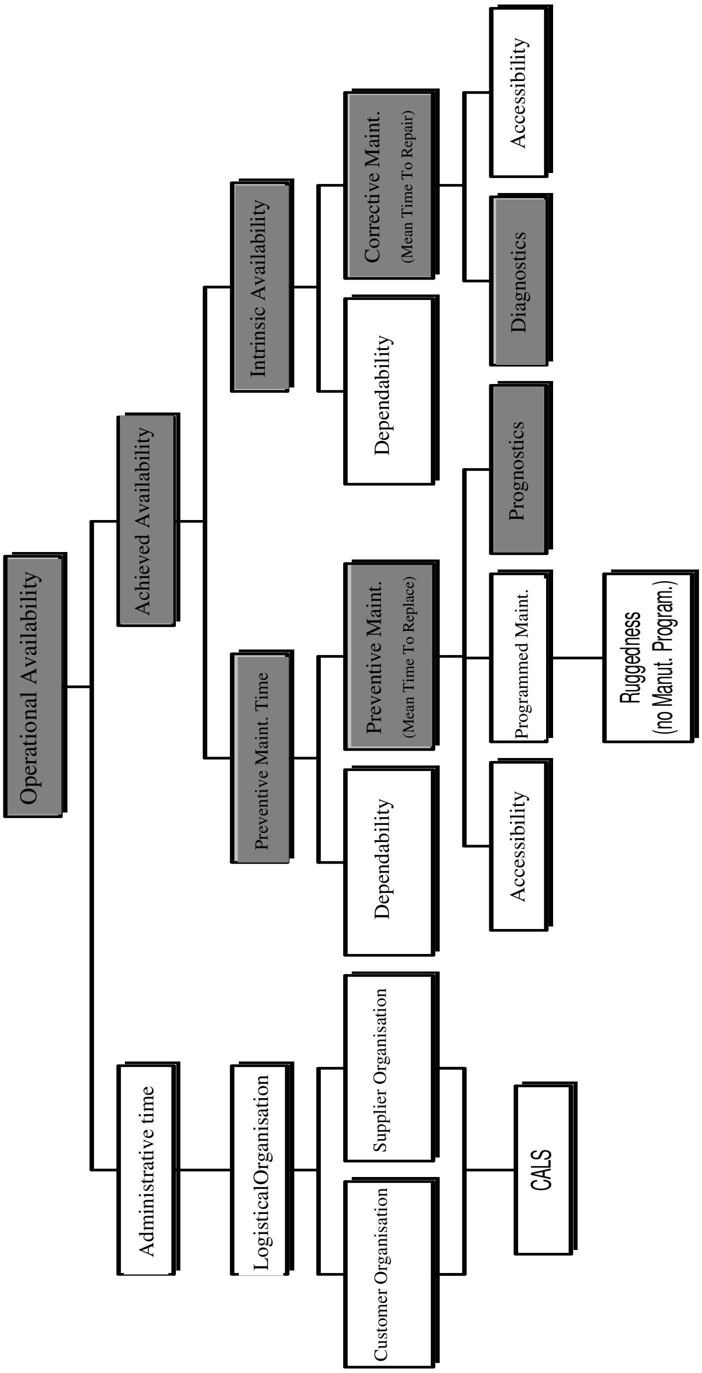

Fig. 6.2 Interdependence of logistical parameters

This generally concerns mechanical devices (turbines, pumps, motors, etc.) or electro mechanical components (electric motors, switches, electrolytic condensers, etc.), but also sometimes concerns electronic devices (cathode ray tubes, *travelling wave tubes*, etc.) and definitively, all components where there is gradual degradation, phenomena of wear, mechanical stress or, in any case, breakdown events related to phenomena of chain reaction deterioration.

Prognosis is included in a more general trend towards *on condition maintenance.* Everything that breaks, or for which appropriate sensors are capable of detecting an approaching situation of malfunction, is replaced. In other words, it is applied only where some form of forewarning exists for an incipient breakdown, avoiding maintenance based exclusively on forecasts made from studying the rate of breakdown.

This is a maintenance approach that has already been used, but which has historically experienced a recent evolution in its possible applications. We have gone from on-condition maintenance, performed on production plants, to the idea of utilising this practice on systems and apparatus as well – namely on products. This would mean, in a not-too-distant future, having the availability of a warning signal that advises us, for example, if our automobile is about to experience a breakdown, or advises the driver of a line coach of an imminent fault (but which permits him to finish his route, in any case), thereby avoiding unpleasant delays for passengers or, even more importantly, which informs the captain of a ship of the need to make repairs with sufficient advance notice to permit him to reach the nearest port, without compromising the functional efficiency of the ship during the mission – and we could go on and on.

All of this obviously has a cost, which may be convenient to sustain when the consequences of a breakdown are sufficiently serious in terms of the damage caused to persons or property (just think, for example, of the distribution belt of an automobile). In any case, this refers to the presence of a certain type of breakdown (mechanical, not typically electronic, due to wear and tear, systems that are difficult to inspect, costly systems, essential systems, etc.). Evidently, in an initial phase, considerations of economic feasibility will permit application of these concepts only to complex, costly or critical systems and apparatus, and those produced in series *(automotive).* Subsequently, however, the experience acquired will lead to a reduction in the cost of the technologies available, making their diffusion feasible. From this point of view, the fact should not be disregarded that one of the most evident consequences of this maintenance approach is the extension of the average useful life of a system, well beyond the maximum foreseen, with the undeniable advantages this entails, in order to set up a correct cost-benefit analysis.

This is an effect of *reliability growth,* namely, the process of taking appropriate counter measures during maintenance, whenever a breakdown occurs, to prevent the same type of malfunction from occurring again. In this manner, by making modifications and improvements between one breakdown and another, the useful life of the system is extended.

In the case of prevalently electronic equipment, on the other hand, for which it is impossible to foresee faults (because they occur in a casual and sudden manner), a policy of *fault tolerance* is implemented. That is to say, an attempt is made to limit the consequences of the failure, fore example through an effective or functional redundancy (the latter is less costly and entails a tolerable degradation of the performance required).

There are many procedures for the application of prognostics, but again, as with testability, it is possible to make an important distinction. Prognostics of an external type may be implemented, when the samples to be analysed are similar and therefore it is convenient to examine them through a single "probe", in a special department, or an internal type of prognostics inside every piece of equipment (whenever it is the most economically viable choice). The cost of this activity decreases substantially when its use has already been foreseen in the design, instead of applying it, as often takes place in this initial phase, when the design has been completed.

6.3.1 Prognostics and Availability

Referring again to the magnitude of dependability, it is possible to establish some extremely important functional relationships in order to understand the effective advantages due to application of the criteria suggested by prognostics.

Obviously, one of the customer's primary interests is to know how many of the elements purchased will be functional at a given time *t*. The problem resides in the fact that the manufacturer is able to foreseen only the Mean Time Between Maintenance (MTBM), but not the Mean Downtime (MDT), which also depends on the customer's organisation, since, as it is known, it is necessary for the Logistical Delay Time (LDT) and Administrative Delay Time (ADT) to be added into the equation. In other words, the manufacturer is able to inform the customer only with regard to Inherent Availability $A_{i,}$ which does not take preventive maintenance into consideration, as this is for the account of the customer. To deal with this inconvenience, we tend to make the supplier partially responsible, even through the knowledge of the logistical and administrative timing, through a CALS policy (for example, a bar code may be included on boards or a micro circuit for recognition, which permit immediate identification of the type of board to be replaced, consequently reducing administrative time (ADT))

The purpose of prognostics is precisely to guarantee a high level of A_i (generally around 99.95% - 99.99%), moving the problem to A_a (Achieved Availability). This results in less frequent recourse to corrective maintenance, in favour of a more accentuated preventive control, with the undeniable advantages due to the ability to provide for maintenance intervention in a prudential manner, to avoid having to stop the plant due to a breakdown, achieving functional and maintenance efficiency.

6.3.2 Logistical Parameters correlated to Prognostics

The logistical parameters that contribute to the determination of the values of availability of systems (especially operational availability) are almost always interdependent or interconnected (Figure 7.1). Prognostics are no exception and are closely related to the dependability of the individual parts they are applied to, but also to maintenance feasibility, safety and to several processes that provide precious instruments of analysis (FMECA) for integrated logistics support.

The feasibility of prognosis of breakdowns allows us to move maintenance from the category of corrective maintenance (performed when the breakdown has already occurred in order to restore the system to functional efficiency) to the category of preventive maintenance (even though it is performed *on-condition*), which prevents the occurrence of machine downtime, conferring, within certain limits, a flexibility of intervention that also takes immediate operational requirements into consideration (thereby avoiding losses in operational continuity).

Let us look briefly at the most important logistical parameters correlated to Prognostics.

6.3.2.1 Dependability

This logistical parameter is a driver in dealing with prognostics, inasmuch as the possibility to predict an event of "failure" depends upon the knowledge of the phenomena of wear and tear, both in terms of their trend (modelling) and the compendium of symptoms that makes them meaningful for prediction. Clearly, we are dealing with phenomena that lead to an increase in the probability of a breakdown and which, through maintenance intervention, allow us to obtain:

- A reduction in the standard rate of breakdown;
- An improvement of machine working conditions such as to avoid the occurrence of induced faults;
- An extension of the useful life of the product.

6.3.2.2 Maintenance Feasibility

It is self evident that the application of sensors (on-line) fixed to the system, or (off-line) applied to the apparatus upon which to perform the prognosis at the time of measurement, makes sense only if the fault subject to prognosis constitute an important percentage with respect to faults that are not subject to prognosis, within the ambit of all the possibilities for breakdown that lead to the same effect.

It is equally self-evident that in order to be feasible, prognosis of a fault must be able to foresee action for prevention (when this also constitutes machine downtime to avoid more serious damage), which should generally consist of maintenance action to be performed without stopping the machine (*hot maintenance*), without intervention on a higher level or, at least, with advance warning time that permits completion of the mission underway. It is therefore indispensable to perform a *Failure Modes, Effects and Criticality Analysis* (FMECA) during design of the Prognostics, in order to identify the faults that are to be subject to examination.

6.3.2.3 Testability

Testability is the parameter that has the greatest affinity with prognostics. Just as testability can be considered a branch of maintenance feasibility, it can be said the prognostics is a branch of testability, together with diagnostics. In apparatus with discontinuous operability (missions on the maximum order of months), where it is important to maintain a high level of operational availability, independently of the logistical organisations, and a high level of achieved availability, diagnostics plays an important role, if and only if rapid and low-cost maintenance solutions can be pursued and realised without excessive training (electronic systems with BITE).

On the other hand, with complex mechanical devices and systems, repair and replacement times and costs increase considerably, and the space taken up by spare parts increases, making recourse to prognosis extremely advantageous to maintain a high level of achieved availability.

It is interesting to stress that many analogies can be drawn between diagnostics (often referred to by itself as testability) and prognosis. In fact, many of the figures of merit that characterise the former are also valid with some adaptation for the latter. Even from the point of view of application, just as there is internal testability (BITE) and external testability (ETE), two approaches to prognosis can be identified: *On-line* prognosis (with resident sensors connected directly to a data collection and processing device) and *off-line* prognosis (with an analysis bench separate from the sensors and a data collection and processing device). *Off-line* analysis, in turn, can be performed *on-site,* namely in real time (this is the case, for example with a ship, when an initial *on-line* analysis turns out doubtful values, suggesting more in-depth short-term study through more complete equipment positioned in a special location), or *off-site,* in an analysis laboratory.

It should also be noted that among the auxiliary devices used to maintain the performance of a system, there are several that are often confused with the parts dedicated to testability (whether for diagnostics or prognostics). These are the devices dedicated to self-protection (speed limiters, power regulators, thermal switches and associated fans, etc.). These devices are part of the primary system design and may often be by-passed with other devices (*battle-short*) that permit extension of the primary system operation, even under conditions that would normally be prohibitive and even up to the point of breakage, when particular emergency situations require it.

6.3.2.4 Safety

Since many breakdowns involve a loss in the safety of operational personnel, it would obviously be desirable to apply prognostics systems on the basis of the probability of occurrence of the most serious breakdowns (catastrophical) that lead to serious risks for the safety of personnel. The FMECA should therefore be extended to aspects relative to safety and a possible *Fault Tree Analysis* (FTA) should be performed in the primary functions of the systems.

6.3.3 The Figures of Merit of Prognostics

Analogously with what takes place for other logistics functions, such as testability and maintenance feasibility, it is considered indispensable to break prognostics down, identifying a set of numerical parameters that are more suitable to make an objective measurement upon which to base evaluation of the system in terms of prognostics. These numerical parameters consist of the figures of merit (FOM).

Clearly, prognostics systems are comparable with each other only on the basis of the correspondence of the FOM required. It is generally important, in any case, to distinguish between on-line systems (which permit continuous and automatic monitoring) and off-line systems, which require periodical human intervention. Another distinction that allows us to determine the limits of feasibility of a system of prognostics is the identification of the life cycle phase of the primary system in which the prognostics system is designed and applied. If prognostics are applied to an existing system or apparatus, the figures of merit can rarely achieve the performance of prognostics applied to a system or apparatus created with the prognostics system. The presence of *markers,* selective sensors, *gauges* and the choice of materials suitable for prognostics are possible only when the design is created complete with its system of prognostics.

Generally, even if the prognostics FOM are adapted and have different meanings, they are inspired by the FOM of testability; this has been determined in spite of the fact that other FOM are necessary, which have nothing to do with testability and which are therefore specific to prognostics.

Notably, while there are publications that define the FOM applicable to testability, the same cannot be said for FOM applicable to prognostics, which have never been dealt with in an organic manner as a whole, and whose values were provided in an inhomogeneous and partial manner by the various authors and organisations that have dealt with the subject. For this reason, the bibliography shown necessarily omits significant references relative to the figures of merit for prognostics. It was also deemed necessary to define figures of merit that establish the "quality" of a system of prognostics and therefore of the primary system to which it is applied, inasmuch as performance depends on both and on their reciprocal adequacy. Therefore, the FOM defined below do not refer to individual sensors, mathematical models used to make predictions or to the apparatus the system of prognostics is applied to, but to the set of all of these components.

These figures of merit are:

- Coverage;
- Accuracy;
- Advance notice;
- Predictive precision.

6.3.3.1 Coverage

This FOM already exists for testability and determines the percentage of faults detected by a system of diagnostics. Analogously, it is possible to define *coverage* for a system of prognostics (which may include several sensors and be extended to various elementary devices) in terms of the *percentage of potential faults subject to prognosis (with respect to all possible faults), weighted by the probability of occurrence.* Clearly, detecting a low percentage of faults and leaving a high percentage undetected or not subject to prognosis cannot be justified, because in most cases this would result in having unexpected events of failure.

The case is quite different when we are able to classify faults on the basis of their consequences. By assigning a high level of criticality to faults that may cause serious inconveniences, machine downtime, important economic losses or even the risk of loss of human life or injury, it would be justifiable to monitor the parameters that lead to such failures. Other types of breakdowns could be ignored if they belonged to a lower class of criticality, or if the consequences of the failure were not so catastrophic. A high level of coverage of catastrophical failures by the prognostics system, therefore, would be a good guideline in design.

Acceptable parameters at the state of the art could be within the range of 30% to 70% of coverage for a system of diagnostics and between 80% and 100% for "catastrophical" failures.

6.3.3.2 Accuracy

This parameter also descends from its testability equivalent. High coverage in itself is not always sufficient to identify the cause of a failure. A vibration on an apparatus may be due to different causes, which may be so different as to be a prelude to different faults, with entirely different times and consequences.

It is therefore necessary for the system of prognosis (often assisted by intrinsic design characteristics of the machine) to be able to identify and isolate the device (or cause) producing the "symptom" detected. *The accuracy of a system of prognosis is therefore the ability to identify and isolate the cause or device that is approaching failure.* The isolation will be for a single cause or a single device (in the best case) or of the presence of ambiguousness between two, three or more causes and devices, when the diagnostics system is not sufficiently "accurate". The correct definition of accuracy of the system of prognosis (or better yet, as assumed in the previous paragraph, the set of the prognostics and primary systems) should establish, in cases of ambiguousness, what the various probabilities are for the different events of failure.

A high degree of accuracy in prognosis is necessary, especially in cases where the same symptom could lead to failures in completely different categories or to long and burdensome procedures to identify the faulty device. A greater degree of accuracy could also be reached through on-line sensors or analyses or, more realistically, off-line sensors or analyses, implemented only when the ambiguous situation occurs. This would therefore constitute an additional process of prognosis, whose purpose would be not only a more accurate isolation of the component that is approaching failure, but also to achieve a more accurate prediction of the remaining useful life (predictive precision) and the possible consequences for other parts of the system.

Accuracy depends a great deal on the application, the type of physical parameter detected and the sensor used. The percentage of breakdowns deemed appropriate to isolate without ambiguousness, therefore, cannot be quantified, therefore, although it should be a goal of design to be able to isolate all of the faults detected in an unequivocal manner (coverage).

6.3.3.3 Advance Notice

This FOM has no exact counterpart in testability, although the "rapidity of the BITE cycle" and the "fault latency time" could recall the meaning to some extent. *The advance notice is the time required to warn the operator of the existence of a process that will lead to a specific fault, due to irrefutable symptoms.*

Since this concerns processes related to partially aleatory phenomena, it is not possible to specifically determine the time for advance notice of the fault. More than the "advance notice time", we may therefore speak of the "mean time of advance notice" with the consequent considerations on the probability of occurrence of the fault, following the various intervals of successive prognoses. Of course, it would be ideal to have the certainty that the fault would occur after a specific period of time starting from the occurrence of the warning symptom permitting prognosis. Lacking this certainty, it is important to identify as precisely as possible the interval of time with the associated probability (probability distribution) of occurrence of the event, to be able to evaluate the risk associated with planning *on-condition* maintenance.

Logically, advance notice time must be such as to permit maintenance intervention upon termination of the mission or, in any case, under conditions and with means that are an advantage over the occurrence of an unexpected failure. Generally, acceptable times range from a score to a hundred hours of operation prior to reaching the maximum level of probability of occurrence.

It should be specified that the numerical values are provided only by way of orientation, inasmuch as they are indissolubly related to the type of system or apparatus being studied, its mission and the type of analysis.

This is true for incipient and conditional faults alike, but with a different value. For incipient breakdowns, it makes sense to speak of advance notice time, even if the breakdown will definitely occur; for conditional breakdowns, on the other hand, resorting to appropriate counter measures may prevent the occurrence.

Finally, it is important to note that the time of advance notice must be associated with a specific manner of operation and specific stress that the component on the verge of failure is subject to. Different operational conditions for the component in use correspond to different remaining life expectancies.

6.3.3.4 Predictive Precision

Lacking a true distribution of probability for the occurrence of a failure, another figure of merit could be introduced, which is the Mean Quadratic Difference (MQD) with respect to the theoretical advance notice time. This is an additional indication of the quality of the prognostics system. The less the difference, the more effective the prognosis on the apparatus is.

An additional FOM could thus be identified: *Predictive precision,* which is closely related to the MQD. In particular, the magnitude of the MQD developed to the left with respect to the point, on the axis of times, which represents the moment foreseen for the breakdown. In other words, we attempt to quantify the probability that the breakdown will occur before the predicted time. So here is an opportunity to introduce a new FOM, such as: the maximum acceptable percentage of MQD lower than the advance notice time. In fact, it could happen that when the system warns the operator of an incipient breakdown, there is already a certain probability that the fault will occur (such is the case of a very "open" bell curve).

6.3.4 Testability Figures of Merit applicable to Prognostics

Other FOM, generally defined for testability, can be applied almost without modification to prognostics. These include:

- Immediacy;
- Immunity to false alarms;
- Immunity to false indications;
- Self-diagnosis capabilities;
- Dependability;
- Expandability;
- Ability to learn.

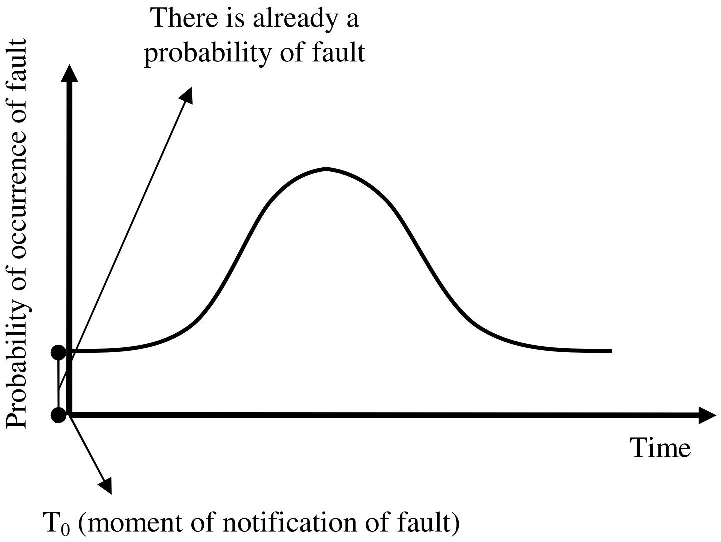

Fig. 6.3 The case of an "open" bell curve

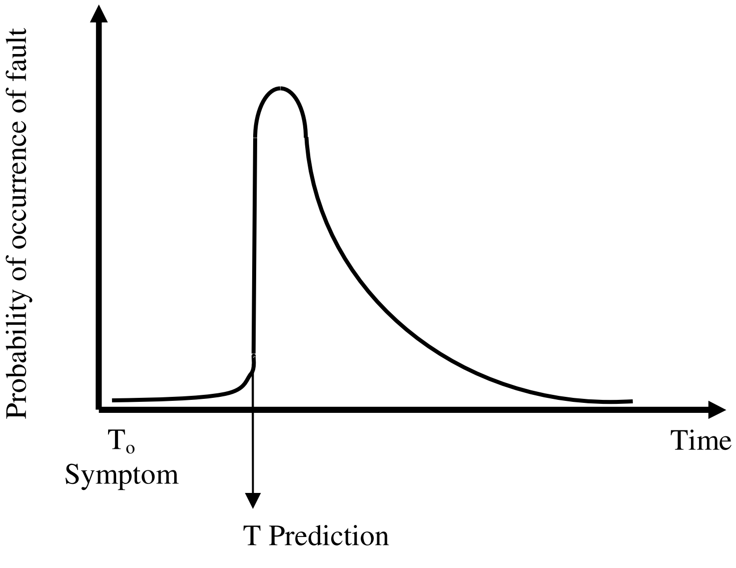

Fig. 6.4 Ideal case

For completeness, a definition is provided below that brings out the application to this science. Table 6.2 shows the figures of merit common to the two logistical magnitudes and those that are characteristic only of prognostics.

6.3.4.1 Immediacy

The importance of a good man-machine interface for prognostics, capable of providing a warning signal that leaves no space for interpretation on the part of the operator, but immediately provides correct information on the type of incipient breakdown, is self-evident.

6.3.4.2 Immunity to False Alarms

It is particularly important for the purposes of prognostics to avoid the use of conditions and symptomatologies that could also occur for causes that are independent of the imminent fault. This refers to the condition in which *the alarm threshold is exceeded without there actually being an imminent fault, which is called a "false alarm".*

The importance of eliminating false alarms is determined by the practical consequences they engender, with the activation of *on-condition* maintenance procedures, when this is not actually necessary (waste of time, possible generation of damages induced by maintenance, costs).

False alarms can be reduced by adopting more in-depth procedures of analysis in all cases where there are symptoms of dubious dependability (which must, in any case, be identified *a priori*).

While in the testability of electronic apparatus, considering the short corrective maintenance times (MTTR), a ratio of false alarms and actual indications of faults of a few percentage points is generally accepted, the probability of having false alarms should be nil for mechanical devices when the consequences involve complex maintenance.

6.3.4.3 Immunity to False Indications

The FOM relative to false indications is in some ways analogous to the one for false alarms and, at the same time, it is related to the accuracy of the system of prognostics. *A false indication takes place when the interpretation of the symptoms read through the sensors (or the analyses) indicates the imminent occurrence of a failure ("G1"); while in reality a different failure ("G2") is about to occur.*

This type of prognostics system shortfall is undoubtedly generated by poor design of the expert system or the type of sensor used. Of course, it is better to retain accuracy with some shortfalls than it is to oblige the user to undertake expensive maintenance, which fails to solve the problem, with the risk of successively incurring unexpected failures. But then poor accuracy can be improved through more discriminating tests and measurements, as already seen in the paragraph on this subject.

Again, as in the case of false alarms, the FOM is defined with the word "Immunity". This indicates that to the extent possible, situations of false alarms and false indications must be avoided in a system of prognostics.

6.3.4.4 Self-diagnosis Capabilities

In order to avoid alarms generated by breakdowns or poor calibration of sensors or systems of analysis[2], the system should be able to detect faults or poor calibration through a system of self-diagnosis and self-calibration. There are a variety of consequences due to possible failures or poor calibration of prognostics systems:

- Lack of advance alarm in the event of imminent breakdown;
- False alarm;
- Poor precision in the prediction of breakdowns.

6.3.4.5 Dependability

The importance of having a dependable system of prognostics[3], is closely related to the need to be constantly aware of the potential an operator can count on. Definitively, therefore, even if the system of prognostics can be considered an ancillary or secondary system with respect to the main functions of the primary system, the requirement of dependability depends a great deal on the essential and critical nature of the primary system monitored.

6.3.4.6 Expandability

This is a characteristic of the primary system that defines to what extent the primary system is organised to accept, without having to perform complex modifications, new sensors and *gauges* to improve the system of prognostics during its use-

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[2] Although there apparently are False Alarms, they cannot logically be identified in this category, inasmuch as they could be identified as a False Indication if the System of Prognostics in on-line and integrated with the primary system (because the system of Prognostics is part of the system itself and indicates at least a malfunction, if not a breakdown); while if the System of Prognostics is off-line (not integrated), we are dealing in any case with an error of external analysis due to a shortcoming of the external process and not of the product.

[3] The word "dependable" in this context is understood in an exquisitely technical sense, as related to the rate of breakdown, because another definition of the word dependable could be ...*which is correct and precise,* and in this sense other FOM have already identified the quality of the System of Prognostics.

ful life. This trait, like other traits of *growth capability,* is difficult to measure, but undoubtedly indicates the technological maturity of the manufacturer of the primary system.

7.3.4.7 Ability to Learn

This figure of merit is related to the algorithms used in the expert system, to the Bayesian process (of substitution of theoretical prediction with experience) and the process of inference adopted and to the predictions and models proposed by the designers of the primary system relative to the symptomatology of imminent breakdowns, more than it is to the system of sensors. Since the ability to learn of an expert system depends on the experience accumulated, it is desirable for the system of prognostics, and in particular for its inferential motor and its database, to be organised to accept, through appropriate filters, the experiences accumulated by similar systems (other apparatus or devices of the same family, comparable technologies, etc.).

Table 6.2 Comparative table of FOM

Prognostics FOM	Testability FOM
Coverage	Coverage
Accuracy	Accuracy
Rapidity	Rapidity
Advance notice	No correspondence
MQD with respect to Advance Notice	No correspondence
Maximum % of MQD lower than the advance notice time	No correspondence
Immediacy	Immediacy
Self-diagnosis capabilities	Self-diagnosis capabilities
Immunity to false alarms	Immunity to false alarms
Immunity to false indications	Immunity to false indications
Dependability	Dependability
Ability to learn.	No correspondence
Expandability	Expandability

6.4 Implementation of Prognostics

The initial phase of implementation of prognostics of a system or apparatus consists in a preliminary analysis targeted to identify the critical Line Replacement Units (LRUs)[4] for the mission that the system is called upon to perform. Successively a scale of priorities must be established on the breakdown rates λ of the various critical items, on their condition as components with a limited life span and on their suitability as subjects for the collection of useful data.

Fore example, breakdowns that occur on mechanical or hydraulic devices are suitable for prediction through monitoring and careful analysis of the data available, recorded in a certain period of time. These devices, subjected to the subject diagnostics procedures can therefore continue to operate normally for a certain period of time, even if they are subject to severe stress. It is quite a bit more difficult to implement prognostics on electrical or electronic components, which are characterised, as stated, by sudden and casual faults, which crop up when a particular characteristic, such as tension, for example, exceeds a certain threshold value. Establishing objectively valid criteria to determine this threshold is quite an arduous task, because the threshold is reached suddenly and with no apparent gradual degradation of performance.

The LRUs with a limited life span and/or with higher λ values will be priority candidates for implementation of prognostics, because of their strong impact on operational availability. The technologies available for the use of measurement devices of the characteristic magnitudes of prognosis (FOM) will be applied to them. The use of MEMS, or sensors designed to monitor temperature, vibrations, humidity, pressure fluid impurities and ultrasounds, has turned out to be particularly useful in this connection.

These devices should be incorporated in new concept LRUs that envision their use from the phase of design forward, to guarantee proper implementation of the requirements of prognostics. Prognostics are based on the idea that every LRU is intrinsically different from the others. The sensors have precisely the function of collecting a certain amount of data in a congruous interval of time, so as to establish the characteristics that make the LRU unique and permit the development of suitable software to determine the threshold values, for each characteristic, which will start a process leading to the fault when they are reached. When these values are exceeded, the prognostics system must notify the presence of an incipient breakdown to the operator responsible, also scheduling the replacement of the piece at the earliest opportunity.

This activity is only one of the procedures related to the management of prognostics, similar to what has been stated for testability. Again in this case, a series of logistical analyses must be prepared, which favour correct allocation of the prognostics requirements on the system or apparatus. It could also be hypothesized to use documents such as the fault catalogue or the FMECA, which are obviously

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[4] LRU = *Line Replaceable Unit*

suitable for the characteristics of this different approach to maintenance. In particular, FMECA must take into account the need to respect the new FOM defined for prognostics, even for the purpose of identifying the category of critical faults, bringing out the faults that may be subject to prognosis.

6.4.1 The process of Prognostics Planning

The complexity necessary for a system of prognostics to perform the various functions referred to can be inferred from what has been stated in the previous paragraph, especially if the right weight is given to the factor of time. In other words, the longer the period of time available to perform the necessary intervention, the more valuable the reporting of an imminent breakdown is. Nevertheless, there are many factors that make this passage difficult. The great quantity of data that productive systems are able to make available to maintenance personnel today is sometimes an obstacle that paralyse the performance of diagnosis, due to the difficulty of interpreting the information and the ambiguous manner in which the mechanisms of cause are explained – an essential effect of the correct evaluation of the phenomena. The interpretation of diagnostics (often *on board*) must be entrusted to specialists, and this involves a decrease in the timeliness of intervention, due both to the simultaneous action of various professional figures and the need to employ personnel with specific professional characteristics, providing they are available. This situation of uncertainty is even more dramatic when the diagnostics data are detected continuously (monitoring or continuous control of the condition) and the need arises to isolate the small amount of important information from the many unimportant bits of data.

In this panorama, a fundamental role can be played by an expert system, more or less integrated with an information technology system of maintenance, for the purpose of improving the effectiveness of technical diagnoses and permitting greater interaction with the user, providing an active support for the rapid identification of faults.

The performance of current information systems is limited to the structure where they are inserted, within traditional data processing systems (PCs, minicomputers). In fact, in the procedural logic of traditional computers, there is no structure that filters the information and re-proposes it, eliminating redundancies and banal cases, permitting the maintenance personnel to concentrate on the most important cases. For this reason, it is important for the maintenance personnel to interact with intelligent instruments, capable of thoroughly examining at least part of the complexity of the problems and capable of offering instruments for the evaluation of the phenomena being examined, rather than a collection and organisation of the information.

Despite this, the spread of expert systems in Italy is still quite limited and concerns only 2 – 3% of industries, while examples of integration between information technology and operation and maintenance are practically inexistent. The reason for this, among other things, is that the expert systems currently produced for maintenance are highly specialised and oriented towards the solution of a particular problem. They are therefore not suitable for generalised use to "troubleshoot" on the basis of information introduced by the maintenance personnel, with the assistance of a pre-existent model (base of knowledge = ability to diagnose).

Nevertheless, the recent progress has opened up some entirely new prospects: it should suffice to think that just a few years ago, expert systems were still considered too slow, requiring important response time to solve the questions posed. These systems also had quite generous proportions, and could only be used with dedicated machines or large computers: all of this entailed high costs in terms of hardware and software alike, which limited diffusion. Today, on the other hand, thanks to the modern electronic computers available, these problems have gradually become less pressing.

Nevertheless, although 80% of Italian industries, for example, possess a maintenance database (50% of which is managed with computerised systems), only 20% of the companies have an information technology system for maintenance, which is complete and therefore includes the following fundamental modules:

- Technical archives;
- Fault management;
- Management of resources;
- Cost control.

But what is the purpose of an expert system? Stated briefly, it formulates a plausible hypothesis on a probable cause and successively verifies it. It therefore uses models of Bayesian inference, according to which we start from a hypothesized situation (for example a distribution of faults) and then modify it on the basis of the knowledge acquired operationally.

The procedure of troubleshooting follows the same logic. The items that do not function properly are observed and analysed, hypothesizing a plausible cause. This hypothesis is verified and the reasoning is repeated until the cause for the malfunction is found. Successively, the cause identified is removed and it is verified whether the symptom has disappeared or not. Substantially, this is a process of seeking the causes, starting from the effects defined technically through *backward chaining:* namely, linking together facts (measurements and controls) to discover the causes (damage, state of wear and tear) and advise the user of the action to be taken. Analysis of the causes of breakdown is based on the following consideration: not only are breakdowns limited to a small number of components, but they are frequently repetitive in nature as well. Repetition is precisely the reason that it makes sense to identify the cause, in order to attempt to remove the problem at the root.

In any case, the expert system is only one of the elements necessary to implement an information technology system of maintenance (Figure 6.5). Such a system must be "integrated" – that is to say capable of communicating with the world of machines (*front end*, detection of status in real time, etc.) and the world of design (analysis of the manner of breakdown, its criticalities, maintenance for improvement, investments, retrofitting, etc.). This permits the activation, even in complex realities, of improvement of diagnosis, through the definition and updating of models of behaviour upon breakdown of the system, calibration of the model permitted by analyses of data from "the field", re-processing in real time of weak signals and all of the information concerning the behaviour of the means of production.

Homologation of the criteria of collection and processing of the information also permits comparison of performance of companies belonging to the same merchandise sector and, more in general, between industry and services. This information technology system cannot reside totally inside a centralised structure, because it requires other devices than the electronic computer that supervises management, such as:

- *Sensors.* The purpose of sensors is to detect elementary signals originating from components and functions of the means of production. They are often already installed on machines or there is already a structure to house them;
- *Communications networks.* The information gathered by the sensors must be concentrated in "nodes", appropriately connected in a reciprocal network and with a *front end,* which permit economic transmission of information from the sensors. Often, such structures are already installed on means of production to transmit data relative to the processing;
- *Front end.* This is a computer that provides for continuous monitoring of the data transmitted by the sensors through the network of communication, and performs the task of filtering the information that is not banal, passing it on to the expert system it is connected to. Preferably this device must be dedicated;
- *Expert system.* This is a hardware and software structure that permits analysis of information coming from the field, through the *front end,* comparing the abnormal situation with the "base of knowledge" fed by the FMECA and the other information gleaned from operations; this is also a dedicated device.

Currently the latest generation of PC technology permits unification of the functions performed by the *front end* and by the expert system, depending on the complexity of the system (in the case of a naval unit, for example, this is definitely possible).

To better understand the successive phases of maintenance related to the system described, it is useful to go into a bit of detail on the operation of the *front end.* The front end collects weak signals (small anomalies and symptoms) and strong signals (faults and productive system down time), which are recognisable on the basis of the following criteria:

- Signals within tolerances foreseen by the system. This is the regimen situation; the *front end* does not transmit this information to the connected system. The means of production is operating;
- The signals are not within tolerances foreseen by the system; nevertheless, no critical event is underway for the means of production. The *front end* transmits

the abnormal signals to the expert system for analysis; the means of production is operating;
- The signals are not within tolerances foreseen by the system and a critical event is underway, which has caused shutting down of the means of production or part of it. The *front end* transmits the information of shut down or failure to the maintenance information system, to provide for activation of immediate intervention; at the same time, the abnormal signals are transmitted to the expert system, which processes them. Appropriately processed, this information will then be of assistance to the maintenance personnel to support diagnosis. The means of production has been shut down.

In a successive phase, the maintenance personnel interacts with the expert system to understand whether it is necessary to intervene for preventive maintenance following the signals detected, or to diagnose the cause of the breakdown. In any case, the maintenance personnel will obtain sufficient information from interaction with the expert system to orient his actions. The retroactive nature of the system is guaranteed by the maintenance personnel, who records the intervention performed in the expert system, which could be a simple adjustment, repair of a fault or a simple control. In the case of a simple control, he will report to the expert system that the particular condition was not critical. Thus, the base of knowledge of the expert system is continuously updated. With this process, the system is able to learn from experience and constantly calibrate itself in relation to the problems to be solved. It should be stressed, in any case, that the alert procedure is different from system to system. An expert system dedicated to prognostics will already have all of the situations that tend to appear before a fault stored in its initial base of knowledge and whose occurrence must be avoided.

The functions of the system just described are the ones that our system of prognosis must be capable of performing. But then these very activities, which in this case are performed by the expert system and by the sensors, had already been included, with much less incisive implementations than the ones that this system can allow today, as an integral part of the RCM application:

- Personnel training;
- Collection of information;
- Identification and division of the system;
- Analysis of the systems;
- Strategy;
- Periodical nature of inspections.

Recapitulating, it is possible to identify at least three phases in the process of planning a System of Prognostics: the phase of analysis of the system under study, definition of the sensors and processing of the data that can be collected.

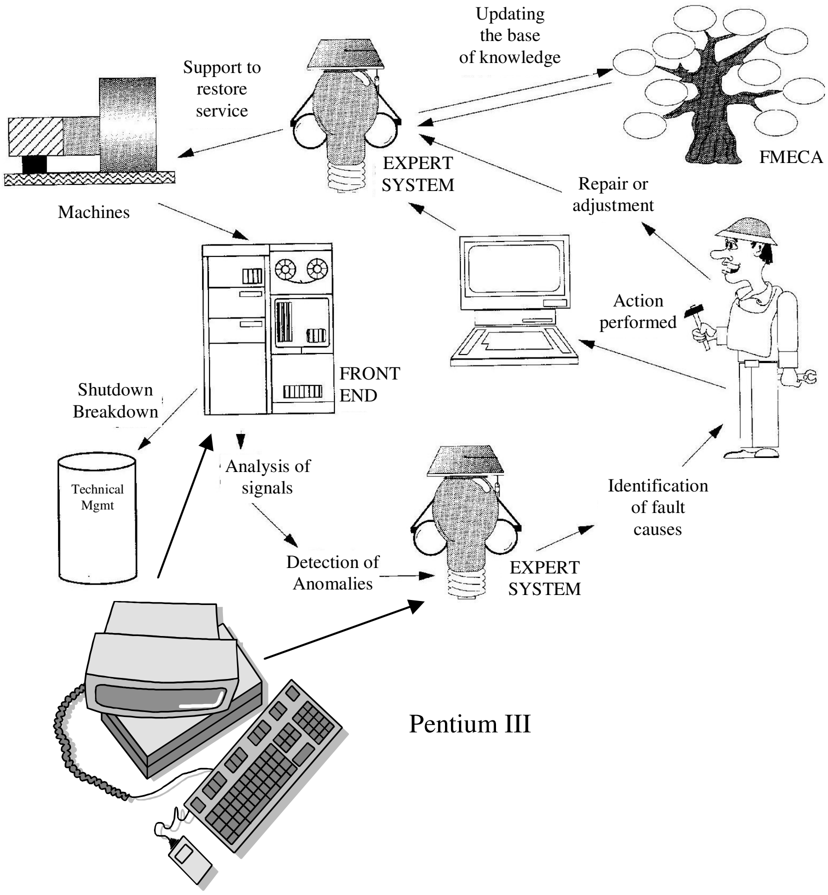

Fig. 6.5 Structure of the Integrated Information System

Schematically:

- Analysis:
  - Definition of the apparatus on which to apply the prognostics (on the basis of their essential and critical nature);
  - Physical parameters to keep under control for the various apparatus;
  - Potential percentage of breakdowns subject to prognosis;
  - FMECA;
  - Definition of design goals for the figures of merit of prognostics for the various apparatus (taking into account the limits due to the state of the art);
- Sensors:
  - Definition of the various types of sensors;

  - Definition of the parts subject to on-line prognosis and those subject to off-line prognosis;
  - Definition of the plan for analogical-digital conversion and multiplexing of the measurements;

- Processing:
  - Definition of the databases;
  - Definition of the expert system (inferential motor and base of knowledge);
  - Definition of the models and processes of inference.

One last consideration is worthy of mention: it is greatly desirable to create and use integrated databases, where information converges relative to an entire type of machinery, apparatus or systems, in order to make knowledge acquired in the field a common patrimony that can be valorised through continuous comparison with other application realities. A general plan of a prognostics system would have the structure shown in Figure 6.6.

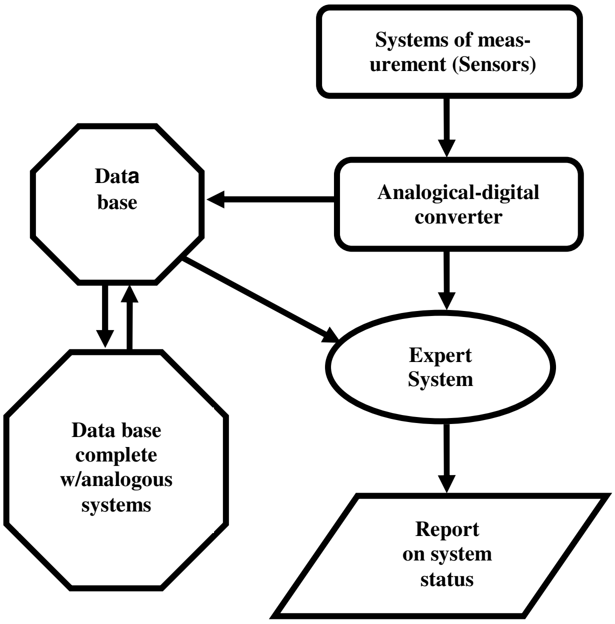

Fig. 6.6 General plan of a prognostics system

This manner of proceeding, based on sharing information, becomes strategic in several particular cases. For example, in applications on naval units with similar characteristics: by adding together the experiences acquired on different ships, we exploit the synergies that this system is capable of guaranteeing to the greatest possible extent (Figure 6.7).

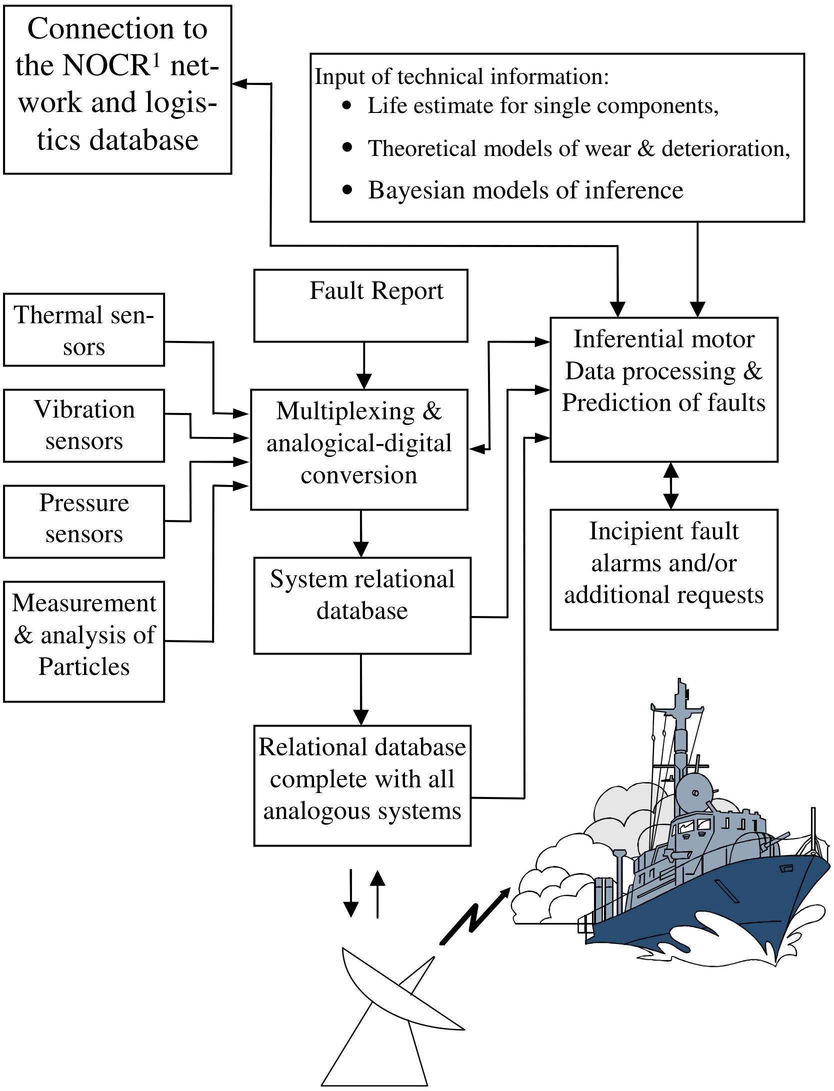

Fig. 6.7 Structure of a Prognostics System of naval units

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PART III

CASE STUDIES

Chapter 7

Intelligent Telematic Maintenance Systems for the Management of Technical Plants (by Lorenzo Fedele and Giampiero Mercuri)

7.1 Introduction

The management of technical production and safety plants is generally a complex activity, especially when the management of a great many plants distributed throughout the territory is required (for example, the increasingly frequent case of entrusting the maintenance of plants to specialised outsourcers), when a guarantee of the quality and results is required (such as in the case of several innovative contractual solutions) and when the technology of the plants is heterogeneous and innovative (for example, in electro-mechanical plants, etc.).

Research for the development of an intelligent telematic maintenance system developed from these considerations, for the management of technical plants, with the objective of controlling and monitoring the plants from a distance, through a remote control centre.

In particular, this study centres on the aspects of diagnosis and the safety of technical plants (such as lifts, thermo technical plants, etc.) through an instrument of analysis software designed for the purpose, based on neural networks and on dependability indicators.

The research was started in the first phase with analysis of the manner of breakdowns of lift plants and of a technical plant for the treatment of water for dialysis. This analysis permitted the identification of the critical elements of the systems analysed and was preceded by a phase of investigation relative to the state of the art.

In order to analyse the manner of breakdown and identify the magnitudes to monitor, an in-depth study was performed on the types of plants chosen for the development of intelligent telematic maintenance systems (lift plants, thermo and electric plants) which permitted the determination of their functional logic and therefore to understand the factors of risk and possible breakdowns or faults in the components of each type of plant.

In general, breakdowns that occur in a machine or plant are provoked by foreseeable or aleatory causes. Breakdowns produced by foreseeable causes are easy to identify and resolve, while those produced by aleatory causes are often related to the characteristics of each component making up the machine or plant and therefore require a more complex analysis. Dependability is also a function of the complexity of the system and it is therefore fundamental to establish which elements of the system are classified as "critical" – or responsible for most of the faults. It was useful for this purpose to proceed first of all with the logical disaggregation of the system, in order to better identify the parts making up the plant and successively analyse the manner of breakdown, resorting to consolidated methods of analysis of the manner of breakdown and realising a synthetic scheme, showing: the name of the component, its function, manner of breakdown, the cause of the breakdown, the local effect and frequency of the fault.

Following this analysis, it was therefore possible to select the magnitudes to monitor in order to use the data collected for successive processing of the system of intelligent telematic maintenance.

The next step was to identify the sensors (of the industrial type) to install on the technical plants to record the magnitudes determined and planning of the system of transportation of these signals and recording of the data collected.

Following the planning of the neural network and processing of the signals collected from the plants and memorised, a software prototype was developed, which makes up the intelligent telematic maintenance system for the management of technical plants.

7.2 The Intelligent Telematic Maintenance System for the Management of Technical Plants

The intelligent telematic maintenance system in question (indicated with the abbreviation STMI or GrAMS in the English version – Granted Availability Management System – consists of a network of industrial type sensors, capable of acquiring data on the part relative to predictive maintenance as well as on the part for purely preventive maintenance and control.

The network then sends this information to the STMI software, which is able to process the signals through the "error back propagation" type neural networks and extrapolate a daily maintenance plan, which unites ordinary maintenance programmed in advance with a heuristic type of maintenance.

Part of the software was developed in LabVIEW and is used for the remote transmission of the data acquired by the sensors. The LabVIEW libraries facilitated implementation of a software architecture based on a hierarchy of customer-server functions that reflect the system architecture. It was possible to solve all of the problems of communication, representation and analysis of the data within the same programming environment, without installing additional "layers" of software.

Control from a personal computer permits access to all components and guarantees recording of all actions that modify the operational status of the plant.

In addition to the procedure activation commands, it is possible to identify a group of plant parameters controlled from field point or PLC (delay times, alarm thresholds, safety settings), which can also be modified from a remote location, to reduce the presence of qualified personnel at the plant in the phase of start up of the plants and to change the operating conditions.

The portion of the software dedicated to interpretation through the neural network and to management of the actual maintenance plans, on the other hand, consists of a proprietary code and will be analysed in greater detail later. The final result of the analysis of input is characterised by the creation of a programme of daily intervention, based on logistical optimisations and security/safety priorities, as well as on possible existing contractual fulfilments.

The programme is capable of managing a great amount of data, thanks to the support of the database developed on the MSAccess platform, and is also capable of storing it to create a historical database, in time, of readings that can be easily and profitably consulted. This information is essential for the correct training of the neural networks.

Figure 7.1 shows the general plan of the intelligent telematic maintenance system for the management of technical plants, which was developed and realised within the ambit of this research. All of the phases leading to the realisation of the attached software are described in detail, along with the operation of the system.

7.3 Choice of Technical Plants to Monitor

7.3.1 General

The intelligent telematic maintenance system for the management of technical plants, realised on the basis of the acquisition of data, could theoretically originate from any type of industrial or civil plant. An asset can be subject to telematic maintenance only if it possesses several essential traits, conferred during "*ex novo*" construction or after successive intervention to adapt the system. Some of these characteristics are independent of the type of asset, while others refer to each type.

A hardware apparatus must be installed on board the asset, along with interface software for the signal captors that monitor it. Interfacing also takes place with the other sources of information used for the purpose of telematic maintenance. The captors are sensors that detect information directly in its original physical nature and translate it into an electronic form suitable for automatic treatment; there are also sources that process information directly in this latter form (PLC, PC, etc.); this takes place, for example, in the successive logical states that the asset gradually goes through in performing its function. The operator and maintenance personnel of the asset must also be considered sources of information, when these professional figures are effectively present.

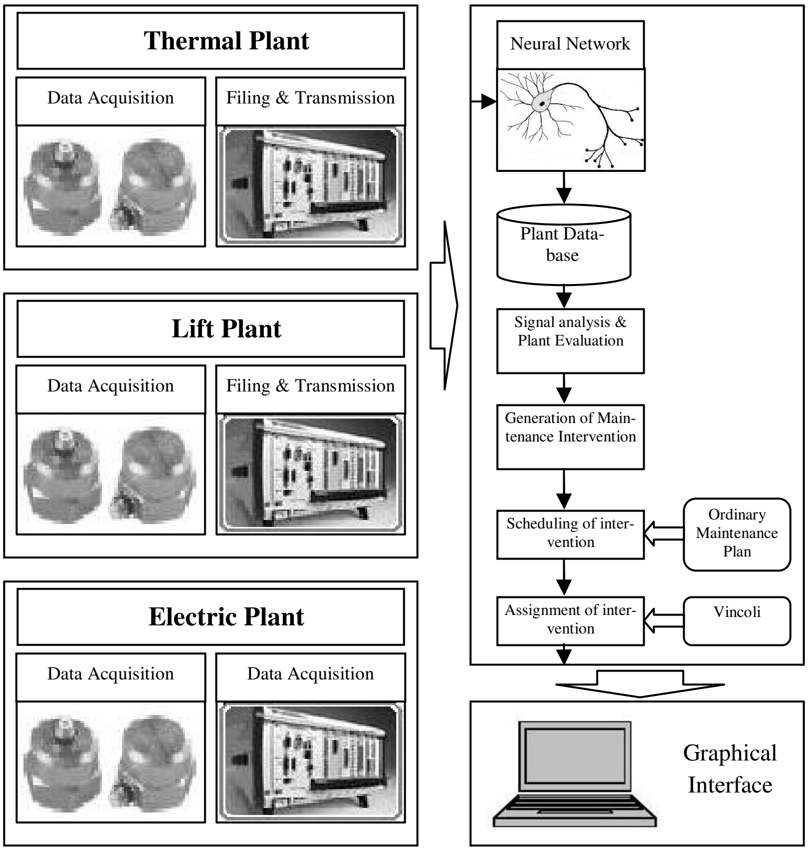


Fig. 7.1 General plan of the intelligent telematic maintenance system for the management of technical plants (STMI)

In addition to the captors, the asset must be equipped in an area of actuators capable of performing commands imported from remote sites, to absolve the maintenance intervention: cylinders, motors, switches, potentiometers, heaters, etc. In order for the actuators to operate, it is necessary for the asset to provide them with the power they need.

The last task that this part of the system of generation of information must absolve, which is of fundamental importance for the purpose of telematic maintenance, is communication with the remote location.

On the level of application, the requirements indicated above must be satisfied through the employment of:

- hardware – sensors, actuators, input/output boards, signal conditioning boards (amplification, linearisation, etc.), PLC, NC, PC and its ancillary units;
- software – code of configuration, code for the management of input and output, possible code for translation from the low level language of the hardware to the high level language and vice versa (this involves the servers of the sensor drivers, the actuators, the PLCs, etc), communications codes.

7.3.2 The Types of Plants to Monitor

As stated, the intelligent telematic maintenance system for technical plants can be used for the management of any type of plant. The system realised was set up for the management of the following types of plants:

- Lift;
- Electrical plant;
- Thermal plant.

Analysis of these three types was conducted through an initial disaggregation of the system into blocks, followed by a FMECA analysis of the various components. The dependability of a system necessarily derives from the complexity of its structure and the importance of each internal component. It is therefore fundamentally important to break the system down and study the relationships between each individual element and the elements connected to it, to bring out every critical aspect.

The results of the block diagram and FMECA analysis performed on the lift, electric and thermal plants are shown below in synthetic schemes, where the name of the element, the manner of breakdown, the cause of breakdown, the local effect and the frequency of the fault are indicated.

7.4 Analysis of the Lift

To perform the analysis of the lift plant, it was broken down into elements to identify possible faults, their frequency and the effect they may provoke. The FMECA method was used for analysis of criticalities. The results of this study are shown below with reference to the lift plant and the electro mechanical drive. The result of the disaggregation into sub-elements is shown in Figure 7.2.

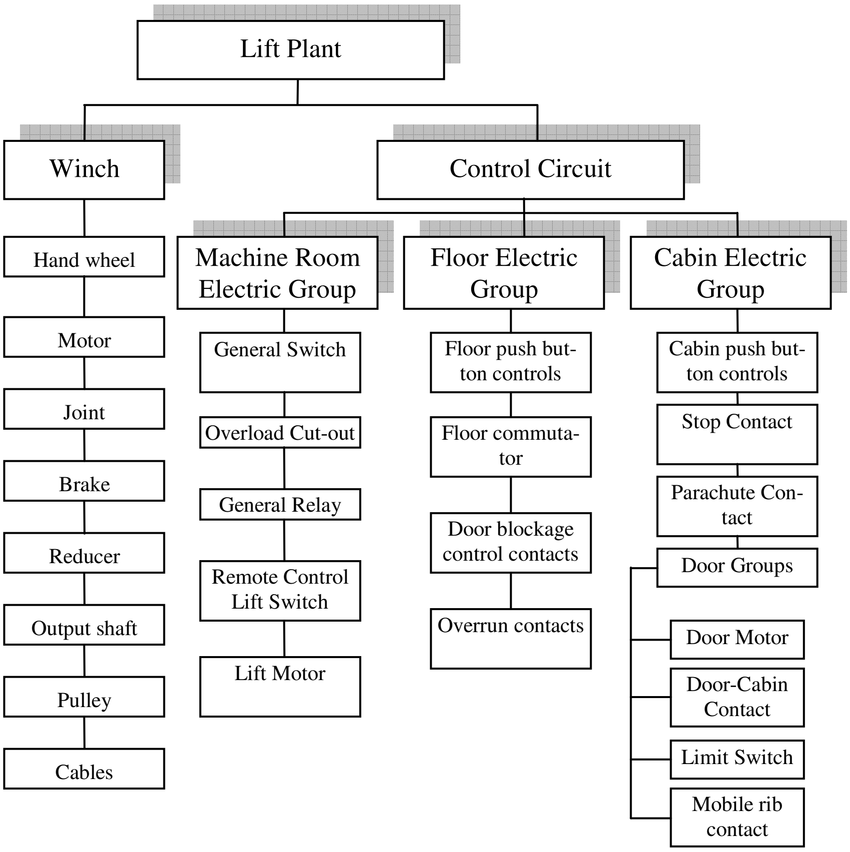


Fig. 7.2 Breakdown of the lift plant into blocks

7.4.1 Table of Faults and Frequencies for the Lift Plant

The function was analysed of each element the lift plant was broken down to, along with its possible manner of breakdown and the relative cause, the local effect derived from the fault in the component and the frequency with which the faults could occur. The following table summarises the results of the analysis performed on the elements of the lift plant identified.

Table 7.1 Table of faults and frequencies for the lift plant

ELEMENT	FUNCTION	MANNER OF BREAKDOWN	CAUSE OF FAULT	LOCAL EFFECT	FREQUENCY OF FAULT
Motor	Permits movement of the cabin	Out of use	Breakdown	OUT OF SERVICE	Remote
Joint	Connects the motor shaft with worm screw (input shaft)	Out of use	Mechanical breakdown	OUT OF SERVICE	Remote
Brake with brake shoes	Blocks movement of the reducer and consequently of the cabin	Malfunction	Wear	The cabin is not braked effectively	Occasional
Reducer	Transmits motor power to pulley	Out of use	Sudden overloads	The cabin cannot be stopped with the brake	Occasional
Cables	Connect cabin to winch pulley	Excessive wear	Poor balancing of counterweights	Slippage of the pulley and ineffective braking	Occasional
General Switch	Engages & disengages the control circuit	Blockage of the device	- Wear of contacts - Wear of construction parts	OUT OF SERVICE	Remote
Overload cut-out	Cuts the motor off from tension when it reaches a temperature out of tolerance	Out of use	Blockage of contacts	Motor not protected from temperatures out of tolerance	Remote
General Relay	Cuts out the manoeuvring circuit after the contacts for lifting or descent have been set	Contacts blocked in off position Contacts blocked in on position Interruption of winding	- Electro erosion - Fusion of contacts	OUT OF SERVICE	Occasional
Remote control lift/descent switch	Cabin lift or descent motor control	Contacts blocked in off position Contacts blocked in on position Interruption of winding	- Electro erosion - Fusion of contacts	OUT OF SERVICE	Occasional
Manoeuvring Transformer	Could lower mains tension	Out of use	Interruption of primary or secondary	OUT OF SERVICE	Remote

			winding		
Lift motor	Rotates lift winch	Out of use	- Mechanical wear - Overheating - Peaks in current	OUT OF SERVICE	Remote
Floor push button controls	Permits calling cabin to floor	Contacts blocked in off position - Contacts blocked in on position	- Wear of contacts - Sabotage	If a button is blocked in the open position the cabin cannot be called to that floor If a button is blocked in the closed position the plant is out of service	Frequent
Floor Commutator	Sets the manoeuvring circuit on lift or descent of the cabin	The relative contacts are no longer closed	- Wear of contacts - Breakage of leverage	If the commutator breaks for the ground floor o top floor the plant is out of service If the commutator breaks for one of the intermediate floors, the lift will be out of service only for that floor	Probable
Door blockage control contact	Closes the manoeuvring circuit when the lift doors are blocked	Fails to close the circuit when the doors are blocked	- Wear of contacts - Mechanical breakdown of door closure system	OUT OF SERVICE	Frequent
Limit Switch contacts	Open the manoeuvring circuit when the cabin continues its run beyond the last floor or ground floor	Contacts blocked in off position - Contacts blocked in on position	- Wear of contacts - Breakage of leverage	If the limit switch is blocked open, the manoeuvring circuit always remains open and therefore out of service If it is blocked in the closed position there is no longer	Remote

				any protection (other protections intervene) in the event the lift goes beyond the floor	
Cabin push button controls	Permit passengers to send the lift to the desired floor	Contacts blocked in off position - Contacts blocked in on position	- Wear of contacts - Sabotage	If a button is blocked in the open position the cabin cannot be sent to that floor If a button is blocked in the closed position the plant is out of service	Frequent
STOP contact	Allows passengers to open the manoeuvring circuit at any time	Contacts blocked in off position - Contacts blocked in on position	- Wear of contacts - Sabotage	If a button is blocked open the lift is out of service If a button is blocked in the closed position the STOP button is out of service	Probable
Parachute contact	Opens the manoeuvring circuit when the parachute device is engaged	Contacts blocked in off position - Contacts blocked in on position	- Wear of contacts - Blockage of contacts	If it is blocked open the lift is out of service If it is blocked closed the manoeuvring circuit no longer opens when the parachute device is engaged (other devices intervene to open the circuit	Remote
Door motor	Engages the door opening device	Out of use	- Mechanical wear - Overheating -Peaks in current	OUT OF SERVICE	Remote
Cabin door contact	Consent contact located n cabin doors	Fails to close the circuit when the doors are blocked	- Wear of contacts - Mechanical breakdown of	OUT OF SERVICE	Frequent

			door closure system		
Door overrun	Cuts the door motor off from the manoeuvring circuit when the doors are completely open	Contacts blocked in off position - Contacts blocked in on position	- Wear of contacts -Deformation of leverage	If blocked open the doors fail to open If blocked closed, the door motor remains under current, when the doors are open, risking burnout	Occasional
Mobile rib contact or photocell	Prevents passengers from being blocked between the closing doors	Out of use	- Wear of contacts - Breakage of the mechanical device (mobile rib contact)	OUT OF SERVICE	Occasional

7.4.2 Analysis of Criticalities for the Lift Plant

Table 7.2 below shows the results of the FMECA analysis performed on the lift plant.

Table 7.2 Results of FMECA analysis for lift plant

		Criticality			
		Minor	Marginal	Critical	Catastrophic
Frequency	Improbable	- Hand wheel	-Motor shaft		-Soft brake -Input shaft
	Remote	-Motor -Overload cut-out	Motor winding - Motor shaft supports - Brake rectifier	Input shaft supports	- Joint - Brake shoes - Output shaft - Pulley - Limit Switch contacts
	Occasional	- General relay switch	- Electro magnetic brake	Output shaft supports	- Worm screw - Helicoidal wheel
	Frequent	Door blockage control contact			

In order to assign the criticalities and frequency, the criteria indicated in the following tables were used:

Table 7.3 Criteria for assignment of criticality in a lift plant

Criticality	Assignment
Catastrophic	Fault that puts the safety of the plant at risk
Critical	Fault that places the plant out of service or damages the elements designed to protect other components of the plant
Marginal	Fault that causes partial out of service
Minor	Fault of an unimportant nature

Table 7.4 Criteria for assignment of criticality in a lift plant

Frequency	Assignment
Frequent	Once per month
Occasional	A few times per year
Remote	Less than once per year
Improbable	Less than every three years

7.5 Analysis of the Electric Plant

To perform the analysis of the electric plant, it was broken down into elements to identify possible faults, their frequency and the effect they may provoke. The result of the division of the electrical plant into sub-elements is shown in Figure 7.3 below.

7.5.1 Table of Faults and Frequencies for the Electric Plant

The function was analysed of each element the electric plant was broken down to, along with its possible manner of breakdown and the relative cause, the local effect derived from the fault in the component and the frequency with which the faults could occur. Table 7.5 below summarises the results of the analysis performed on the elements of the electric plant identified.

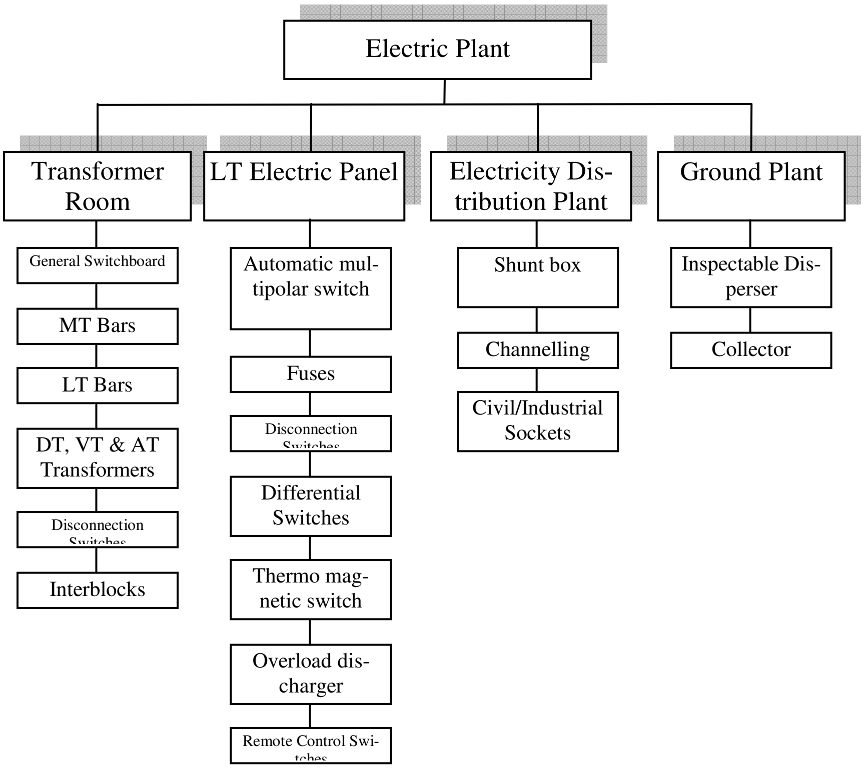


Fig. 7.3 Breakdown of the lift plant into blocks

Table 7.5 Table of faults and frequencies for the electric plant

ELEMENT	FUNCTION	MANNER OF BREAKDOWN	CAUSE OF FAULT	LOCAL EFFECT	FREQUENCY OF FAULT
General switchboard	Container where electric lines arrive and depart from The various manoeuvring, measurement and protective devices are installed here.	Breakdown of the device	- Wear of contacts - Wear of components	OUT OF SERVICE	Probable
MT bars	Rigid conductors, supported by insulators, from which transformer connections	Wear	Tension drops on bar	Excessive drops in tension	Remote

	depart				
LT bars	Rigid conductors, supported by insulators, from which transformer connections depart	Wear	Tension drops on bar	Excessive drops in tension	Remote
AT Transformer	Permit the connection of instruments of measurement on MT (ammeter) lines	Out of use	Interruption of primary or secondary winding	OUT OF SERVICE	Occasional
VT Transformer	Permit the connection of instruments of measurement on MT (voltmeter) lines	Out of use	Interruption of primary or secondary winding	OUT OF SERVICE	Occasional
Cut off switches:	Manoeuvring device suitable for opening in the absence of current, closure in the absence of current and grounding in an evident manner	Fault on cut off command	Wear of components	Impossible to secure transformers from a remote location	Remote
Interblocks	Safety blocks for the cut-off switch	Out of use	Fusion of contacts	Impossible to adjust the combined opening and closure of the various cut off switches	Occasional
Automatic multiplier switch	Automatic switch with relative cut off power	Out of use	- Wear of contacts - Wear of components	Blockage of plant	Occasional
Fuses	Device capable of interrupting the circuit irreversibly	Breakage of the filament	Excessive amperage	OUT OF SERVICE	Probable
Differential switch	Relay switch for differential current	The switch does not trip and does not interrupt the circuit	Wear of components	Plant not protected against direct contact	Occasional

Magneto thermal switch	Electro magnetic relay for max current + thermal relay against overloads	The switch does not trip and does not interrupt the circuit	Wear of components	Plant not protected against overloads	Occasional
Ground cabin	Set of conductors connecting the cabin to the ground	Out of use	- Loss of insulation of conductors - - Wear of contacts	Plant not protected against indirect contact	Remote
Ground room	Set of conductors connecting the cabin to the ground	Out of use	- Loss of insulation of conductors - - Wear of contacts	Plant not protected against indirect contact	Remote
Overload discharger	Components of protection against temporary overloads	Out of use	Wear on electrodes	Plant isolated and not protected against overloads	Remote
Relay switches:	Switch capable of being commanded at a distance by telematic controls	Out of use	- Electro erosion - Fusion of contacts	OUT OF SERVICE	Occasional
Shunt box	For cabling of the network of wiring	Out of use	- Loss of insulation of conductors - - Wear of contacts	OUT OF SERVICE	Occasional
Channelling	Self-extinguishing plastic tubes	Loss of structural integrity	Wear	None	Remote
Civil/Industrial sockets	Points of access for use of electricity	Out of use - Short circuit	- Wear of contacts - Wiring exposed	OUT OF SERVICE	Occasional
Disperser	Conductor element that guarantees good electric contact between the ground plant and the ground	Out of use	-Wear - Lack of electric continuity	Plant isolated and not protected against indirect contact	Occasional
Collector	Terminal or bar that permits the collection of	Out of use	-Wear - Lack of electric continuity	Plant isolated and not protected against	Occasional

	charges or electric current	indirect contact

7.5.2 Analysis of Criticalities for the Electric Plant

Table 7.6 below shows the results of the FMECA analysis performed on the electric plant.

Table 7.6 Results of FMECA analysis for lift plant

		Criticality			
		Minor	Marginal	Critical	Catastrophic
Frequency	Improbable	TM/LT bars - Channelling	Cut off switches:	Overload discharger	
	Remote		VT/AT Transformers - Shunt boxes		- Ground cabin - Disperser - Collector
	Occasional	- Remote control switches	- Interblocks - Automatic multiplier switch	- Differential switch - Magneto thermal switch - Civil/Industrial sockets	
	Frequent	- Fuses	- General switchboard		

In order to assign the criticalities and frequency, the criteria indicated in the following tables were used:

Table 7.7 Criteria for assignment of criticality in an electric plant

Criticality	Assignment
Catastrophic	Fault that puts the safety of the plant at risk
Critical	Fault that places the plant out of service or damages the elements designed to protect other components of the plant
Marginal	Fault that causes partial out of service
Minor	Fault of an unimportant nature

Table 7.8 Criteria for assignment of criticality in an electric plant

Frequency	Assignment

Frequent	Once per month
Occasional	A few times per year
Remote	Less than once per year
Improbable	Less than every three years

7.6 Analysis of the Thermal Plant

To perform the analysis of the thermal plant, it was broken down into elements to identify possible faults, their frequency and the effect they may provoke. The result of the division of the thermal plant into sub-elements is shown in Figure 7.4 below.

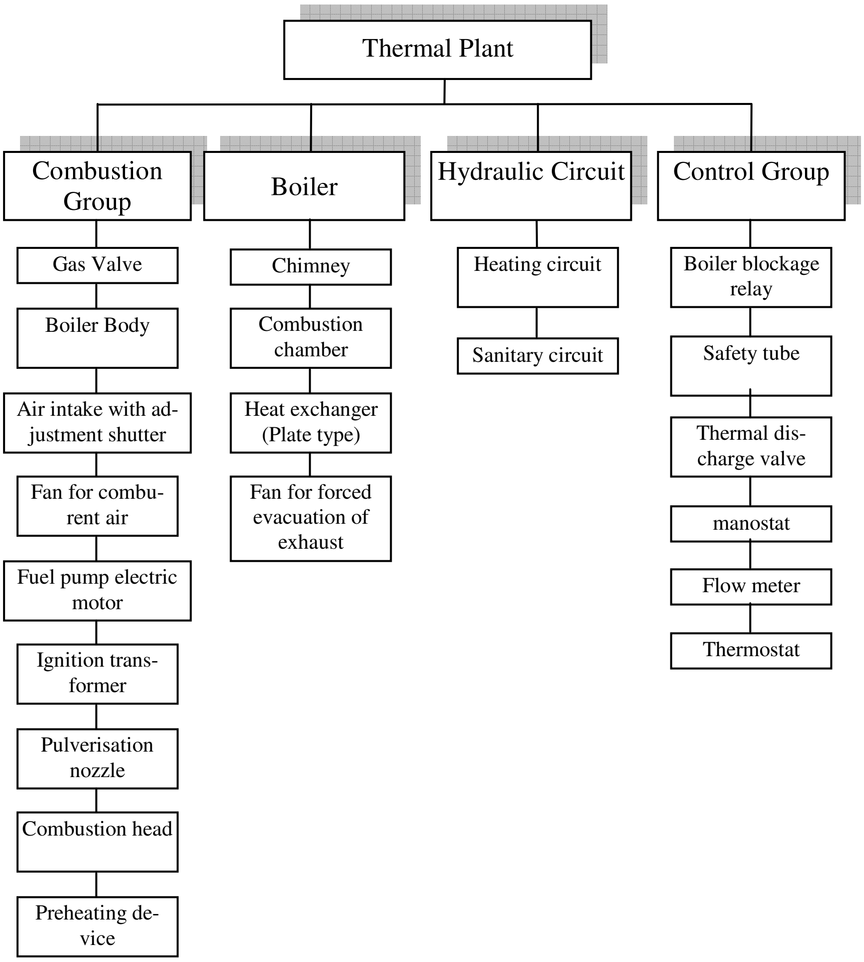


Fig. 7.4 Breakdown of the thermal plant into blocks

7.6.1 Table of Faults and Frequencies for the Thermal Plant

The function was analysed of each element the thermal plant was broken down to, along with its possible manner of breakdown and the relative cause, the local effect derived from the fault in the component and the frequency with which the faults could occur. Table 7.9 below summarises the results of the analysis performed on the elements of the thermal plant identified.

Table 7.9 Table of faults and frequencies for the thermal plant

ELEMENT	FUNCTION	MANNER OF BREAKDOWN	CAUSE OF FAULT	LOCAL EFFECT	FREQUENCY OF FAULT
Gas valve (only gas plants)	Regulates gas pressure arriving to boiler	- Gas drawn towards boiler - Blockage	- Manufacturing defect - Wear - Presence of impurities	Blockage of plant due to excess loss of pressure	Probable
Boiler body	Contains the elements of the burner and permits distribution of air through the Archimedean screw	Breakage of lining	- Excessive pressure - Wear	Low performance in combustion	Remote
Air intake with adjustment shutter	Doses quantity of comburent air	Blockage of the shutter	- Breakdown	Low performance in combustion	Occasional
Air fan	Pushes air into the Archimedean screw	Poor mixture	- Fan tube blocked - Fan blocked	Low performance in combustion	Occasional
Fuel pump (with relative single-phase motor	Provides fuel to the burner	Loss of pressure	- Poor condition of hydraulic connections and joints - Electric components faulty	Blockage of plant	Probable
Ignition transformer	Supplies high tension necessary to start the ignition spark	- Transformer out of service and failure to fire ignition spark	- Electric power down - Fuse broken -Erroneous electrode transformer cable connection	Plant fails to start	Probable
Pulverisation nozzle	Finely pulverizes fuel, mixing it with air	Low fuel supply	Nozzle encrusted	Low performance in combustion	Occasional

Combustion head	Ensures good mixture, stability of flame and yield in combustion	Leakage or breakage	Presence of impurities	Bad mixture in burner	Occasional
Preheating device (only for fuel oil burners)	Electric resistance necessary to bring oil to the optimum temperature for pulverisation	Preheater not functioning	- Electrical fault	Poor mixture	Occasional
Chimney	Conveys and discharges combustion exhaust	Chimney blocked	- Presence of impurities and soot	Low draught	Remote
Combustion chamber	Where the thermal exchange takes place, prevalently through irradiation	- Cracks in structure - Deposit of impurities - Damage to the internal screen	- Thermal stress - Poor combustion	Loss of heat	Remote
Plate exchanger	Thermal exchange for sanitary system	Deposit of impurities	- Normal operation	Lo efficiency of exchanger	Remote
Fan for forced evacuation	Ensures evacuation of boiler fumes	Malfunction	- Faulty electrical components	Possible only natural draught	Occasional
Burner blockage relay	Blocks burner due to lack of fuel, air or electricity	Contacts blocked in off position	- Electro erosion - Fusion of contacts	Blockage of plant	Occasional
Safety tube (Wood stove)	Places the upper part of the generator in communication with the atmosphere	Obstruction		Impossible to disperse any vapour present in the combustion chamber	Remote
Heat exhaust valve	Self-engaged valve whose obturators open when the temperature is too high	- Undesired opening	- Wear	Impossibility to avoid excessive temperature of the plant	Remote
Manostat	Controls and regulates pressure in the generator within set values	- Block in phase of interruption. - Block in phase of operation.	- Faulty mechanical components - Wear of contacts	Blockage of plant	Occasional
Flow meter	Controls burner to prevent arri-	- Block in phase of interruption.	- Faulty mechanical com-	Blockage of plant	Occasional

	val of fuel when the temperature is too high	- Block in phase of operation.	ponents -Wear of contacts		
Thermostat	Regulates temperature in the generator	- Block in phase of interruption. - Block in phase of operation.	- Faulty mechanical components - Wear of contacts	Blockage of plant	Occasional

7.6.2 Analysis of Criticalities for the Thermal Plant

Table 7.10 below shows the results of the FMECA analysis performed on the thermal plant.

Table 7.10 Results of FMECA analysis for thermal plant

		Criticality			
		Minor	Marginal	Critical	Catastrophic
Frequency	Improbable		- Combustion chamber	- Safety tube	
	Remote		- Boiler body - Air intake with adjustment shutter	- Chimney	- Heat exhaust valve
	Occasional	- Preheating device	- Air fan - - Combustion head	- Pulverisation nozzle - Fan for forced evacuation	- Burner blockage relay - Manostat - Flow meter - Thermostat
	Frequent		- Gas valve - Fuel pump - Ignition transformer		

In order to assign the criticalities and frequency, the criteria indicated in the following tables were used:

Table 7.11 Criteria for assignment of criticality in a thermal plant

Criticality	Assignment
Catastrophic	Fault that puts the safety of the plant at risk
Critical	Fault that places the plant out of service or damages the elements designed to

	protect other components of the plant
Marginal	Fault that causes partial out of service
Minor	Fault of an unimportant nature

Table 7.12 Criteria for assignment of criticality in a thermal plant

Frequency	Assignment
Frequent	Once per month
Occasional	A few times per year
Remote	Less than once per year
Improbable	Less than every three years

7.7 Network sensors and hardware

7.7.1 The FieldPoint Network

The network of acquisition is based on the use of products belonging to the FieldPoint family, which guarantees facilitated development, implementation and maintenance, thanks to the software that can be configured and to the modular hardware in the network.

Each of these intelligent nodes can act as an independent component in a system on line and can nevertheless communicate with a Windows host computer. It is also possible to integrate the modules via Ethernet into existing systems and connect them to RS-232 serial devices or communicate with them. FieldPoint consists of a great many analogical and digital I/O modules and various interfaces for I/O distributed through Ethernet, serial, Foundation Fieldbus and wireless networks.

The FieldPoint modules offer high performance I/O and conditioning of signals, as well as direct connectivity towards many sensors, including those of tension and current, RTD, thermocouples, relays and impulse generators. They are available with 8 or 16 channels, but there are also modules with double channels for extremely diverse signal systems (in terms of nature and range).

The FP-1601 (network module) chosen is capable of controlling a bank of I/O modules that can be configured by the user. These individual nodes, programmed with LabVIEW Real-Time, can perform machine monitoring, data acquisition and data processing operations and programmable distributed control.

A single network module can manage a maximum of nine FieldPoint I/O modules, including any combination of analogical and discrete I/O of the FieldPoint line of products, including the FP A1-110 (8 Analogical inputs), FP DI-330 (8 Digital inputs) and FP TB 1 (standard terminal box) chosen for the system.

The node based on FP-1601 automatically negotiates a10BaseT or 100BaseT Ethernet connection on line. Every FP-1601 module also includes a RS-232 serial port that can be used to communicate with other serial devices of the system, like FieldPoint systems and modem radios.

These modules were chosen because they exploit technologies like the development of LabVIEW and the Ethernet network backbone, and it is possible to develop, install and easily maintain these systems, thereby reducing the cost of investment. The applications can wait for control by the network or simply kick off a stand-alone performance.

The FieldPoint systems can be mounted on DIN rails on panels and have various packaging options that permit simple and safe assembly of the modules.

In order to monitor each plant, it will therefore be necessary to purchase and install the following components:

- FP 1601 (network interface);
- FP A1-110 (8 Analogic input);
- FP DI-330 (8 Digital input);
- 2* FP TB1 (Standard terminal box);
- PS5 (transformer);
- STAR Modem by Datalogic.

It will be necessary to purchase a LABVIEW software licence to interact with the FieldPoint system for the software portion.

7.7.2 Signal Conveyance Systems

Radio-modems were chosen for the transmissionof the signal from the plant to the remote control station (Figure 7.5), which are easily connectable to the FieldPoint network used for the colleciton of signals from the sensors installed on the plants to be monitored.

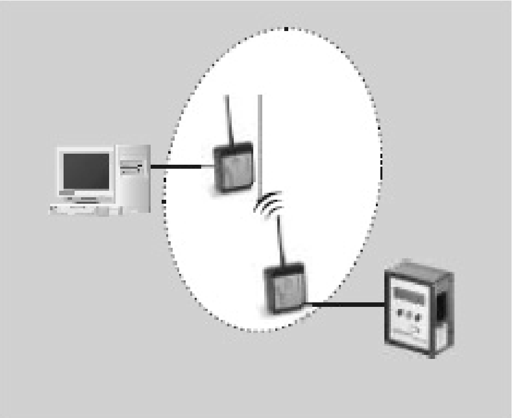


Fig. 7.5 Scheme of radio-modem connection

Of course, in place of the radio-modem, a traditional telephone line can also be used, interfacing the various field-points with the remote server through routers or ADSL modems (Figure 7.6).

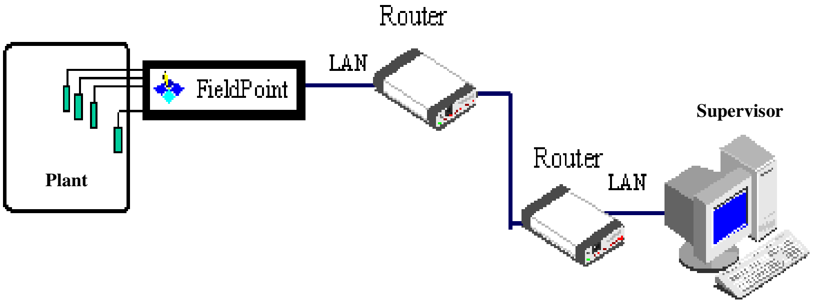


Fig. 7.6 Scheme of connection with routers or ADSL modems

7.7.3 The sensors

Concerning the sensors to be managed through the FieldPoint systems, only some magnitudes, and precisely the "intelligent" ones, require dedicated sensors, while for the diagnostics part, the signals from the various switchboard and switches can be interfaced quite well with the I/O modules.

The FMECA analysis previously shown, indicated the various critical components of the systems, which will therefore be subject to telematic control by the system. Only a few of them, however, are suitable for an intelligent and predictive type of analysis, therefore most of them will be managed through the acquisition of a signal for telematic control and more complete and effective diagnostics of the system.

Let us look at each system to identify the sensors of an idustrial type chosen and necessary to acquire the signals with the required precision, which must then be analysed by the various neural networks of the STMI software program.

7.7.3.1 The Sensors to use for the Electric Plant

The following four sensors have been identified to monitor the electric plant following the FMECA analysis performed:

- Magnitude: **ground resistance**
  - Measurement of the resistance to ground, through the use of a HR300 tester (4 wire method);
- Magnitude: **temperature of the electric control panel**
  - Temperature and voltage of the electric control panel, through the CPM control module;
- Magnitude: **voltage of the electric control panel**
  - Temperature and voltage of the electric control panel, through the CPM control module;
- Magnitude: **dispersion of current in the circuit**
  - Dispersion of current in the circuit, through the toroid (Split Core) of the "Elite Pro Power";

Additional signals may be collected using the network analyser of the "Elite Pro Power".

7.7.3.2 The sensors to use for the thermal plant

The following four sensors have been identified to monitor the thermal plant following the FMECA analysis performed:

- Magnitude: **Chimney fume pressure**
  - Measurement of the chimney fume pressure, through a digital DMM 414.R2 manometer (to ensure the draught and air-tightness in the boiler is optimal)
- Magnitude: **fume temperature**

  - Measurement of the fume temperature, through an FTA 125 thermocouple produced by ALMENO (to monitor possible loss of heat due to incomplete combustion, loss due to less than optimal irradiation and air-tightness);

- Magnitude: **pressure of the hydraulic circuit**
  - Measurement of the output circuit, through a digital DMM 414.R2 manometer;
- Magnitude: **water temperature of the output circuit**
  - Measurement through an FTA 125 thermocouple produced by ALMENO.

Additional signals may be collected using the telematic systems available for thermal plants.

7.7.3.3 The Sensors to use for the Lift Plant

The following five sensors were identified to monitor the electromechanical lift plant, in view of the FMECA analysis performed:

- Magnitude: **Electrical resistance of the blocking devices of the doors on the various floors**
  - Probe for the measurement of insulation, placed on the electrical contacts of the door blocks on the various floors, interfaced to the electric control panel with a suitable electric board.
- Magnitude: **brake adjustment of the which-motor group**
  - Detection of the difference in height between the lift and floor, with a differential encoder, which is already in use at point 3;
- Magnitude: **slippage between the cables and friction pulley**
  - Revolution counter on the axis of the winch with a KUBLER transducer, model 5810, to detect the distance travelled on the pulley in correlation to the distance travelled on the cables (depending on the length of run of the lift) measured with an incremental encoder produced by ELCIS, model AF13I;
- Magnitude: **amplitude of vibrations of the winch**
  - Measured with an accelerometer produced by WILCOXON, model PC420V, installed on the winch;
- Magnitude: **load (cabin + persons/materials aboard)**

– Liftsentry load cell series 901, installed under the floor of the cabin to measure the effective load placed in the cabin.

Additional signals may be collected using the diagnostics systems available for manoeuvring groups of lift plants.

7.7.4 The Signal Generator

Signals generated artificially through the LABVIEW software, which simulates the sensors installed on the plants, were used for the realisation of the STMI software. In this manner, it was possible to simulate the monitoring of many plants distributed throughout the territory and to test the performance of the STMI software realised. The next paragraph describes the prototype of the intelligent telematic maintenance system for the management of technical plants.

7.8 The Neural Network

Processing of the magnitudes was performed with the assistance of the neural networks The following steps were taken in designing the neural network:

- Definition of the input and output;
- Data collection and assignment of the target values;
- Definition of the architecture of the neural network;
- Training of the neural network;
- Analysis of the results of training;
- Performance of tests on the neural network designed.

7.8.1 Definition of the Input and Output

The input to the artificial neural network that every type of plant monitored is equipped with consists of the values of the magnitudes monitored through the sensors described in the previous paragraphs.

The output of the neural network is represented by the following dependability and accident prevention parameters:

1. Ks – plant safety index;
2. Ka – plant dependability/availability index.

The Ks index assumes values between 0 and 1, depending on the scale of values foreseen in the following table:

Table 7.13 Values assumed by Ks (plant safety index)

Ks Value	Safety	Intervention
0	Plant safe	None
0.25	Plant safe to keep under control	Verify parameters during ordinary visits for scheduled periodical maintenance
0.5	Plant safe to keep under close control	Schedule specific controls during ordinary maintenance visits
0.75	Level of attention	Schedule specific intervention to verify the condition and to restore the plant to safety if necessary
1	Unacceptable risk	Shut the plant down and intervene urgently

The Ka index assumes values between 0 and 1 (following table):

Table 7.14 Values assumed by Ka (plant dependability/availability index)

Ka Value	Dependability/Availability	Intervention
0	Plant dependable and available	None
0.25	Plant dependable and available, to be kept under control	Verify parameters during ordinary visits for scheduled periodical maintenance
0.5	Plant dependable and available, to be kept under close control	Schedule specific controls during ordinary maintenance visits
0.75	Incipient breakdown	Schedule specific intervention to verify the condition and to restore the plant to a situation of dependability and availability.
1	Breakdowns	Condition of imminent breakdown; intervene urgently on the plant to avoid downtime and reduce the period of unavailability of the plant.

7.8.2 Data Collection and Assignment of the Target Values

In order to assign the target values necessary for training of the neural networks, operational conditions for the plants were simulated using adequate mathematical models. In this manner, the possible conditions of safety, dependability and availability of the technical plants examined were simulated, the input data was collected and the Ka and Ks target values were assigned.

Input values at time n (n ranges from 0 to N, where N is the instant in which a breakdown and/or unacceptable risk situation occurred) were collected and recorded at established intervals (Tr) for each simulation experiment. In order to assign the Ka and Ks target values, an adequate procedure was utilised, with which it was possible to train the neural network to enable it to forecast (during normal on-line operation of the plant) the conditions of breakdown and unacceptable risk, through the approaching value of 1 of Ka and Ks estimated by the network.

7.8.3 Definition of the Architecture of the Neural Network

The neural network designed has the following structure and features.

Type of neural network: feed-forward;
Number of layers: 3;
Number of neurons of the input layer:
    5 (for the lift plant);
    4 (for the thermal plant);
    4 (for the electric plant).
Number of neurons of the "hidden"layer: 15;
Number of neurons of the output layer: 2;
Function of transferral between the input layer and the "hidden" layer:
    Sigmoid function;
Function of transferral between the "hidden" layer and the output layer:
    Sigmoid function.

The following Figures 7.7, 7.8 and 7.9 show the plan of architecture of the neural networks used in this research for the different types of technological plants. The neurons are represented by the nodes and the synapses by the arches connected the nodes. The values of weights of the synapses represent the strength of the connection between the neurons on different layers (nodes). These values are calculated through the process of training of the neural network.

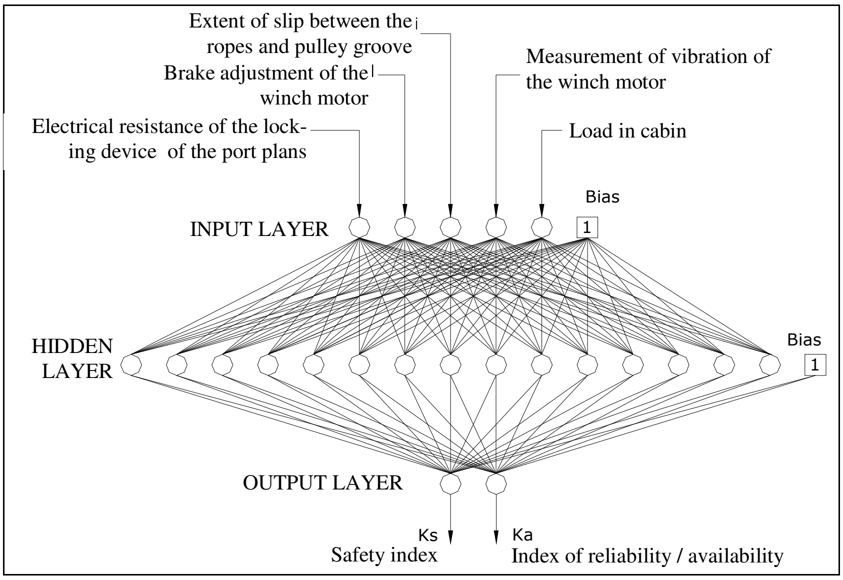


Fig. 7.7 Plan of the architecture of the neural network used for the lift plants

7.8.4 Training of the Neural Network

Various efficient algorithms are available in scientific literature for the training of artificial neural networks. One of the most widely used and efficient of these is the algorithm of Levenberg-Marquardt. It is an algorithm of the retro-propagation of error type, which realises supervised training (Figure 7.10). The values of the input collected were used to train the neural network (training set). In correspondence to these values, the relative Ks and Ka target values were assigned (expected values).

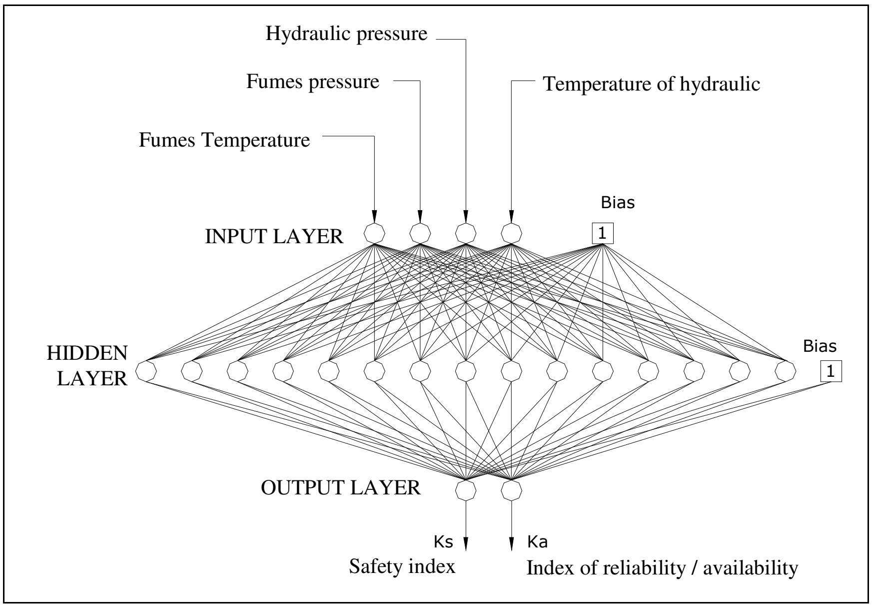


Fig. 7.8 Plan of the architecture of the neural network used for the thermal plants

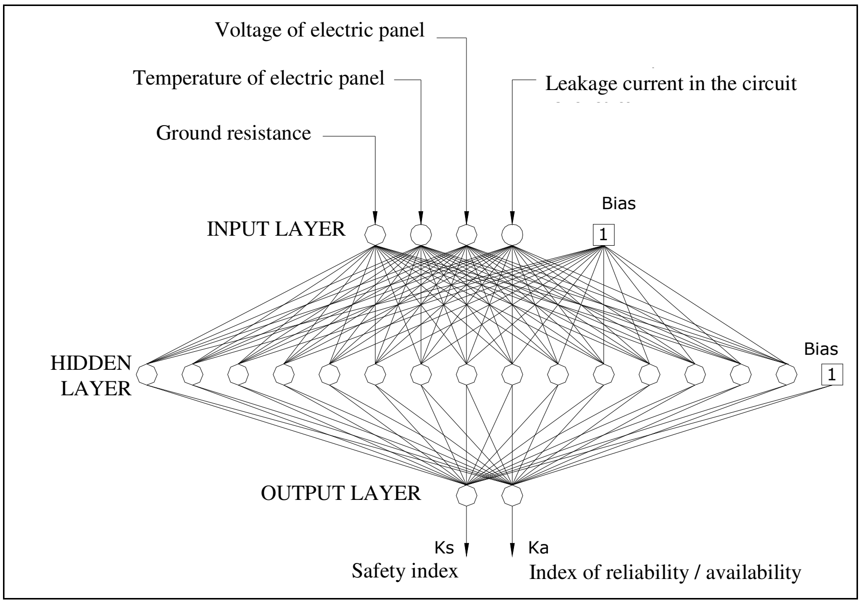


Fig. 7.9 Plan of the architecture of the neural network used for the electric plants

The error of the network (error recalling) is the sum of the squares of the differences (Sum Squared Error "SSE") between the expected values and the output of the network, calculated using the training set data. For proper training of the neural network, the value of the SSE error must be lower than 0.02.

The training of the neural network is therefore a process of reiteration of correction of the values of the weights of the synapses (the entity of the correction depends on the resulting SSE values), which terminates when the final SSE error value is less than 0.02.

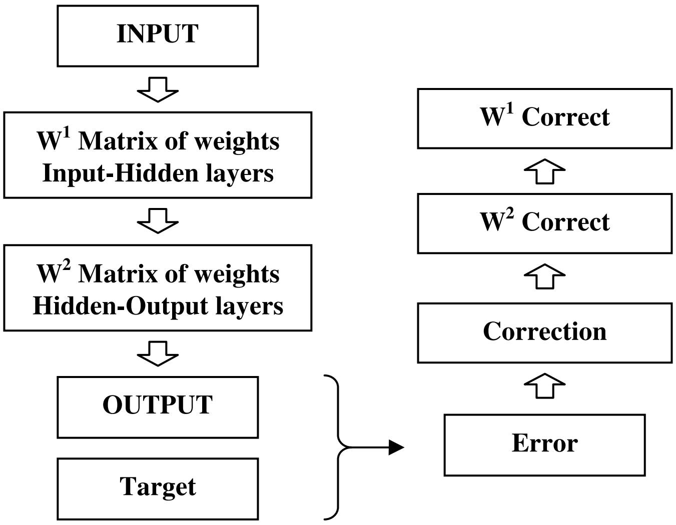


Fig. 7.10 Supervised retro-propagation of error training plan

Each cycle of correction of the weights is called a "period of training".

The neural networks set up for the types of plants taken into consideration were trained using the Levenberg-Marquardt algorithm, obtaining good results in terms of speed of convergence (SSE<0.02) and in terms of effectiveness of the training. In fact, the training of the neural network relative to the lift plant, for example, ended with the following results:

Period of training = 49;
Recalling error SSE = 0.0198.

7.8.5 Verification of the Neural Network

In order to verify the process of training of the neural network, a set of verification data (verifying set) was used to evaluate the response of the network with the expected Ka and Ks values. It was then possible to verify the proper response of the neural network. In fact the recognition error (SSE calculated on the verifying set in relation to the expected Ka and Ks values) was less than 0.02.

7.8.6 Experimentation and Updating of the Neural Network

The trained neural network was used to forecast the conditions of danger and breakdown of the plant during its on-line operation, through evaluation of the Ks and Ka indexes calculated as a function of the measured input values. The operation of the plants is simulated through opportune signal generators in the software realised.

The Ka and Ks values calculated by the network and successively processed by the management software present at the remote control station provide a measurement of the conditions of risk and the probability of a breakdown of the technical system during on-line operation.

Additional training may be imparted to the neural networks when the technician visits the plant (for obligatory visits, ordinary and extraordinary maintenance visits scheduled due to faults, accidents, etc.). During these visits, the technician will compile a special evaluation card, which will enable the network to assign new Ks and Ka values, if there is a discrepancy between the value calculated by the network and the actual status of the plant. In this manner, the neural network will be able to adapt itself to the "changes" that take place in the technical system during its life cycle, which could occur over time due to the wear and tear of the components of the plants and the variations in its use (frequency and duration of use, average loads, environmental factors, etc.).

7.9 The Intelligent Telematic Maintenance System for the management of Technical Plants (STMI)

The intelligent telematic maintenance system for the management of technical plants (STMI) allows the user to collect and organise all of the information from the various plants monitored, manage the scheduled maintenance program and the collection of historical data, giving maintenance operators the possibility to immediately visualise and print out any technical detail relative to the machine they must perform maintenance on.

It is an intelligent and adaptable software, capable of learning over a period of time and thus becoming increasingly efficient and effective. A printout of the maintenance intervention to be performed or analysed, in the case of maintenance already performed, may be generated at any time.

The STMI software is capable of acquiring operational data from a system of supervision, thus realising continuous and effective control over the state of wear of the equipment. Every event can be recorded in a historical maintenance archive, which can be used by the quality assurance service to obtain the information necessary for the improvement of production and/or the efficiency of the plants. The ordinary maintenance plan established in advance by the company, may be visualised and modified, if necessary, choosing to visualise only the parts concerning an individual plant.

The operational scheme of the software can be summarised with the flow chart shown in Figure 7.11. The diagram is obviously preceded by the part of acquisition and the signal through the hardware network, which have already been dealt with, and by the analysis of the data by the neural network. At this point the software has a series of readings available, which have already been associated with a logistical index, related to the plant, the time data and the Ka and Ks indexes necessary for predictive maintenance.

Through a series of files where the technical information on the various plants is stored, the weights of the associated neural networks, the resources of the company and contractual information, the programme is able to develop an optimal maintenance strategy, automatically managing every technician available in the most efficient and effective manner possible.

The following types of files are included among the program archives:

DB (Data Base) Plants, containing:

- Collection of all readings made over time on the various plants, with associated logistics information;
- Historical DB with readings that effectively show the presence of a breakdown (the neural networks are trained with this database);
- DB of intervention, where all maintenance intervention on the plants is memorised, along with any comments;
- Ordinary maintenance DB, which obviously contains the intervention for preventive maintenance.

.list Files

These are normal text files where a list of maintenance intervention and supervision to be performed is recorded whenever the system predictively detects a possible fault, without the certainty of the effective nature of the fault.

.log Files

These files contain information concerning a certain plant, therefore technical data, neural network weights and information on the managers and on the location of the plant.

Executable file created with Labview

These files permit the system to interface with the fieldpoint units in the data acquisition network and to control them from remote locations.

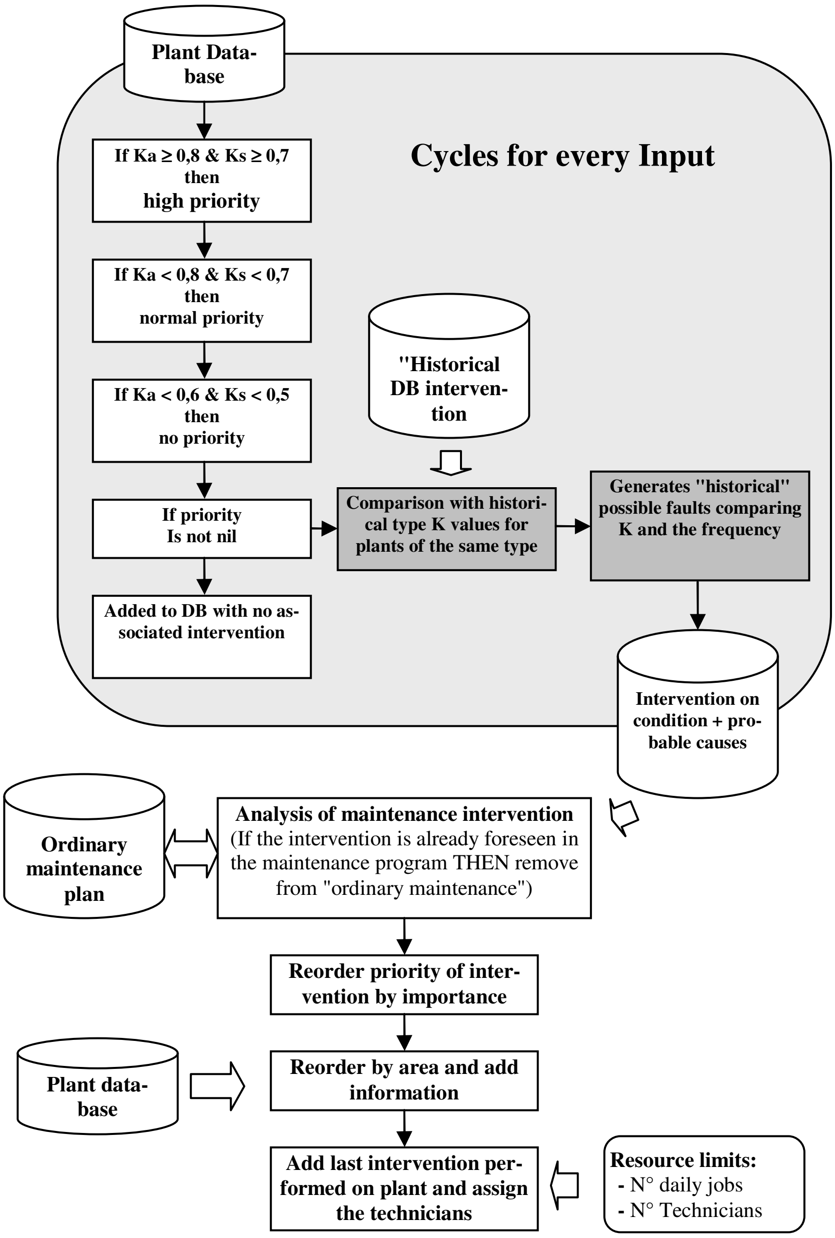


Fig. 7.11 Operational plan of the STMI software

Distance.files and technician.files

These are also text files, in the first of which information on the distances between one area of intervention and another have been entered, through parameters that summarise the duration of movement between two points on the map. The second, on the other hand, is a list of technicians that the company has available to perform maintenance, specifying the specialisation of each technician.

7.9.1 Most Important Sub-Routines of the STMI software

In Figures 7.12 and 7.13 below, a block diagram is shown of the two principle sub-routines of the STMI software.

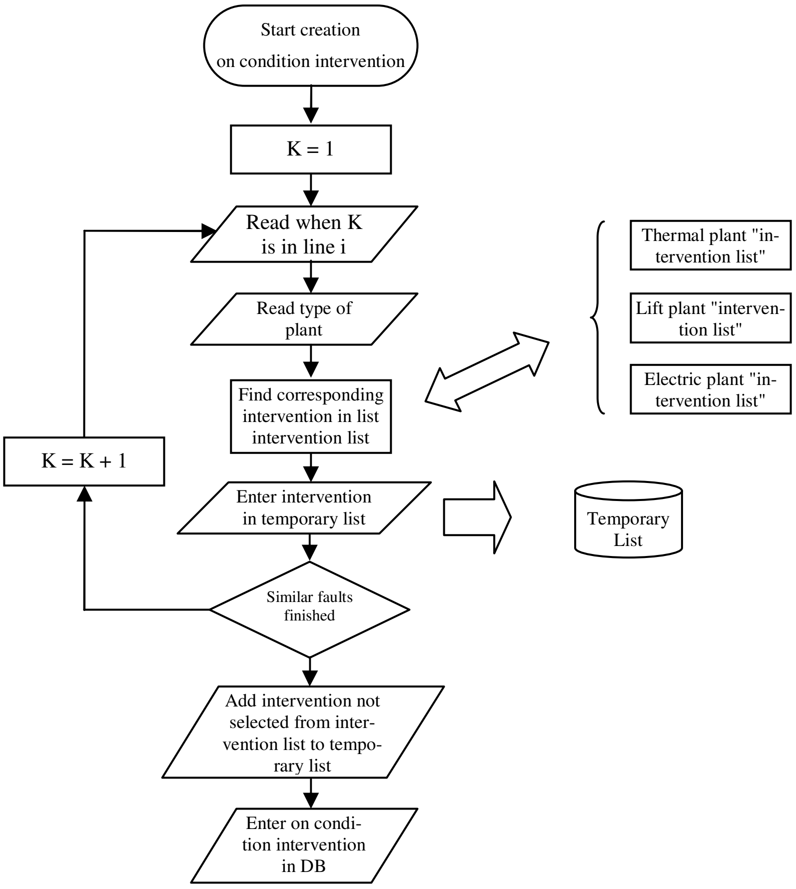


Fig. 7.12 Block diagram of the sub-routine of the STMI software for the creation of on condition (predictive) maintenance intervention

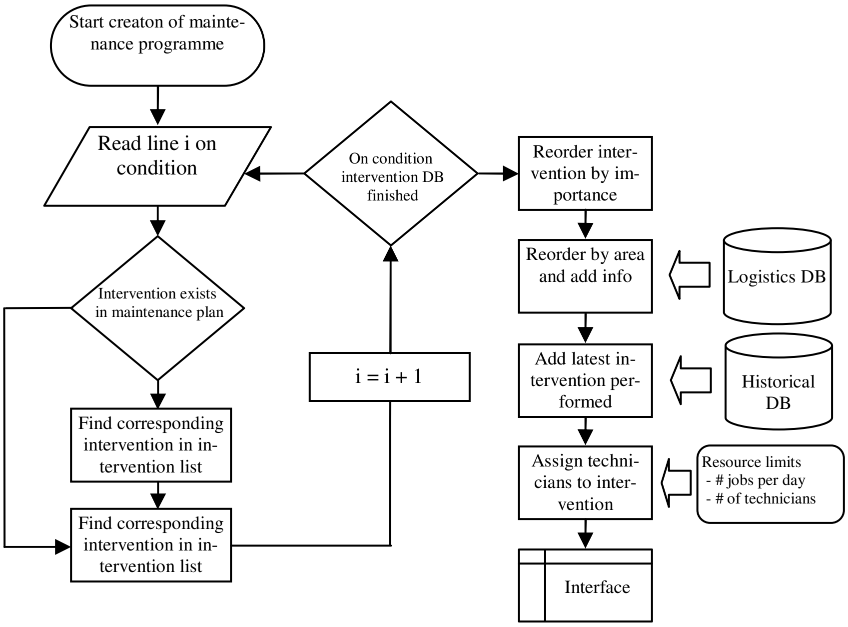
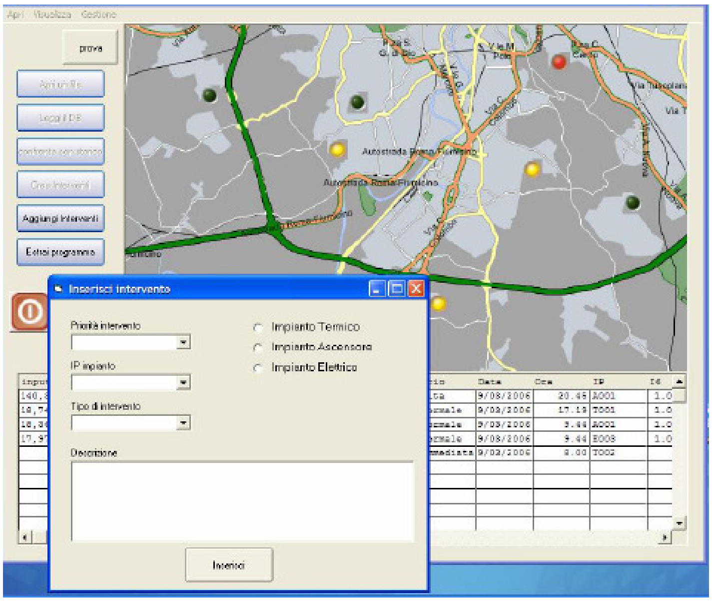


Fig. 7.13 Block diagram of the sub-routine of the STMI software for the planning and management of maintenance intervention

In Figures 7.14, 7.15, 7.16 and 7.17 below, several screen displays of the STMI software management are shown.



rio	Data	Ora	IP	Id
ta	9/08/2006	20.46	A001	1.0
rmale	9/08/2006	17.19	T001	1.0
rmale	9/08/2006	3.44	A001	1.0
rmale	9/08/2006	9.44	E008	1.0
mediata	9/08/2006	8.00	T002	

Fig. 7.14 Screen display of the STMI software – Management of technical plants distributed throughout the territory

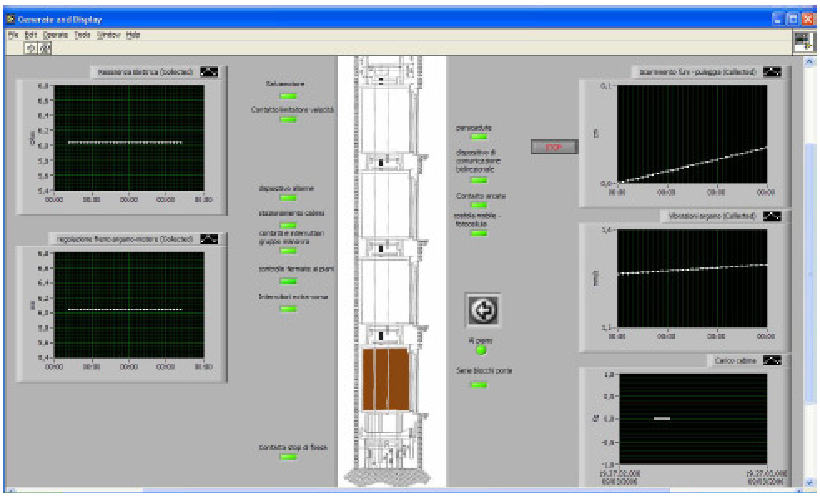


Fig. 7.15 STMI software screen display – Monitoring of the lift plant

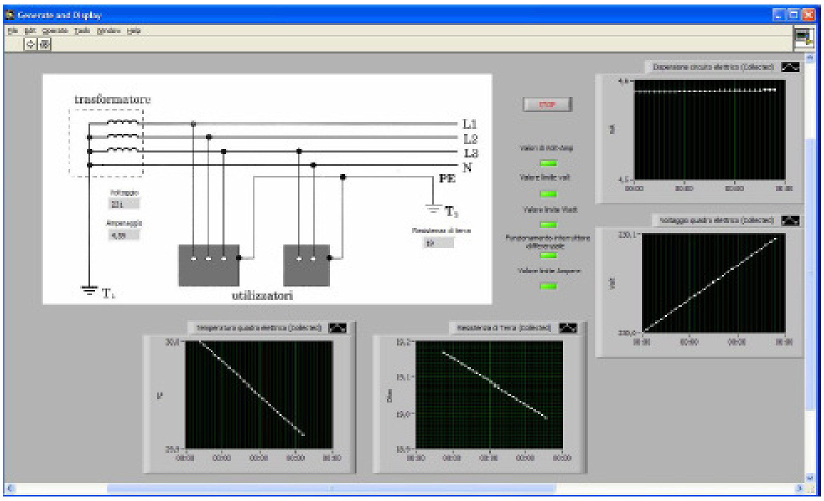


Fig. 7.16 STMI software screen display – Monitoring of the electric plant

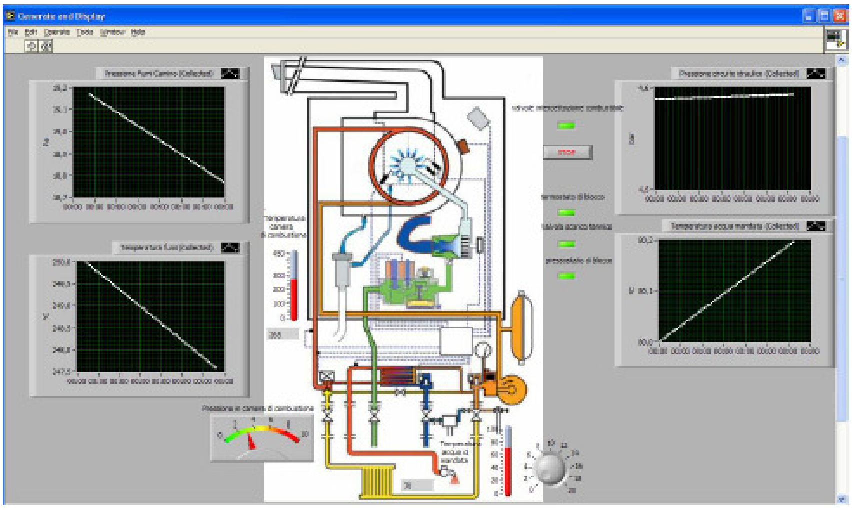


Fig. 7.17 STMI software screen display – Monitoring of the thermal plant

Chapter 8

Model for the Overall Evaluation of Management and Maintenance Contracts (by Massimo Concetti and Lorenzo Fedele)

8.1 Introduction

The investigation conducted on the state of the art was performed through analysis of the most important instruments available in literature and practice for the measurement of quality in services, especially focused on the extension of these approaches to the management of quality in the field of maintenance services. This also referred in particular to cases where these services are entrusted to third parties through global service contracts.

The technical norms available were taken into account for this purpose and the results deemed most meaningful were analysed of specific research reported through university works, the acts of conventions, tests and business experiences.

8.2 Quality in Services

Quality is defined as "the total elements and characteristics of a product or service that contribute to its ability to satisfy specific or implicit requirements" (UNI EN ISO 9000.2000).

Contrary to what has taken place in the field of industrial products, where a series of statistical methods based on the evaluation of tangible elements for quality control of processes, the services sector has no universally accepted reference scheme available.

This shortcoming is related to the peculiar characteristics that the class of services possesses with respect to products, which can be summarised as follows:

- They have an intangible nature, which is apparent in the difficulty of procuring physical or functional parameters that can be assumed as indexes of quality;
- They are heterogeneous, due to the fact that contrary to the total number of products in a given series or lot, whose quality tends to be the same from one

product to another, in services quality is variable from one service to another of the same type, depending on the standardisation of the producer and customer;
- Interaction, attributable to the participation of the user in the production and distribution of the service through contact with the supplier.

On the basis of these brief considerations, the models in literature relative to the measurement of quality in services essentially take three aspects of the service into consideration: the *expectations* of the customer relative to a given characteristic of the service; *the importance* attributed to this characteristic; and the evaluation of the *effective performance* of the service.

Among the existing instruments, the most well known is called ServQual (Parasuraman, Zeithaml and Berry), which measures quality as the difference between performance and expectations. The instruments used consist of two questionnaires made up of 22 questions for evaluation, on an assigned scale, of expectations and performance of several indictors relative to five dimensions (tangible aspects, dependability, response capability, reassurance capability and empathy).

The data collected are then analysed with statistical methods.

The use of customer satisfaction questionnaires, in any case, is an instrument that has strong strategic value in the measurement of quality in services, permitting to verify the level of efficiency and effectiveness of a service, as it is perceived by the users, with a view to improvement of performance.

In order to fulfil this function, customer satisfaction must be adequately planned, following a correct path that permits the provider to clearly establish objectives, instruments, actors and means of investigation, as well as to monitor the correct implementation of the project, the relative support actions and the manner of verification of the results obtained.

8.3 The Global Service of Maintenance

Through the recent norms emanated, the concept of maintenance as a service has been gradually asserted. In particular, the UNI EN 13306:2003 norm *"Maintenance Terminology",* defines maintenance as: "the combination of all technical and administrative actions, including actions of supervision, intended to maintain or restore an entity to a condition enabling it to perform the required function".

Parallel to this, interest in maintenance has grown, beyond the traditional ambits where it has historically developed, and, for example, the tendency to outsource maintenance in a regimen of global service has increased.

Global service is "a contract referring to a set of services that substitute normal maintenance activities, with full responsibility for the results on the part of the provider".

This instrument, initially developed in the USA and then imported throughout Europe, is spreading rapidly both in the public and private sector, involving all activities that do not fall within the ambit of the company's core business, but which are nevertheless necessary for the effective operation of an organisation. This complex set of activities can be divided into three distinctive groups of services:

- Facility services (building maintenance, maintenance and management of technological plants, etc.);
- Spatial services (services supporting office activities, the management of archives, the layout of offices, furnishing, etc.);
- Personnel services (catering, cleaning, safety, porterage, reception, etc.).

Until a few years ago, recourse to outsourcing was not widespread in Italy and concerned only some types of services. We have witnessed growth and increasing demand for company services in this sector recently. Business concerns consider it more important to concentrate on their core business, in fact, and tend to delegate the management of auxiliary services for the operation of their business to qualified outsourcers.

Although the advantages of this contractual form, based on the results, show up in terms of costs, competencies and the quality of the service distributed, the main problem the companies face in stipulating a Global Services contract has remained partially unsolved – namely the difficulty of evaluating the results, which is related to payment of the fees to the provider. This element is decidedly more complex with respect to the evidence of performance, especially in the field of services, where achievement of results may appear to be subjective.

In Global Service contracts, the constant measurement of customer satisfaction relative to the services distributed has become a fundamental element. In order to perform these measurements, it is necessary to extend the considerations made relative to the measurement of quality in services, crossing the *perceived quality* with the *importance* the customer attributes to the individual service and with the *quality distributed* by the supplier. The reason for this is because the procurement of outsourced services takes place through suitable tertiary contracts, which govern the supply of a service by a qualified provider at an established cost, through appropriate specifications of obligations and technical specifications, which define the provider's obligations, the manner in which the services are distributed and the minimum standards of quality to be guaranteed, as well as any mechanisms of penalties and credits.

In this connection, it is interesting to indicate the results of an American study on the *"Service level agreement framework for business service"*, in which it is asserted that the measurement of customer satisfaction must be related to what are considered, according to various other works, the two key elements for the evaluation of the results of a global contract service: the Service Level Agreement and the reporting system.

The Service Level Agreement (SLA) is a dynamic document that contains the expectations of the customer in terms of the quality of service expected and through which all of the operational aspects of the customer-provider relationship are managed, defining the manner of distribution of the services and the structure of awards and penalties.

The reporting system, on the other hand, is an instrument of connection of the results, defined in the Service Level Agreement, with indicators or Key Performance Indicators (KPI), capable of objectively recording the results during performance of the services.

The choice of these indicators must be such as to bring out specific aspects of the service rendered, bringing out the strong points and ambits of possible improvement.

The requirements of a good KPI are:

- Synthetic statement;
- Clarity;
- Simplicity of interpretation;
- Simplicity of calculation;
- Ease in procuring the data (through the information technology system).

The study identifies an initial set of indicators within the ambit of an integrated Global Service arrangement, corresponding to the aspects that it is fundamentally important to monitor: the speed with which the provider intervenes, the frequency of any delays; continuity in distribution of the services; the capability of operationally implementing planning; the verification of the quality distributed; the overall satisfaction of the customer.

The primary and most important parameters of verification of the quality of service rendered in global services arrangements are:

- The satisfaction of the user or citizen. In order to measure this element, it is necessary to be aware of the assessment of the users relative to the quality of the service, the competence of the operators and the courtesy of the switchboard operators;
- The trend of response time, which must be shortened during the period of the contract;
- The relationship between on condition and scheduled maintenance, which must bring out a continuous percentile decrease in unscheduled intervention during the period of the contract;
- The performance of the plants under equal conditions, which must indicate a continuous reduction in consumption.

These are just a few of the possible indicators that literature has suggested be taken into consideration on this subject, stressing the importance of adjusting the choice to the specific reality studied.

The peculiarity of maintenance management contracts for Global Services brings out the need for specific models of evaluation of the quality of the services rendered.

Although many indicators have been proposed by norms and studies conducted on the subject in the field of Global Service maintenance, documented experiences of implementation or experimentation of models in which these indicators are merged in a single index capable of making a synthetic global evaluation of the quality rendered are lacking today.

In fact, in most cases, indexes are instruments that are used individually and explained in the technical specifications attached to contracts, for the application of mechanisms of credits and penalties, through the comparison of values guaranteed and values measured relative to appropriate parameters that it is agreed to monitor.

8.4 Identification and Classification of Objectives

The primary objective, declared explicitly, is to measure and bring out, through a synthetic global parameter, the performance provided in terms of well-being, image, availability and safety, associating the relative price with it.

The achievement of this objective is determined by the achievement of secondary objectives, whose analysis leads to an initial classification made on the basis of the recipients of the model itself, which aims, in fact, to be an instrument capable of addressing the customer to show him the results of the management and maintenance, but also a useful means of internal verification, which may be the starting point upon which to plan maintenance and improvement of the results achieved.

On this basis, the objectives are initially grouped in two principle classes, **objectives of self-diagnosis** and **customer objectives,** in which the objective is unvaried, but the point of view and therefore the final purpose changes.

These objectives are listed below:

- *To show and evaluate* the initial situation.
- *To detect and evaluate* possible improvement.
- *To detect and measure,* through a synthetic parameter, the level of service guaranteed, connected with the cost estimated.
- *To justify and calculate* the price connected with the level of service guaranteed.
- *To demonstrate and evaluate* performance, in terms of the well-being and safety of those working in the infrastructure, the image of the customer towards his infrastructure and the availability of the infrastructure assets.
- *To demonstrate and evaluate* the effectiveness and efficiency of the service, on the basis of the price/performance ratio.
- *To demonstrate and evaluate* the achievement of the result guaranteed, through a numerical summary parameter (quality index).
- *To demonstrate and detect* improvements made.
- *To detect* where to intervene to make improvements.

These objectives show how the instrument is designed to achieve an evaluation of performance that is not independent from the cost associated with it and which possesses the characteristics of a means of management through which to plan, implement, verify and improve the results of the activities performed.

In particular, further analysis of the objectives shows how they are classified in two categories, according to a more suitable criterion for management purposes: **planning objectives** and **objectives of verification and improvement,** whose achievement will take place over a period of time, to permit the initial definition of the level of service, estimation and justification of the related cost and, successively, implementation of the activities planned, evaluation and demonstration of the achievement of the level of service guaranteed as the established price.

This criterion of classification has brought out the need for a model that contains two instruments: an instrument of planning, to define and justify the level of service and the related cost; and an instrument of verification and improvement, where the level of service and cost are subject to evaluation and are therefore assumed as fixed data.

In order to achieve these objectives the model must meet the requirements of:

- Comprehensibility and ease in use, obtained through the realisation of documents at different levels of detail and the use of parameters whose meaning is known;
- Streamlining, achieved through the classification of the contract in homogeneous areas, which are dealt with in an analogous manner and through the use of a limited number of meaningful parameters;
- Economic viability, realised with the use, where possible, of parameters that are already available;
- Adaptability and flexibility, obtained with an instrument on the level of general detail;
- Synthesis, achieved with the return of a global performance index;
- Meaningful and effective, obtained with the use of an index that leaves a trace of the weight of the individual parameters;
- Dynamism, achieved through the identification of return parameters whose analysis enables definition of actions for improvement;
- Updating, achieved through the progressive collection of data.

Definitions:

Well-being: environmental comfort, understood as the psychological and physical comfort of the occupants of a building/infrastructure during the work shift;

Availability: the aptitude of an entity of being able to perform a required function, under specific conditions, at a specific time or during a given interval of time, starting from the supposition that the necessary external resources are supplied (*source: UNI EN 13306:2001);*

Image: the aspect of the infrastructure, especially concerning the most important management pathways;

Safety: the absence of unacceptable risks (combination of (e) probability of occurrence and (e) consequences of a certain dangerous event) *(source: OHSAS 18001:1999 "Specific Safety Management System")*.

8.5 Identification and Classification of Performance Indexes

The term indexes refers to the set of parameters that a model uses to define the global quality index, originating from the combination of several parameters.

From the investigation conducted on the state of the art, it emerged that relative to the measurement of the quality of services and specifically in the evaluation of performance rendered through global service contracts, performance indicators (KPI) are used to monitor customer satisfaction, to cross perceived quality with the importance attribute to individual services and with the quality distributed by the supplier, which measure the divergence from the level of service agreed upon (SLA).

On the basis of this result it was decided to define three types of indexes, designated with the terms **SLA, Incidence** and **Index,** defined as follows, relative to the four factors of performance it is desired to take into account in evaluating the quality of the service distributed.

SLA: the result with reference to a definite period of time, of the performance of services distributed, relative to a specific technological system;

Well Being Incidence: degree to which a technological system influences the well-being perceived by the customer (the personnel present in the facility);

Image Incidence: degree to which a technological system influences the image that the contractor transmits to his customer;

Availability Incidence: degree to which a technological system influences the availability of an infrastructure;

Safety Incidence: degree to which a technological system influences the safety of the customer (the personnel present in the facility);

Well Being Index: measurement of the well being perceived by the customer, taking into consideration the technical and environmental traits of the specific system and performance of the services distributed relative to the technological system itself;

Image Index: measurement of the image that the contractor transmits to his customer, taking into consideration the technical and environmental traits of the specific system and performance of the services distributed relative to the technological system itself;

Availability Index: measurement of the availability of the technological system managed, taking into consideration the technical and environmental traits of the specific system and performance of the services distributed relative to the technological system itself;

Safety Index: measurement of the level of safety of the technological system managed, taking into consideration the technical and environmental traits of the specific system and performance of the services distributed relative to the technological system itself;

It can be inferred from these definitions that the **SLA** parameters contain a measurement of the performance provided, while the parameters of **incidence** contain an estimate of the weight of the individual system on the factors of performance and the **index** parameters contain a measurement of the level of performance perceived by the customer relative to the factors of performance. Their combination defines the global index of quality that takes the economic factors into consideration.

The successive phase of specific definition of these indexes was preceded by the identification of the requirements that these and the parameters they are derived from must satisfy, on the basis of the analysis of the objectives it is desired to obtain through use of the model.

These indexes are required to be:

- Objective, so as not to leave space for subjective judgments;
- Quantifiable, and therefore capable of being expressed numerically;
- Measurable and monitorable, so that the measurement is meaningful, reproducible and easy to perform;
- Meaningful, in that their meaning is known and useful for the purposes of the model;
- Easy, in the sense of being easily understandable, manageable and measurable;
- Comparable, so as to permit meaningful integration for the construction of the global index;
- Definite, in terms of what is measured and how it is measured;
- Dynamic, to provide useful indications for intervention to make improvements.

The realisation of these requirements lead to the definition of parameters that did not resort to interviews on the level of satisfaction, which were drawn from the analysis of the meaningfulness of the parameters already being monitored, which were normalised, for which a reference target could be set, which were deduced from the analysis of the parameters used in similar experiences and advised by maintenance norms in force.

It was thus chosen to calculate the SLA through a combination of parameters that took the divergence from the threshold values of several guaranteed results into consideration, with reference to the number and timing of planned maintenance activities.

In particular, the maintenance activities were classified by strategy: scheduled maintenance, on condition maintenance (both types of preventive maintenance performed at established intervals or on the basis of prescribed criteria designed to reduce the probability of fault or deterioration of the operation of the entity), corrective maintenance (or breakdown maintenance), defined according to UNI EN 13306:2003 *"Maintenance Terminology"* as follows:

Scheduled maintenance: preventive maintenance performed on the basis of a time schedule or an established number of magnitudes.

On condition maintenance: preventive maintenance based on monitoring of the performance of an entity and/or of meaningful parameters for its operation and on control of the consequent action taken.

Breakdown Maintenance (or corrective maintenance): maintenance performed following the detection of a fault and intended t restore the entity to a condition that enables it to perform a required function.

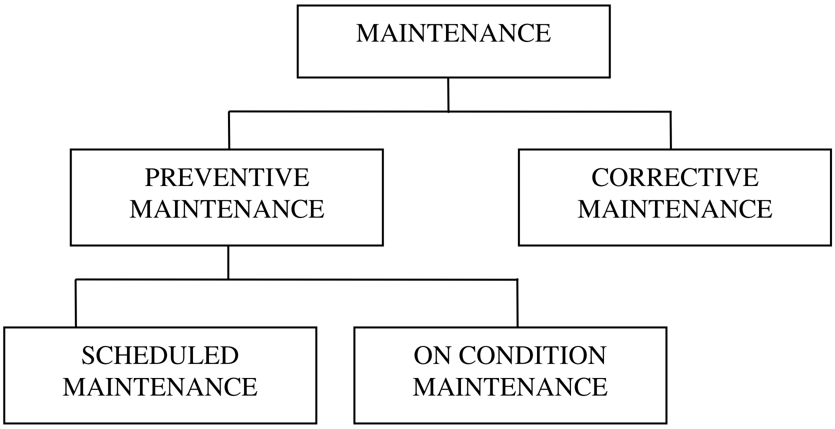


Fig. 8.1 Maintenance strategies

For scheduled maintenance the parameter of control is the number of interventions performed, which provides a measurement of the correspondence to the maintenance plan, when compared with the number of interventions planned.

For corrective (or breakdown) maintenance and on condition maintenance, we refer to the studies on reparable systems, for which a flow of faults and repairs is determined, giving rise to the specification of meaningful periods of time from the point of view of the system and its components (Figure 8.2):

Mean Down Time (MDT): this is the average period of non-performance of the system following a fault, which is the sum of three other intervals of time identified with respective parameters (Figure 8.3):

- *Logistical Delay Time* (LDT), which is the down time of the component necessary to prepare the means of logistical support required (technical, spare parts, equipment, documentation);
- *Administrative Delay Time* (ADT), which is the down time of the component due to questions of a management or administrative nature (priority in the assignment of personnel, strikes, delays to obtain authorisations, etc.);
- *Mean Active Maintenance Time* (MAMT), which is the average time required to perform maintenance, either automatically or manually, on an entity, including the delays due to technical and/or logistical causes, which do not include ADT or LTD.

Once repaired, the system or component remains operational for an additional period of time, which defines a new parameter: *Mean Up Time* (MUT).

The sum of MUT and MDT leads to the definition of a new term, which is the *Mean Time Between Failures* (MTBF), or the interval, expressed in hours of operation, within which the occurrence of failures can be expected.

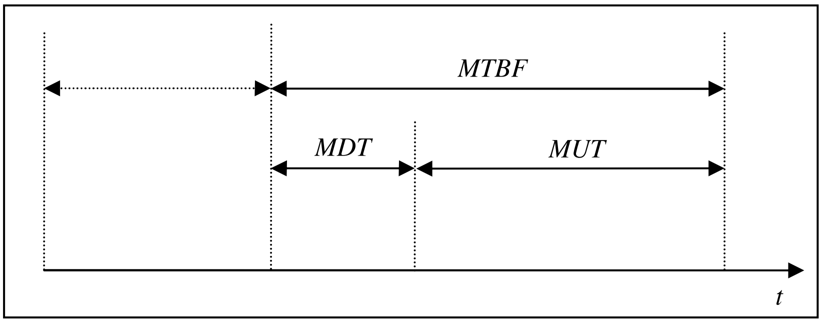


Fig. 8.2 Flow of faults and repairs in reparable systems

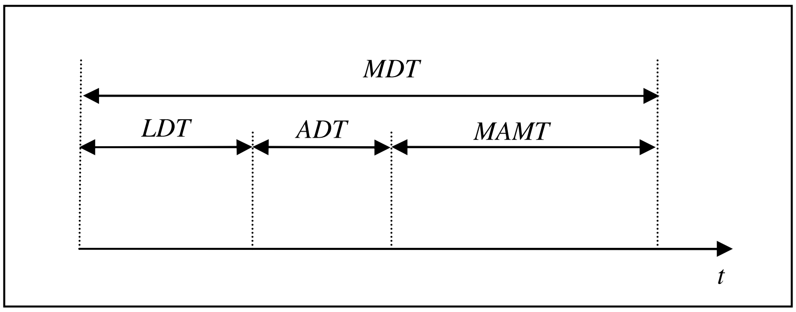


Fig. 8.3 Mean Down Time

These theoretical bases, together with the analysis of the parameters monitored, led to the definition of three guaranteed results and three corresponding parameters of monitoring for corrective (or breakdown) maintenance: intervention time, which is the sum of LDT and ADT and is defined as the period of time between receipt of the report of failure and the start of the intervention for repair; the time of restoration to service, which is understood as *Down Time* and is defined as the period of time between receipt of the report and closure of the intervention, the average time between two failures (MTBF), calculated through the monitoring time and the number of failures that have occurred.

Additionally, the *Mean Time To Repair* was added, which is defined as the portion of the *Mean Active Maintenance Time* during which the repairs are performed.

For on condition maintenance, the parameter to monitor was established as the MDT, defined above.

Parameters defined as Global were also considered among the guaranteed results. These parameters do not refer to specific maintenance strategies, but are important in evaluating the efficiency and effectiveness of the maintenance plan as a whole. These include the total annual time of disservice, which will be compared with the maximum annual time of disservice as a guaranteed result; the relationship between corrective and on condition maintenance.

The combination of guaranteed results and monitored results, realised through simple functions constructed case by case, defines the indicators that are merged in a single performance index, which in our case is called the **SLA** and is calculated for every system in the contract.

In order to avoid incoherence between the service distributed and the expectations of the user, that is to say, to avoid a service that is considered non-fundamental from being provided with a standard of excellent, it is necessary to relate to these levels indexes that measure the importance attributed to each service rendered with respect to total quality.

This function is performed by the **incidence indexes** in the model, which will be assigned as a percentage, considering the function that each system is required to perform, as well as the technical parameters specific to the various systems, which reduce or increase the weight of the performance.

By crossing **SLA** and **incidences,** we define the four **indexes** of performance, which is a measurement of the perceived quality.

The total quality index will take into account, in addition to the indexes, factors of an economic nature, for an evaluation of the quality rendered, based on the price/content ratio.

A summary is shown below of the indexes and indicators that specify the reference, the field of variability and the manner of measurement.

Table 8.1 Summary of indexes/indicators, reference, field of variability and method of measurement

INDEXES/INDICATORS	REFERENCE	FIELD	METHOD OF MEASUREMENT
SLA	System	0-1	Calculated for every system as an average of the value of parameters that measure deviation between the value of the guaranteed result and the measured value of the result
% of Incidence	System and performance factor	0-100 %	Assigned for every system and every performance factor on the basis of the type of system and several technical-registry characteristics
Partial indexes	Contract and performance factor	0-10	Calculated for every performance factor as a weighted average of levels, of each system relative to that performance factor, assuming the incidences as weights
Partial quality index	Contract	0-10	Calculated for the contract as a weighted average of partial indexes
Estimated cost	Contract		Estimated for the contract by the provider on the basis of the complexity, system and technical characteristics of the systems of the contract and on the basis of the consequent maintenance plan designed to guarantee the operation of the systems according to times of intervention, restoration and disservice guaranteed.
Cost sustained	Contract		Calculated for the contract by the provider on the basis of the intervention effectively performed
Cost delta	Contract		Calculated for the contract as the ratio between the difference between the cost sustained and the cost estimated, divided by the cost estimated
TOTAL QUALITY INDEX	Contract	0-100	Calculated for the contract as the partial quality index, reduced by a percentage equal to the cost delta.

8.6 Definition of Model Characteristics

An attempt was made to satisfy many different requirements in the construction of the model:

- Applicability: the model uses parameters that can be easily measured, especially parameters inferred from the technical specifications. These leads to a dual advantage: on one hand, it avoids wasting additional resources, thanks to the use of parameters that are already monitored; on the other, it permits the measurement of the quality of the service rendered on the basis of objective and quantifiable parameters shared with the customer, inasmuch as they are contained in the document of the technical specifications attached to the contract;
- Robustness; the model was constructed to guarantee the dependability of the result, even in the event of partial compilation of the data, which are considered difficult to procure in their entirety, starting from the initial phase;
- Technical-scientific content; the entire model was constructed on the basis of the results obtained from analysis of the current state of the art and using indexes and methodologies advised by technical norms, by meaningful studies conducted on the subject and taking into account consolidated knowledge in the field of maintenance. The scientific rigorousness justifies the dependability of the results;
- Compatibility; the disaggregation of the contract into systems was maintained to facilitate the collection of data according to an existing structure and to consequently make it easy to integrate the model with the existing information technology system;
- Enhancement; each system was broken down further into the total number of its components, to permit an in-depth vision of the dimension and complexity of the contract. Each element was determined to belong to the Core, Distribution and Final categories, to bring out its functional placement in the line;
- Internal benchmarking; the structure of the model makes it suitable for the different contracts, to permit internal comparison of results, from which to start an analysis on possible improvements;
- Facility in use; the model uses the excel program for calculation, guaranteeing simplicity in use due to a well-known software operating in a windows environment;
- Meaningfulness; through the return of a global quality index, obtained through rigorous methods, the model leaves a trace of the weight of the individual parameters, thereby facilitating understanding.

8.7 Definition of a Model

The model realised provides a global quality index for each contract, through a series of phases that are shown below in a block diagram, and which are described below in detail.

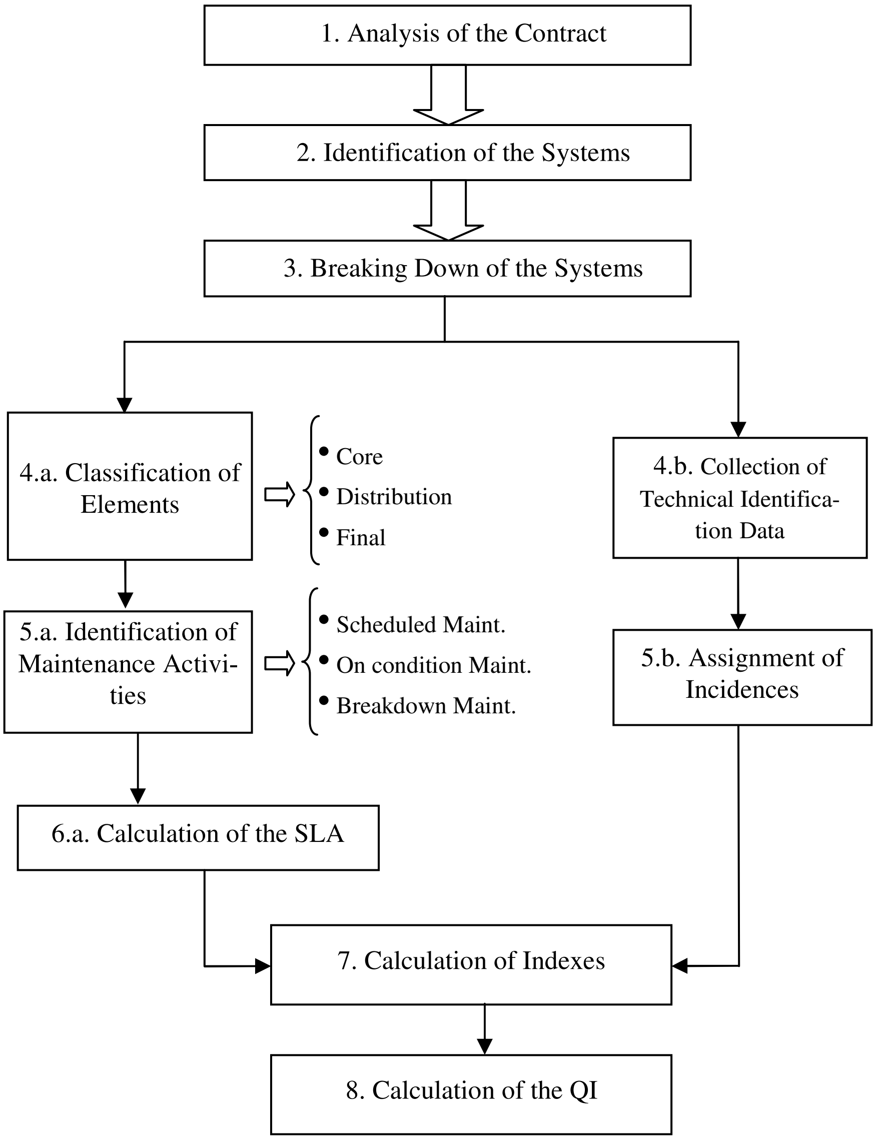


Fig. 8.4 4 Block Diagram

Phase 1. Analysis of the Contract

The model calls for a preliminary phase of contract analysis, in which the documents are collected for use in gathering general meaningful information on costs, consumption and resources.

Phase 2. Identification of the Systems

The contract is broken down into its component systems. The term system indicates a set of technological lines and services and of the facility management rendered.

A list of the types of systems in which the code TL indicates Technological Lines and the code FM indicates Facility Management (FM) services.

Table 8.2 List of types of systems by technological lines

TECHNOLOGICAL LINES	
LT 01	Production of heat
LT 02	Telephony and Data Transmission
LT 03	Lifting + fork lifts
LT 04	Production of cold
LT 05	Distribution of electricity
LT 06	Distribution of water
LT 07	Treatment of civil and industrial water
LT 08	Fire prevention
LT 09	Cogeneration
LT 10	Production of compressed air
LT 11	Emergency network
LT 12	Supervision
LT 13	Buildings
LT 14	Refectory and store

Table 8.3 List of types of systems by facility management

FACILITY MANAGMENT	
FM 01	Vigilance
FM 03	Gardening
FM 04	Internal post
FM 05	Road signs
FM 06	Waste Disposal
FM 07	Conference rooms and equipment
FM 08	Infirmary
FM 09	Travel agency

FM 10	Automobile management
FM 11	Warehouses
FM 12	Cleaning
FM 13	PDL
FM 14	Re-layout
FM 15	Metrological laboratory

Phase 3. Disaggregation of the systems

For the Technological lines, we proceeded with disaggregation on several levels of detail, identifying, on the first level, the component plants and works and proceeding to a second, more detailed level, separating each plant or works into their component elements.

For the Facility Management services, given the specific nature, the disaggregation will be performed on a case-by-case basis.

Phase 4.a. Classification of the elements

Once the component elements have been defined, they are identified as belonging to Core, Distribution and Final, as follows:

Core:

Distribution:

Final:

This classification will be shown in the form of an identification code assigned to each element:

- C: for Core elements;
- D: for Distribution elements;
- F. for Final elements.

Additional identification codes will be assigned:

- S: for safety elements;
- ACC: for accessory elements;
- CMD: for command elements.

Phase 4.b. Collection of technical identification data

Meaningful technical identification data is shown for each parameter, including, in particular:

- Age, or year of installation;
- Status, or judgement expressed following initial inspection and reported in the plant inspection report;
- Technical parameters deemed meaningful and specific for each element.

Phase 5.a. Assignment of Incidences (IN_i)

The technical identification data collected is processed and summarised in a table, reporting synthetic data for each system:

- Age, understood as the percentage of elements with year of installation earlier than an established date;
- Status, understood as the percentage of elements with negative judgement;
- Dimensions/complexity, understood as the set of summarising parameters capable of defining the entity of the system in terms of its level of complexity. These synthetic parameters will be specific for each system;
- User, which reports synthetic data useful in defining the characteristics of the recipients of the service;
- Redundancy, which reports parameters useful in defining the presence of more than one means to perform the required function;
- Safety; which reports synthetic parameters useful in defining the ability of the system to guarantee the physical integrity of the users.

The set of these synthetic data will support assignment of the incidences that each system has on the four factors of performance, Well-being, Image, Availability and Safety.

These incidences are assigned for each factor of performance as a percentage of the entire contract.

This phase will take place in collaboration with the Customer.

Phase 5.b. Identification of the maintenance activities

The collection of technical identification data for the entire contract, together with the inspection to determine the initial status of the systems and the price that the customer is willing to pay, permit definition of a maintenance plan, which will be compiled according to the cases of scheduled, on condition and corrective (or Breakdown) maintenance strategies. Upon identification of the human, technical and material resources necessary for implementation of the plan defined, it is possible to calculate the cost of the maintenance activity, plus the mark-up, which defines the price.

Every maintenance strategy is associated with guaranteed results, as described, whose achievement will be measured, reporting the corresponding monitoring parameter for each of them.

A table is shown below summarising the guaranteed results and the corresponding results monitored:

Table 8.4 Table summarising the guaranteed and monitored results

MAINTENANCE STRATEGIES	Guaranteed Results	Id.	Monitored Results	Id.
Scheduled maintenance	Number of scheduled maintenance interventions programmed	RG 01	Number of scheduled maintenance interventions performed	RM 01
Corrective (Breakdown) Maintenance	Maximum intervention time for corrective (breakdown) maintenance	RG 02	Number of breakdown interventions performed with greater than maximum intervention time	RM 02a
			Number of repair interventions performed	RM 02b
	Maximum intervention time to restore system to operation, or corrective (breakdown) maintenance	RG 03	Number of breakdown interventions performed with greater than maximum restoration time	RM 03
			Number of repair interventions performed	RM 02b
	Mean Time Between Failure guaranteed	RG 04	Mean Time Between Failure measured	RM 04
	Mean Time To Repair guaranteed	RG 05	Mean Time To Repair measured	RM 05
On condition maintenance	Mean Up Time guaranteed	RG 06	Mean Up Time measured	RM 06a
			Number of on condition maintenance interventions performed	RM 06b
Global	Maximum disservice time guaranteed	RG 07	Maximum disservice time measured	RM 07
		RG 08		RM 08

These parameters will be defined and reported for all of the core, distribution and final elements relative to each plant or works of each system.

Phase 6.a. Calculation of the SLA

The SLA is calculated for each system according to the following method:

The parameters are calculated, which are called evaluations, through simple functions that combine each guaranteed result with the corresponding monitored result.

Table 8.5 Evaluation Parameters

MAINTENANCE STRATEGIES	Evaluations	Id.
Scheduled maintenance	$1-\frac{RM01}{RG01}$	V 01
Corrective (breakdown) maintenance	$1-\left(\frac{RM02-RM02b}{RM02b}\right)$	V 02
	$1-\left(\frac{RM03-RM02b}{RM02b}\right)$	V 03
	$\left(\frac{RG04-RM04}{RG04}\right)$	V 04
	$\left(\frac{RM05-RG05}{RG05}\right)$	V 05
On condition maintenance	$1-\left(\frac{RM06b-RM06a}{RM06b}\right)$	V 06
Global	$\left(\frac{RM07-RG07}{RG07}\right)$	V 07
	$\left(\frac{RM07b}{RM07B-RM02b}\right)$	V 08

The parameters of evaluation merge in the calculation algorithm of SLA relative to the individual system, through the following formula:

$$SLA = 1-\frac{A\{Scheduled\ M.\}+B\{Failure\ M.\}+C\{Conditioning\ M.\}+D\{Global\}}{A+B+C+D} \tag{8.1}$$

with:

$$\{Scheduled\ M.\} = \frac{A1\{V01\}}{A1} \tag{8.2}$$

$$\{V01\}=\left[\frac{E\{V01_{Core}\}+F\{V01_{Distr.}\}+G\{V01_{Final}\}}{E+F+G}\right] \tag{8.3}$$

$$\{Failure\ M.\}=\frac{B1\{V02\}+B2\{V02\}+B3\{V03\}+B4\{V04\}}{B1+B2+B3+B4} \tag{8.4}$$

$$\{V02\}=\left[\frac{E\{V02_{Core}\}+F\{V02_{Distr.}\}+G\{V02_{Final}\}}{E+F+G}\right] \tag{8.5}$$

$$\{V03\}=\left[\frac{E\{V03_{Core}\}+F\{V03_{Distr.}\}+G\{V03_{Final}\}}{E+F+G}\right] \tag{8.6}$$

$$\{V04\}=\left[\frac{E\{V04_{Core}\}+F\{V04_{Distr.}\}+G\{V04_{Final}\}}{E+F+G}\right] \tag{8.7}$$

$$\{V05\}=\left[\frac{E\{V05_{Core}\}+F\{V05_{Distr.}\}+G\{V05_{Final}\}}{E+F+G}\right] \tag{8.8}$$

$$\{Conditioning\ M.\}=\frac{C1\{V06\}}{C1} \tag{8.9}$$

$$\{V06\}=\left[\frac{E\{V06_{Core}\}+F\{V06_{Distr.}\}+G\{V06_{Final}\}}{E+F+G}\right] \tag{8.10}$$

$$\{Global\}=\frac{D1\{V07\}+D2\{V08\}}{D1+D2} \tag{8.11}$$

$$\{V07\}=\left[\frac{E\{V07_{Core}\}+F\{V07_{Distr.}\}+G\{V07_{Final}\}}{E+F+G}\right] \tag{8.12}$$

$$\{V08\} = \left[\frac{E\{V08_{Core}\} + F\{V08_{Distr.}\} + G\{V08_{Final}\}}{E+F+G} \right] \tag{8.13}$$

Each evaluation parameter is weighted on three levels:

- Weight assigned to the maintenance strategy:

  - A: Weight assigned to scheduled maintenance;
  - B: Weight assigned to breakdown maintenance;
  - C: Weight assigned to on condition maintenance;
  - D: Weight assigned to global maintenance.

  with A+B+C+D=1

- Weight assigned to the type of parameter of the maintenance strategy:
  Scheduled maintenance:
  A_1=1 weight assigned to the evaluation parameter V01

  Corrective (Breakdown) Maintenance:
  B_1: weight assigned to evaluation parameter V02;
  B_2: weight assigned to evaluation parameter V03;
  B_3: weight assigned to evaluation parameter V04;
  B_4: weight assigned to evaluation parameter V05.
  with $B_1 + B_2 + B_3 + B_4 = 1$

  On condition maintenance:
  C_2: weight assigned to evaluation parameter V06

  Global maintenance:
  D_1: weight assigned to evaluation parameter V07;
  D_2: weight assigned to evaluation parameter V08.
  with $D_1 + D_2 = 1$

- Weight assigned to the type of element:
  E: weight assigned to Core elements;
  F: weight assigned to Distribution elements;
  G: weight assigned to Final elements;
  with E+F+G =1

In the event of failure to perform one or more of the maintenance strategies, inasmuch as it is not foreseen, a value of zero will be assigned to the corresponding weight.

In the event of the lack of data referring to the measured result, a default value of 50% of the optimal value will be assigned. In the event of the presence of several plants or works in the same system, calculation of the SLA will be performed according to the method illustrated for each plant or works and the SLA for the system will be calculated as a weighted average of each individual SLA.

Phase 7. Calculation of the Indexes ($\mathbf{ID_i}$)

Four indexes are calculated for the entire contract, which refer to the four performance factors, as the weighted average of the system SLAs, assuming the weights of the Incidences, according to the formulas:

Well Being Index:

$$ID_B = \frac{\sum_i SLA_i * IN_{B_i}}{\sum_i IN_{B_i}} * 100 \tag{8.14}$$

Image Index:

$$ID_I = \frac{\sum_i SLA_i * IN_{I_i}}{\sum_i IN_{I_i}} * 100 \tag{8.15}$$

Availability Index:

$$ID_D = \frac{\sum_i SLA_i * IN_{D_i}}{\sum_i IN_{D_i}} * 100 \tag{8.16}$$

Safety Index:

$$ID_s = \frac{\sum_i SLA_i * IN_{S_i}}{\sum_i IN_{S_i}} * 100 \tag{8.17}$$

Phase 8. Calculation of the QI

The QI for the contract is calculated as the arithmetical average of the indexes, taking into account the economic factors.

$$QI = \frac{ID_S + ID_D + ID_I + ID_B}{4} \tag{8.18}$$

Chapter 9

The System of Unified Diagnostics and Standard Maintenance of Bridges and Infrastructures

9.1 The State of the Art

Regular inspection and maintenance is the most rational and economic way to ensure a satisfactory useful life of infrastructures.

In the sector of structural concrete constructions, these themes have been the subject of systematisation by the European Beton Committee, stimulated by the widespread state of deterioration of structures realised in Europe after the second world war, especially where bridges and parking lots are concerned. Testimony of the condition of deterioration of these structures can be found in the acts of international congresses: in 1975, the "Colloquium Inter Association I.A.B.S.E. – F.I.P. – C.E.B. – R.I.L.E.M. – I.A.S.S. Behaviour in Service of Concrete Structures" held in Liegi; in 1980, one of the themes of the "1st International Congress of the Association for Bridge and Structural Engineering (I.A.B.S.E.)" held in Vienna was "Lessons from the Behaviour of Structures"; in 1988, one of the themes of the 13th I.A.B.S.E. Congress, held in Helsinki, examined "Inspection, Assessment and Maintenance"; in 1992, one of the themes of the 14th I.A.B.S.E. Congress, held in New Delhi, concerned "Bridge Management Systems". One of the contributions to this theme, "A Decision System for Bridge Management", by J. De Brito and F. A. Branco, of the Technical University of Lisbon, confirms the high percentage of deterioration observed in reinforced concrete and pre-compressed reinforced concrete bridges, realised in recent decades, proposing a decision-making system based on the data collected from three levels of inspection: current inspection, based almost exclusively on visual observation, detailed inspection, integrated by non-destructive on site tests and ascertainment of the structural conditions of the works. These analyses proved the elements to determine an index of evaluation, which is used to decide upon any corrective intervention, within the ambit of maintenance procedures and, if necessary, to make repairs or provide for reinforcement.

In 1995 a symposium of the I.A.B.S.E. was held in San Francisco, dedicated to the general theme of "Extending the lifespan of structures", with sessions dedicated to the general aspects of bridge repair, methods of inspection and monitoring, the durability of the concrete, the maintenance of the structure and on structural assessment of bridges.

The 15th Congress of the IABSE, held in 1996 in Copenhagen, dedicated a special session to the problems of structure management and maintenance and another session to the experimental control of structures in service.

In 1997 the IABSE dedicated the Lausanne Workshop to "Evaluations of existing steel and composite structure bridges".

From examination of the bibliography, it emerges that there is a growing interest in extending the methods of expert systems to the field of civil engineering.

The IABSE Coloquium, held in Bergamo in 1989, is dedicated precisely to the theme of "Expert Systems in Civil Engineering". One of the sessions dealt with expert systems in service, in maintenance and in the assessment of damages.

An updated and clear exposition of these themes is contained in two CEB bulletins, n. 239, of 1997, “Safety Evaluation and Monitoring” and n. 242 of 1998 "Strategies for Testing and Assessment of Concrete Structures, Guidance Report”.

In the following paragraph, the essential contents of these documents are set forth, with the dual purpose of providing a state of the art in the field of bridge maintenance systems and providing the conceptual bases and methodology of the case study.

It should be noted that the systematic references to structural concrete structures is due to the multiplicity of the physical and chemical reasons for deterioration of the construction materials, concrete, normal steel, highly elastic steel for the pre-compressed product. Moreover, from the methodological point of view, the phases of data collection, inspection and identification of possible defects and the assessment of their importance are also applicable to the state of the art realised for walls, in steel, in composite "steel-concrete" structures and structures with steel beams, incorporated in heavy duty slabs of reinforced concrete.

Finally, it is observed that in the bibliography cited the reference to roadway and motorway bridges are much more frequent than those relative to railway bridges, where intervention in individual works are generally illustrated, especially three railway bridges in Switzerland, built respectively in 1859, 1875 and 1894 (Acts of the IABSE Symposium in San Francisco, 1995).

A problem of a general nature, the "Evolution of large railway bridges", was illustrated by Engineer J. L. Picquand, Chief of the Department of works of art of the French National Railway Company, in 1980, during the 11th IABSE Congress.

9.1.1 Recent Trends in Procedures of Ascertainment and Assessment of Structures

It behoves us to recall the essential lines of the various phases in which the ascertainment of the remaining performance capabilities of a given structure are articulated. The reason for this is that several of these phases are common to bridge maintenance.

Ascertainment starts with the collection of existing documentation: executive design, certificates of static testing, reports on previous inspections with the reporting of possible symptoms of pathological phenomena underway. This phase corresponds to "anamnesis" (case history) in medicine.

This is followed by an on site inspection, which brings out the morphological and physical situation of the environment, which may determine phenomena of interaction with the structure and its foundations and the terrain, which are worthy of specific observations. This naturally varies on a case-by-case basis.

The visual examination of the structure, extended to all of its parts, allows comparison of the current situation with the situation described in the documentation relative to previous inspections. During the inspection, non-invasive tests are performed (surface delamination inspection with percussion, surface hardness with a Schmidt hammer, thickness of the iron covering with the pachometer, the amplitude of lesions with the portable type of graduated microscope used in the textiles industry). Determination of the thickness of the carbonated area of the concrete, through application of Phenolphthalein on an element of removed iron covering, provides and important element to assess the degree of protection from corrosion provided by the reinforcement.

On the basis of the visual inspection and the aforementioned tests, expert technicians are capable of expressing a preliminary assessment of the structure's condition, which may exclude the need for further investigation, or may determine the need for further testing of the concrete, the normal and pre-compressed reinforcement and ascertainment of the geometry of the structure, the forces applied, the static or dynamic response, through special tests.

A phase of ascertainment of the remaining performance capabilities of the work follows, based on the compendium of objective elements acquired.

From these brief references, it emerges that the management of maintenance requires the preliminary acquisition of a compendium of information on the structure, the environmental situation and the results of previous inspections, followed by periodical inspections, which include visual examination, non-destructive tests and the evaluation, on a time-by-time basis, of the importance of the phenomena observed. In the event the management of maintenance concerns a great number of works of art, it is necessary to rationalise the procedures, permitting the association of objective criteria of evaluation with the inspections, based on experiences acquire previously by technicians of proven experience and competence, to be used in a dependable manner by the available, appropriately trained technical personnel. This is a problem of transmission and utilisation of the specialist knowledge of a limited number of experts, in order to respond to the needs of a great number of actual situations, to guarantee, in any case, the quality of performance related to the service required.

From consultation of the documentation mentioned previously, it emerges that the typical defects of steel bridges consist of phenomena of corrosion of the metal, cracks in welding and loosening of nails and bolts, while in concrete bridges the, washout of mortar, fissures and, at times, the loss of verticality of walls and pilings are detected.

The panorama of defects in reinforced structural concrete and pre-compressed reinforced concrete works appears to be more varied.

Presumably, this is the reason that led to more thorough research on this construction system.

It should be noted that the procedure of assessment with points and consequent classification of the works (applied for structural concrete works) is generally valid for all materials employed in the construction of bridges.

In the specific field of assessment and evaluation procedures for structural concrete works, the CEB promoted specific studies, referred to previously, recently achieving results of undoubted interest for practical application.

The methodologies we owe to Konrad Bergmeister of the Institute of Structural Engineering, Boku (University of Applied Sciences) of Vienna (CEB Bulletin n. 239, 1997), Jas Snidaric and Iztok Perus of the ZAG, Slovenian National Institute of Construction and Civil Engineering, of Ljubljana, are briefly illustrated below.

In K. Bergmeister's work, entitled "Assessment procedures and safety evaluation of concrete bridges", there is a preliminary illustration of the procedures of evaluation applied in Germany, France and Japan, based on the classification of different categories of damage, detected in the preliminary phases of inspection. Within the ambit of this formulation, the procedure proposed in 1987 by M. Wicke, W. Straninger, G. Stehno and K. Bergmeister is described, which is articulated in four phases:

1. Listing of all types of defects that can be detected during the phase of inspection, which amount to 32 different types;
2. Definition of 5 characteristics, through which every defect can be described, namely:
   - Characteristic G, which describes the importance of the defect on the bearing capacity of the structure and which varies from 1 to 5;
   - Characteristic K_1, which is a measurement of the spatial extension of the damage and can be stated in values from 0 to 1;
   - Characteristic K_2, which describes the intensity of the defect, which may vary from 0 to 1;
   - Characteristic K_3, which depends on the contribution that the damaged structural component provides to the bearing capacity of the entire structure, which varies from 0 to 1;
   - Characteristic K_4, which describes the expert's estimated urgency, which varies from 0 to 10.
3. Determination of the function of evaluation, with the following sum of the products:

$$\sum_{i=1}^{32} G_i \bullet K_{1i} \bullet K_{2i} \bullet K_{3i} \bullet K_{4i} \tag{9.1}$$

4. Assignment of the category of damage (6 categories) on the basis of the value of the function assessed.

Class	Damage	Evaluation
1	none	0-3
2	small	2-8
3	medium	6-13
4	large.	10-25
5	very large	20-70, K4 = 10
6	out of service	> 50, K4 = 10

Prescriptions on the provisions to take are associated with the categories of damage: long term, short term, immediate maintenance intervention and suspension of service.

As the note continues, a non-linear function of evaluation is also proposed and the method of safety distance β is used, whose value, as it is known, is associated with the value of the probability of breakdown. For example, if $\beta = 2{,}327$ the probability of breakdown P_f is equal to $10^{-2;}$ for $\beta = 4{,}265$ $P_f = 10^{-5,}$ for $\beta = 5{,}199$ $P_f = 10^{-7}$.

Some considerations are then made on the assessment of the probability associated with the last limit status and the operating limit status of excessive deformation.

In the work of J. Znikdarik and I. Perus, entitled "Condition rating methods for concrete structures" reference is made to the method proposed by M. Wicke and others in 1987, reported by K. Bergmeister, to which several modifications are made.

The index of evaluation, indicated as R_c, is not expressed with a sum of the values of damage, but by the relationship between two sums. The effective sum ΣV_D of the values of damage, which is obtained taking into account a closed list of types of potential damage, of types of damage detected during the phase of inspection and the reference sum $\Sigma V_{D,ref}$ of the values of damage, calculating from the same list every type of damage that can occur on the same structure and multiplying by I, the coefficient of intensity and extension assumed, equal to one:

$$R_c = \sum V_D \bullet 100 \tag{9.2}$$

$$\sum D_{,ref} \tag{9.3}$$

where

$$\sum V_D = \sum B_i \bullet K_{1i} \bullet K_{2i} \bullet K_{3i} \bullet K_{4i} \tag{9.4}$$

B_i = the value associated with the type of damage "i", variable between 1 and 4;

K_{1i}= the factor relative to the individual structural component (beam, pavment,diaphragm), reported in the special Table;

K_{2i} = the factor that indicates the level of damage, which varies from 0.5 to 2;

K_{3i} = factor relative to the extent of the damage, variable from 0.5 to 2;

K_{4i} = factor of urgency of intervention, variable from 1 to 5.

The index of damage is calculated not only for the overall structure, but also for each of its main components, such as the framework, the overlying structure and the pavement of the bridge.

There are 6 classes of deterioration, as proposed by M. Wicke and others:

Class	Index of evaluation
I	0 – 5
II	3 – 10
III	7 – 15
IV	12 – 25
V	22 – 35
VI	$\geq$ 30

A judgement on the condition of the work is expressed for each class, on the intervention necessary and examples of deterioration are provided.

The note concludes with a numerical example relative to the structure of the bridge, for which the following elements are calculated:

R_{cm} = index of evaluation of the structural element "m"

R_c = index of evaluation of component "C" of the bridge (framework, superstructure)

R_{cB} = index of evaluation including the components of the bridge observed

The same CEB Bulletin n. 243 indicates a further communication of the authors, entitled "Deterioration categorization and priority of a neural network-like approach", which shows how the method of neural networks can be used to determine the category of damage.

Clarification on this method is provided in the following paragraph.

9.1.2 Notes on Non-Linear Methods for Diagnostics and Classification

In many ambits, it is necessary to classify objects and/or phenomena on the basis of their evident properties at a given time. As long as the properties displayed by the objects are few in number and can be valorised in an objective manner, we are dealing with a problem of classification that can almost definitely be solved with linear methods. But as soon as the object or phenomenon being observed is characterised by a large number of properties and/or by a non-linear relationship between those properties, or the valorisations of the properties displayed cannot be objective, but are subjective (i.e. visual observations), then the problem of classification is complex and non-linear approaches are required to solve it.

The case of classification of works of art is in an intermediate position on the scale of difficulty; it is not purely linear, but neither is it such as to require a completely heuristic solution.

In observing this problem, we must take into account that:

- The number of properties involved in classification of the work is not extremely high – other properties, albeit they characterise the work, do not fall within the mechanism of classification;
- The problem of classification of the work of art is not dynamic in nature and the relationships between these properties are linear and have been established over a period of time;
- Valorisation of a certain number of these properties is often possible only from a visual inspection, therefore it is a valorisation that has a low level of objectivity and may vary according to the judgement of the observer;
- The valorisation of the other properties, on the other hand, is possible from an instrumental investigation and is therefore more objective.

Some non-linear methods are capable of providing answers to this type of classification problem and, more in general, to all of the problems of a diagnostic nature (a diagnosis assigns the object of investigation to a set and therefore classifies it).

We shall briefly investigate the nature of the three most widely used systems in this ambit below, and will conclude with an evaluation of their applicability to our field of intervention.

These three systems are, in their order of importance:

- Fuzzy logic;
- Neural Networks
- Expert Systems (Predicate Logic – Bayesian Networks – Rules of Production – etc.).

We voluntarily neglect to investigate the applicability of the genetic algorithms within this ambit, inasmuch as the problem being examined does not lend itself to being analysed with this instrument.

In reality, genetic algorithms are more suitable to solve problems of optimisation, classification and additionally, since they are not static algorithms, but evolutionary ones, they require sophisticated means of representation of phenomena. In conclusion, as we shall see below for the other paradigms as well, the problem of the cost of this solution is posed, of the especially trained human resources required and the rather long time required for implementation.

The problem at hand is substantially a problem of diagnostics and classification that is not excessively complex.

Definitively it is a question of *understanding* what the status of the work is at a specific time.

This is obtained through an analysis of the symptoms observed on the work (activity of diagnosis) and subsequent association of the work of art itself with a value (activity of classification) that expresses the general state of usability.

All three of the techniques described above could theoretically be used, but with efforts of formalisation that are not indifferent.

- Fuzzy logic should be classified before all of the others and their linguistic structures and therefore should guarantee their use as a manner of description and visual observation. In other words, we should agree on a lexicon that should obligatorily be used in all cases during inspections. This is elementary for systems characterised by a low number of variables in play, whose linguistic values of "nuances" are not large, but becomes expensive in other cases;
- Neural networks – this would be their area of election and therefore would be widely recommendable, if it were not for the fact that the training of a neural network is a complex and long activity, which must be repeated in all cases where the dominion of intervention changes. In order to train a neural network, it is necessary to have a sufficient number of input configurations (usually a few hundred), for which the output value of the network is known *a priori.* The network is trained by repeatedly applying all of the configurations to the inputs and progressively correcting the network until the output is the one expected. From that moment forward the network is capable of classifying the input configurations correctly, even if they differ significantly from those used for the training. The effort required is considerable, both in terms of construction of the network and in terms of training.
- Expert systems – are normally quite flexible, but perhaps they are a bit excessive in this case, although theoretically they could be easily adapted. The greatest disadvantage is having to depend on a complete formalisation of the expert human knowledge capable of performing the work of diagnosis and classifica-

> tion required by the system. This formalisation is not possible for a normal information technology user, because it requires the knowledge of formalisms and methods of representation of the knowledge that normally refer to rather rare professional figures, known as knowledge engineers. Their task is to translate the heuristic knowledge possessed by an individual or organisation into a formal representation capable of being understood by a special computer program. Additionally, it is now an acquired fact that expert systems are costly and lengthy to implement and maintain.

In relation to the nature of the problem of classification of the works of art and the use of the information technology application, the most advantageous solution in terms of functional efficiency, economy and implementation is considered to be that of using a subsystem of the basic algorithm of a neural network, which contains the concept of the sum of the inputs, but excludes the mechanism of learning. Moreover, this is the path that was taken for the model of classification developed by the University of Ljubljana, which has already been experimented. It is not a heuristic technique, but it can guarantee a sufficient attenuation of the errors of evaluation (subjectivity of observation).

If desired, corrective elements equivalent to the synaptic values (weights) applied to the inputs of a neural network could be added to this algorithm and, in any case, fuzzy corrections could be applied to the inputs or to their weights in future, once the experience with the algorithm has been established.

Adoption of the algorithm instead of one of the techniques seen above would make it unnecessary to undertake a continuous effort to maintain the application.

In fact, if the neural networks were used, we would have to imagine their progressive training in a close relationship with the variations in the park of works in service; similarly, if expert systems were used, it would be necessary to progressively update the base of knowledge of the system.

In conclusion, although the algorithm proposed is simpler that those described above, it has the great advantage of being stable over a period of time and does not require progressive intervention to maintain it. It is therefore a viable objective for an information technology system.

Once in service, it can be corrected and improved if necessary, but always through rather modest intervention that can be performed in a short period of time.

On the basis of a comparative analysis of the scientific and information technology procedures above, global evaluation of the state of damage of a work through the relationship between the effective sum of the values attributed to the various phenomena of damage and the sum of reference of the values of damage according to the work of J. Snidaric and I. Perus appeared to be particularly expressive.

Therefore, also in light of the previous considerations on the "information technology feasibility", it was deemed opportune to use the criteria upon which these studies are based in the algorithm.

9.2 Definition of Macro-Families and Families

A work of art is seen as a complex system, which, during its existence, undergoes physiological decay and a series of possible internal, external or combined actions.

Problems related to the period of realisation (norms in force, quality of materials, etc.) can be added to these natural actions.

The aforementioned actions could reduce the mechanical resistance of the work, limiting its ability to sustain external stress.

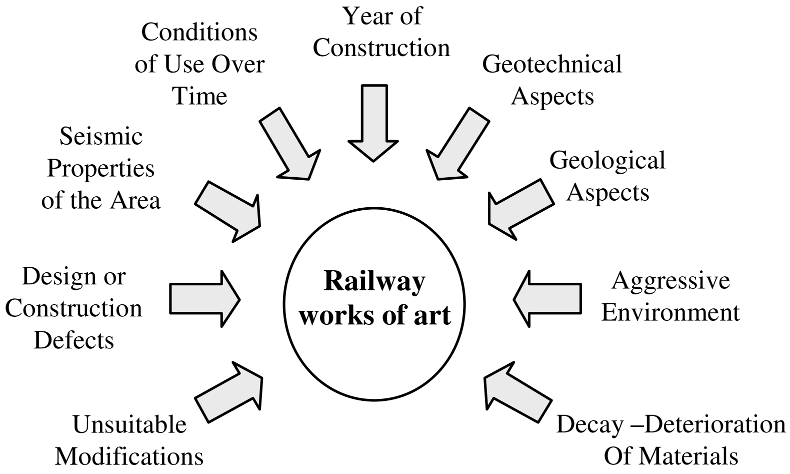


Fig. 9.1 Actions that could reduce the mechanical resistance of the work

Schematically, the limit of equality between resistance and stress can be represented through a resistance-stress Cartesian coordinate system, as the line of bisection.

In the generic situation represented by point "P", we are under this limit, the abscissa "resistance" is greater than the ordinate "stress".

Situations of possible structural crisis could be induced by an increase in the loads (+ΔS) or by a loss of resistance (-ΔR).

But the causes of a possible loss in the bearing capacity of the work of art must be analysed and interpreted as a system related to several parameters on a different scale and whose combination, *a priori,* cannot be expressed schematically in a simple manner.

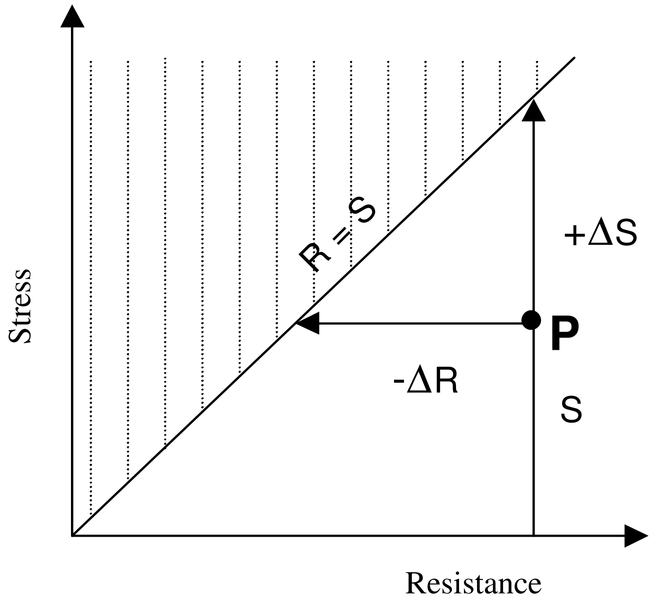


Fig. 9.2 Resistance-stress diagram

This complexity substantially shows the "individual" nature of the work.

This gives rise to the need to have a "profile" for each individual work of art.

With a view to the entire project, the purpose of this choice is to simplify the activity of control and maintenance by assigned personnel.

The parameters of identification of macro families and families make up the common part of the identification data card, which must then be completed with the characteristics of each work of art.

Once entry of the "identification data" is completed, the inspection cards and the relative catalogues of defects can be generated for each "bridge object".

9.3 Definition of the Identification Card

9.3.1 Structure of the Identification Card

The identification card consists of a structured set of data to describe the work of art, which include the constructions commonly indicated with the names *bridge, viaduct, overpass, small bridge, underpass, manhole, tunnel, siphon spillway, etc.*

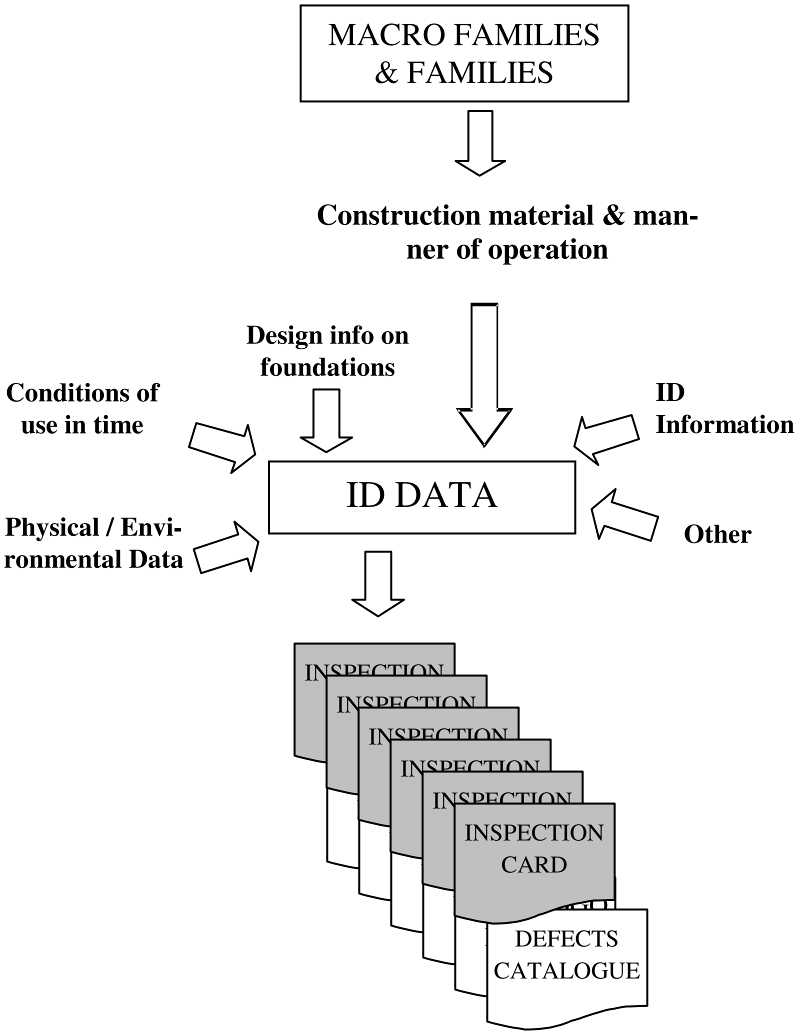


Fig. 9.3 Inspection Cards and Defects Catalogue

The identification card is structured to describe the overall work, even for works made up of several spans. This choice is justified by the fact that the work of art requires the availability of exhaustive and homogeneous information, such as to describe the entire *environmental-geotechnical-structural* complex, for maintenance purposes (an identification description for the components, such as the spans, for example, would not permit cataloguing of the information describing the work as a whole). Additionally, cataloguing of identification cards for each work permits better information technology management of the data, since the work is the highest-level element in the hierarchy, with respect to its sub-components (spans, pilings, abutments and foundations).

Additionally, it must be stressed that the identification card contains information that is primarily useful for the definition of the inspection cards, necessary for monitoring the state of health of the work. Consequently, only the descriptive data for the entire work is considered for this purpose (for example, data that describes the environment where the work is located, because it may play an important role on the state of health of the work and its components). Nevertheless, the identification card is structured to contain all of the data necessary to describe all of the construction elements of the work as well.

The data is organised in homogeneous groups of information, indicated with a numerical group code.

Eight groups of information considered below. Each group of information is associated with sub-groups.

1. **Work profile**
    - ***1.1 Identification***
    - ***1.2 Structure***
    - ***1.3 Territorial location***
2. **Railway data**
    - ***2.1 Railway location***
    - ***2.2 Railway***
    - ***2.3 Interferences***
3. **Historical and project (design) data**
    - ***3.1 Initial time***
    - ***3.2 Project data***
    - ***3.3 History***
4. **Geometrical and structural data**
    - ***4.1 Geometry of the work***
    - ***4.2 Description of horizontal elements***
        - ***4.2.1 Spans with a beam structure – 1 2 3***
        - ***4.2.2 Spans with an arch structure – 4 5 6***
        - ***4.2.3 Cable stayed or suspended spans – 7 8 9***
    - ***4.3 Description of vertical elements***
    - ***4.4 Mechanisms of connection***

5 **Data on foundations**
- ***5.1 Type***
- ***5.2 Terrain***

6 **Characteristics of the materials**
- ***6.1 Horizontal elements materials***
    - ***6.1.1 Macro family A - Steel***
    - ***6.1.2 Macro family I – Incorporated steel beams***
    - ***6.1.3 Macro family S – Steel-concrete composite System***
    - ***6.1.4 Macro family C – concrete, reinforced concrete***

        6.1.5 Macro family P – pre-compressed concrete
        6.1.6 Macro family M - brickwork
    6.2 Vertical elements materials
    6.3 Connection mechanisms materials

7 **Data on the environment where the materials are used**
    7.1 Atmospheric exposure
    7.2 Exposure to water

8 Data for maintenance and for inspection cards
    8.1 Data for access to the work
    8.2 Construction details
    8.3 Data summarising inspections performed

The information in group **1. Profile of work** is the information deemed necessary for a description that characterises the work. The information contained in this group must be considered of a general nature, useful in cataloguing the work according to various criteria. All of the fields of information may be considered as a perspective from which to look at the complete set of information. In particular, all of the works can be classified and numbered, if necessary, with respect to one of the pieces of information indicated in the work "profile".

The information in group **2. Railway data** is necessary to place the work with respect to the railway line and contains all information pertinent for the purpose of descriptive maintenance of the type of railway line involving the work.

The information in group **3. Historical and project (design) data** includes information necessary to describe the history of the work, from design to the current state of services.

The information in group **4. Geometric and structural data** includes all information necessary to describe the work from the geometric and structural points of view. Some data is specific and is activated as a function of the individual spans belonging to the families already defined for the works.

The information in group **5. Foundation data** includes all information necessary to describe the elements that determine the interaction of the work with the terrain. Additionally, it provides indications on the geological – geotechnical – hydraulic complexity of the site.

The information in group **6. Characteristics of materials** includes all information necessary to describe the materials the work is made from. The characteristics of the materials of the construction elements are described through groups of analogous information to those that define the macro families to which the group belongs.

The information in group **7. Data on the environment of exposure of the materials** includes all information necessary to describe the environment where the bridge is located, for the purpose of determining its interaction with the materials the bridge is made of.

The information in group **8. Maintenance and Inspection Data** includes all information useful for the knowledge of the systems of access to the constructive elements of the work. Additionally, this contains information summarising the state of health of the work obtained through inspections.

9.4 Performance of Inspections

In recent years, the interest in methods of control and verification of the state of repair of a structure has increased considerably. This is due to the widely accepted circumstance that it is convenient to perform maintenance for conservation of an asset rather than allow it to deteriorate and become unserviceable. The question is quite a bit more serious when the deterioration can compromise the necessary level of safety to permit its continued use.

Inspection, monitoring and maintenance are fundamental ingredients to ensure appropriate conditions during the useful life of a work.

In general, the structural and functional evaluation of an individual work is performed:

- To establish whether the intensity and extent of the deterioration places safety and serviceability at risk;
- To acquire the data necessary for the definition of a maintenance intervention (repairs, restoration) or re-construction;
- To determine the ability of the work to sustain additional loads.

When we go from a single structure to a population of structures, such as the bridges in a national railway network, ascertainment of the condition of the structures becomes a periodical operation performed according to established rules and timing. The management of safety and functional efficiency requires a database containing updated elements on the condition and use of each bridge, and elements suitable to establish the priority of maintenance intervention.

In the solution proposed by the project, the classification is represented by a numerical indicator, calculated on the basis of the indexed evaluation of the damages and defects identified during a routine inspection.

To classify the priority of intervention, however, the routine inspection is insufficient if the value of the condition indicator is "at risk".

Specific in-depth investigation then becomes necessary in order to evaluate the consequences produced by deterioration in terms of safety, functional efficiency and durability.

Which and how many tests to perform in the specific situation is a decision of the team of technicians assigned to manage the population of bridges, which we shall call the *"Technical Management Committee"*.

For example, in the case of a bridge whose deterioration is essentially due to the advanced state of corrosion of the framework, it is necessary to perform tests of an electro chemical nature in order to establish the extent and speed of corrosion, tests on the cement and framework to determine the properties involved in mechanical aspects and durability and, when the numerical index of the condition indicates a particularly serious situation, it is necessary to resort to tests on the structural response.

Acquisition of design and construction documents and collection of all of the information concerning the history and condition of use of the bridge is a preliminary measure prior to planning the operational process of ascertainment.

Of course, the more complete the information gathered is, the easier the operational process will be to determine the effective structural and functional condition of the work.

The project is centred on **periodical inspections,** which are the first phase of ascertainment, common to all bridges.

In cases where the value of the algorithm indicates a situation at risk, it will be necessary to proceed with all of the safety and functional verifications that the Technical Management Committee deems necessary upon comparing the updated and design data.

The main purposes of the inspections are:

- To identify the cause or causes of the defects;
- To establish the degree and extent of the defects;
- To establish the evolution of the defects and whether they are capable of being extended to the part of the structure that is currently unaltered;
- To ascertain whether the defects affect the safety of the structure;
- To identify all of the areas that require protection or repair.

The periodical inspections include:

- Visual inspection, to select the information on the damage and defects visible;
- Non-destructive tests, which are necessary to estimate the intensity and extension of the prevalent phenomena of deterioration;
- Useful destructive tests to examine the state of advancement of the pitting of the framework;
- To identify the main mechanisms of deterioration underway.

For correct identification of the area involved by the generic defect detected in the work subject to examination, it is necessary to establish beforehand a precise method of division into fields of the individual elements belonging to each class identified.

Correct identification of the area affected by the defect, even if it is not strictly necessary for the purpose of operation of the algorithm of evaluation of the level of safety of the work, is however deemed important for the purposes of maintenance and to immediately identify, in the course of successive inspections, the area involved by the defect and to be able to consequently monitory it over time, to evaluate the evolution of the phenomenon.

Monitoring the damage is more effective if photographic evidence on the defects detected is gathered during the inspection.

In this case, the division into fields of the individual element allows immediate correlation between the photographic image and the point of photographic detection.

Before dividing the individual element into fields, however, it is necessary to establish a method of cataloguing the individual elements within the ambit of each class, and this is performed by assigning a progressive number to the elements, which primarily takes into account the direction of the railway line, defined as the area from the lowest progressive Km to the greatest progressive Km and, in the second place, of how the elements are arranged with a view from above or a cross section.

Three distinct blocks of homogeneous data are identified in the generic card.

In the first block, all of the data of a general nature is reported, which permits identification of the individual element within the ambit of the work subject to investigation.

In the second block, a grid is envisioned, more or less large enough to cover the type of element, where the useful data is shown for the algorithm of evaluation, which is assigned directly during the inspection.

The last block consists of the list of possible defects that may involve the element subject to compilation of the card.

The identification data of the individual element, contained in the first block of information, consists of:

- Data relative to the date of the inspection;
- Name or identification code of the work the element or elements belong to;
- Letter distinguishing the group the constructive element belongs to;
- Reference number of the individual element that is part of one of the generic types referred to the total number of elements present for the type of work being examined, according to the format $n_i \backslash N_{tot}$

The specific data relative to the defects detected is shown in special boxes according to a table layout, which calls for a number of lines and functional columns of the type of element being analysed, such as to permit the precise identification of the location of the defect.

The data relative to possible defects consists of a list that may involve the individual element:

- Specific for the type of material it is made of;
- Related to the structural performance of the generic element;
- Of a general nature, relative to the loss of the original configuration.

For each work, knowing the type of structure and the type of material used to produce its constructive elements, a definite inspection card number is established automatically relative to the individual elements belonging to each class.

From this information, every work will have a file of cards that make up its maintenance handbook, where the presence and consistency of anomalies detected are recorded on a time-by-time basis and the condition of the work is recorded.

The functions of the generic operator are stated synthetically below:

- To report the code corresponding to the defect detected for each individual element identified within the ambit of the entire structural complex (the work);
- To assign a degree of importance of one of the four possible values of the K_2 coefficient, as a function of the extent of the damage (according to objectively measurable and predefined bases);
- To assign a level of intensity to each defect, as a function of the state of evolution of the phenomenon as it is witnessed upon inspection, also chosen from a set of four possible values of the K_3 coefficient;
- To assign the level of urgency for possible intervention to each defect, as a function of the situation witnessed (K_4 coefficient value).

These values must be reported in the box corresponding to the position where the defect was witnessed in the subject element, to pinpoint the exact location of the defect, to ensure immediate identification of the area involved by the defect during future inspections.

9.5 Defects Catalogue

In order to facilitate compilation of the detection cards and more immediate identification of the defects on a specific structural element, the defects and anomalies have been described through nine specific pieces of data that represent the type of structure or framework being examined and the construction material damaged or in the vicinity of the defect. This classification of information, which is far from being complete, has the purpose of being used as an effective aid for the operator upon compilation of the card for detection of defects and damages. In fact, it is obvious that adequate identification of the structural defect and an equally suitable evaluation of its entity and importance depend upon the equilibrium of two distinct elements – which are characteristic of the catalogue of defects – but which are intrinsically different:

1. Great detail and exhaustiveness of the defects foreseen in order to contemplate every possible "deviation" of the structure from its original state, which guarantees – by definition – its full operational and functional efficiency;
2. Simplicity in reading and identifying the defect, with a consequent important reduction in the rate of human error affecting the data manually reported.

Every defect in the catalogue is provided with the following information:

- Code of identification of the defect to report on the detection card;
- Name of the defect;
- Code of association with the identification card;
- Synthetic description;
- Phase of inspection in which the defect can be detected (1 = visual; 2 = instrumental);
- Instrumentation useful in detecting the defect (in the event the previous field is 2);
- Criterion of evaluation of the coefficient K2 i;
- Bi: base value associated with type i damage, which expresses the potential effects of the defect on the safety and/or durability of the structural element observed (values from 1 to 4 in growing order of dangerousness and consequent importance);
- K2 i: factor of intensity of the damage (4 classes are assumed I, II, III and IV, in which the factor of intensity takes on a value from 0.5 to 2 in growing order of intensity. See table 1 for the general criteria, while the specific values for evaluation of the individual defects are shown below);

Table 9.1 K2i factors for evaluation of the effects of the intensity of damage to a single structural element

CLASS	Level of intensity	Criterion	K_{2i}
I	Initial Low	Damage of small dimensions, generally confined to a single area of a structural element	0.5
II	Propagating. Average e	Damage of average dimensions, limited to a single area, or damage of a small entity located in a few points or in a small area of a structural element (e.g. < 25%)	1.0
III	High. Active.	Damage of large dimensions, limited to a single area, or damage of a small entity located in a great many points or in a large area of a structural element (e.g. from 25% to 75%)	1.5
IV	Very high. Critical	Damage of extremely large dimensions, limited to a single area, or damage of a small entity located in most of a structural element (e.g. > 50%)	2.0

A distinction is made in this document between the defects taken into consideration for the works being examined. In particular, we speak of a **"type α defect"** for defects that are considered for the purposes of the algorithm of evaluation of the degree of safety of the bridge and of “**type β anomalies"** for defects that are not evaluated in the algorithm, but which are useful in describing the evolution of several specific phenomenon in greater detail.

9.6 Definition of an Algorithm for Evaluation of Railway Bridge Deterioration

The algorithm must in any case offer a homogeneous and uniform judgement in terms of importance and priority, even if it is used in the evaluation of structures belonging to different families. It should permit identification of at least four groups of works:

- Works in good condition, which do not require intervention for repair;
- Works on which it is necessary to perform in-depth instrumental investigation or on which it is necessary to install monitoring systems or increase the frequency of inspections;
- Works on which it is necessary to perform maintenance and repair intervention that cannot be delayed and;
- Works that are not in serviceable condition.

The idea of numerically assigning a grade S relative to the "state of health" of a certain work is an effective measurement to quantify the general deterioration of a structure inspected, especially if homogeneous works are dealt with, at least with respect to the type, as in the case of the railway bridges subject to this project. The method was generally developed for bridge management purposes. The general purpose is to identify damaged structures, which will be identified with the highest level of the parameter of total damage S (mark on the "state of health"), to programme inspections and more detailed examinations, and to establish preliminary priorities for future maintenance intervention.

An objective of the method of assignment of the S parameter should be based not on a generic assignment of the level of damage to attribute to the structural elements inspected and/or consequently to the entire structure, but arise from a veritable numerical evaluation of the type, intensity and extent of the damage witnessed during an inspection. Consequently, a reasonable evaluation of the damage should take into consideration:

- The type of damage and its effects on the safety and/or durability of the structural components;
- The effects of the damaged structural components on the structural behaviour of the entire structural system;
- The maximum intensity assumed by the type of damage examined on the particular structural element;
- The extension and propagation expected from the type of damage on the structural components;
- The urgency of intervention;
- The expression of the function of evaluation of the condition of a damaged structure is defined by the sum of the values of damage VD:

$$R = \sum V_D = \sum B_i \times K_{1i} \times K_{2i} \times K_{3i} \times K_{4i} \tag{9.5}$$

where the various factor terms have the following meaning:

- VD – value of the damage;
- Bi – basic value associated with a specific type of damage, which expresses the potential effects of the type "i" damage on the safety and/or durability of the structural component observed, and assumes values between 1 and 4;
- K1i – factor or importance of the individual element on the structural plant; the factor takes into consideration the importance of the element where the type "i" damage appears, taking into account the effect of the element on the safety and global durability of the structure. Several values to use for the "standard" elements of the structural framework, typical of bridges, are shown in Table 9.1;
- K2i – factor of intensity and degree of type "i" damage. The values and general descriptive criteria are provided in the defects catalogue, while the numerical criteria associated with certain types are shown together with several basic values present in the defects catalogue;
- K3i – factor of extension of the damage. The coefficient represents the extension of propagation of the type "i" damage on the entire structural component observed on all of the realisations of the same type of element;
- K4i – factor of urgency. The coefficient emphasizes the urgency of intervention necessary in the event the type "i" damage places the safety of the structure or its users at risk.

In accordance with the statements made previously, the parameter of total damage, which permits evaluation of the state of health of a structure inspected, is the following:

$$S = R_c = \frac{R}{R_r} \times 100 = \frac{\sum V_D}{\sum V_{D,ref}} \times 100 \tag{9.6}$$

where:

$R = \sum V_D$ is the effective sum of values of the damage calculated for the structure or for part of the structure, relative to the type of damage contained in the defects catalogue;

$R_r = \sum V_{D,ref}$ is the reference sum obtained, considering for all of the damage foreseen for a certain family, to which the work belongs, multiplied by the maximum values of the factors of intensity and extension (K2i = K3i=2 ; K4i=const=1.

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