Maintenance Audits Handbook

A Performance Measurement Framework



Diego Galar Pascual
Uday Kumar

CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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CRC Press is an imprint of Taylor & Francis Group, an Informa business

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Version Date: 20160113

International Standard Book Number-13: 978-1-4665-8392-4 (eBook - PDF)

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To our parents

Marisol Pascual and Jesus María

Kamlavati Devi and Raghunandan Prasad

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Preface

Good asset management ensures equipment uptime, asset longevity, and safety (all of which are critical for operational excellence) and delivers the required performance at the lowest cost. However, good asset management requires modern tools, technologies, and management systems with the appropriate features and functionalities.

Maintenance is an information-driven process and, keeping this in mind during the past few years, we have directed our strategic focus on the development of tools and technologies that address the industrial priorities expressed through data fusion, information sharing, and seamless connectivity. The driving forces have been the ever-increasing power and scope of information and communication technologies (ICT), which not only help in solving industrial problems in real time but also create the right environment and databases for conducting theoretical research in maintenance.

This book repeatedly stresses that the ultimate objective of maintenance management is continuous improvement. All methodologies and technologies of asset management seek to improve various aspects of both plants and production, but continuous improvement only results from the use of a system of performance measurement. Maintenance organizations implementing such metrics reap numerous benefits, including increased life and availability of equipment, improved product quality, and reduced costs because of fewer breakdowns, better management of spare parts inventory, and more economical maintenance. These, in turn, lead to improved budgeting and planning processes.

The measurement of maintenance performance can be tricky. Accordingly, the first chapters in this book analyze existing metrics, disjointed metrics, and inappropriate indicators. They explain how and why they are deficient as maintenance indices.

An aspect often undervalued by maintenance audits is the human factor, in this case, the end user. Here, the book explains another problem of existing metrics: indicators should differentiate between users and owners. Metrics should be resilient; point to problems, regardless of the hierarchical level; and suggest improvements.

This book provides both indicators and reference measures, identifying the user or owner of each, setting the basis for external or internal audits. The resulting audit model is mixed. It combines sets of surveys, as the opinions of those involved are important, with numerical indicators obtained from the information systems of the organization. The mixture of information validates or invalidates the perceptions of operators and managers.

It also proposes a logical sequence for the maintenance process auditor. The traditional literature and the proposed indicators do not provide information on calculation intervals. The book suggests a logical succession of surveys and indicators, grouped by hierarchical levels, thereby positioning the audit process in real time. It then explains how to structure the data collection and results based on the level of maturity of the maintenance organization.

Maintenance Indicators

The book addresses the collection and creation of maintenance indicators for an audit, and explains how to monitor their performance. This rationale of this in-depth study supports any set of maintenance indicators and, therefore, any measure of maintenance.

Broken down into their basic building blocks, these indicators are RAMS parameters, the cost model, and the human factor. These elements combine to form indexes measuring performance based on the translation of corporate objectives to the maintenance department. It is necessary for the indicators to measure aspects reflecting the transfer of company objectives to the maintenance department. The mission and vision of the company must translate into concrete maintenance objectives and be measured. They are configured for both management and maintenance, not as aims in themselves, but as a means to measure the transmission of the company's mission and vision into the management of productive assets.

An additional important feature of the indicators used in this system is that they must be dynamic. Some indicators make sense at certain times in the implementation of specific technologies or methodologies, so they can be eliminated from our scorecard. Our indicators must be dynamic and adaptable, not linked to specific time and place in a specific piece of equipment. They must be adaptable to various production systems. This dynamism must come from what the company needs from maintenance at all times, not just one time, with different milestones and different cycles of products and equipment, along with the methodological and technological changes reflecting evolving corporate objectives.

The Human Factor

The human factor is extremely important in the audit process:

- Performance measurement in organizations is unwelcome, because the starting point usually represents an attempt to improve a situation; this will clearly affect those working in the areas, as it implies things are not being done as well as they might be.
- Measurement of maintenance management is important, especially when the history of the maintenance function in companies is marked by organizational changes. This too will have an obvious influence on the individuals linked to the department. Morale, motivation or a sense of belonging may have suffered if there have been too many changes.

The combination of these two factors will suggest the best way to measure the maintenance function in an organization, both in measurements and surveys and in the way to carry them out.

A Cost Model

An appropriate cost model is a second element of good maintenance indicators. The cost model and human factors are the basis of the indicators selected to measure the maintenance function, that is, how resources are optimized to achieve the company's objectives.

The book stresses the ongoing struggle between effectiveness and efficiency. The latter is more difficult to calculate than the former, highlighting the difficulty of estimating the parameters we want to measure, such as the impact of a training activity on the quality of the

work done by workers, or the level of reading comprehension. By contrast, while the costs are a hidden part of the consequences of failure and the difficulty of attribution, they have readily quantifiable elements; the cost model measures both "hard" and "soft" aspects—in other words, those readily available and those less readily available, respectively.

In defining our cost model, we select easily measurable aspects from which we can extract the information necessary to prepare the indicators. It is difficult to measure the impacts of actions or technological improvements, especially as both often have a large component of the human factor. The proposed cost model stays away from such costs because they cannot be objectified, nor can they be benchmarked between organizations.

RAMS Parameters

Finally, RAMS parameters, that is, the combination of reliability, maintainability, availability, and security, are considered in the proposed model. This final area of measurement is more solid and consistent, as it refers to system efficiency.

RAMS parameters are used to develop indicators to measure the effectiveness of the maintenance function. Parameters include such things as the cost of one hour of unavailability or the amount of work in an average work order.

The information on effectiveness provided by RAMS parameters is necessary but not sufficient, however, and must be accompanied by an efficient use of resources. Therefore, the book proposes a reorganization and redistribution of the indicators of effectiveness and efficiency. This reorganization permeates all technical and economic indicators in all hierarchical spheres so all levels can accept and adapt the corporate objectives.

Scorecard and Indicators Proposed

The book proposes a new set of indicators for maintenance. The classic way of structuring indicators presupposes accessibility to knowledge and consistency that are nonexistent in many organizations. Accordingly, in the classic method, the indicator often becomes an end in itself, ignoring the real objective, which is what is expected of the maintenance function within the organization. This lack of vision constitutes the major shortcoming of traditional systems.

This lack of vision is rectified here, as the book suggests a better way to measure and also introduces three new aspects of measurement:

1. *Reference values:* Benchmarking leads to the derivation of indicators considered the result of good practice. A scorecard should include maximum, minimum, or desirable objective thresholds. Otherwise indicators such as those given in UNE 15341 become useless.
2. *Logical grouping:* Indicators should be based on business goals. These goals should be understandable at all levels of the organization. In this definition, the need for maintenance goes beyond the perspective of technological elements of equipment maintenance to include the strategic objectives of the organization, with maintenance personnel integrating them into their daily work.
3. *Hierarchical model:* Indicators are grouped in five organizational levels, ranging from the highest level, or general manager, to the maintenance team leaders.

> Traditional approaches do not clarify the owners of the indicators in the organizations; owners have the capacity to modify their daily work based on the data received. Examples of owners and their indicators include the following: data on the maintenance budget and the value of assets are required by members at the highest levels in the company; information on the impact of training actions affects the direction of the HR function; elements such as MTBF or MTTR affect the operators of the equipment. The hierarchical segmentation means dozens of indicators are not offered to a level where only a few are necessary.

The book suggests a scorecard, or BSC, composed of these indicators and provides references that allow quantification, comparison, and the development of recommendations. This structuring of the BSC results in the clear identification of four perspectives (customer, financial, internal processes, learning and growth) and a clear link with the interested actors at each hierarchical level.

The customer perspective interests those working with productive assets, the financial perspective is overseen by the finance department, the internal processes perspective serves the maintenance manager, and learning and growth serve human resources.

Each target in each perspective can be met by using the appropriate strategies and monitoring success with the selected indicators. The model proposed and tested here is able to measure success or failure in each perspective.

Maintenance Audit

A maintenance audit is complex because of regulatory gaps and is seldom used in companies because of disparate opinions on its use and value. That said, there is growing interest in performance measurement of the maintenance function. To date, however, the work in this field rarely promotes standards, and if it does, the standards are educational, not regulatory in nature. At the present time, maintenance audits are not mandatory in most countries of the world. In addition, they generally oppose qualitative (surveys) and quantitative (indicators) features, with the two measuring quite different things. The model proposed here integrates these two disparate modes of measurement. As noted above, the human factor is important. On the one hand the maintenance function has a human element, and surveys reflect the perceptions and feelings of the staff, as well as their knowledge and commitment. On the other hand, numerical indicators, drawn from objective data systems reflect the everyday reality that may or may not coincide with the human perception. The ability to combine these two types of data provides both a quantitative scenario on the status of the department in numbers and an assessment of feeling and commitment to these figures, thereby setting the stage for improvement.

The proposed audit model has a simple measurement methodology, consistent with the proposed indicators and scorecard, with four perspectives. The maintenance function can audit the degree to which it has achieved its objectives from each of these perspectives.

The model adopts the BSC, breaking it down into a series of steps based on the maturity of maintenance to follow a logical sequence of performance measurement.

The audit combines qualitative and quantitative methods.

- The qualitative method consists of surveys for the various hierarchical levels using Likert scale measures and covering all aspects of the evolution of maturity in the maintenance function.

- The quantitative method associates indicators on the scorecard with different levels and aspects of maturity. These are numerical indicators, often measured in percentages and retrievable from the information systems of the company as objectively as possible.

The combination of qualitative and quantitative methods either validates the impressions of the respondents or invalidates them, as objective data may contradict subjective findings.

The scorecard can be adapted to audit different production processes. It is equally suitable for continuous process industries and intensive production. Each type of industry can identify and remove inapplicable indicators. This has previously been a concern for those attempting to measure maintenance performance because the same indicators do not apply unilaterally or globally.

Another common concern is ownership of the indicators. However, the use of a scorecard based on the maturity levels of the department will divide the assessment appropriately. For example, strategies for job scheduling will remain in the hands of planners and middle management, if they are identified as responsible for (i.e., owners of) those strategies. This hierarchical division allows rapid identification of those responsible for improving a strategy and encourages that improvement.

Finally, the model proposed here is dynamic and flexible. The audit process and the associated scorecard allow companies to adapt to technological changes, with the maintenance function evolving appropriately.

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Acknowledgments

We thank our colleagues from different academic institutions and universities, who have helped us in different ways in the preparation of this book. Their unfailing support and constructive criticism made the work lively and enjoyable. It was a challenge to create a reader-friendly book that would be equally useful to academia and maintenance practitioners. Thanks all for your contribution and hours reading and correcting. Without you, this book would not be a reality.

A special thank-you to our partner and wife Ana Val and Renu Sinha. Words cannot describe how lucky we are to have them in our lives. Without their continuous support and encouragement we never would have been able to achieve our goals. They have selflessly given more to us than we ever could have asked for.

Finally, we acknowledge the support from the Division of Operation and Maintenance Engineering, Lulea University of Technology, in preparation of the manuscript.

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1

The Need for Maintenance Metrics

1.1 Introduction

The maintenance function is inherent to production, but its activities are not always understood or quantified. This chapter uses the terms "department" and "function" interchangeably because a characteristic of maintenance is that its activity involves more than a group of people or a workshop and goes beyond the limits of a traditional department.

The scope of maintenance in a manufacturing environment is illustrated by its various definitions. British Standards Institute defines maintenance as a combination of all technical and associated administrative activities required to keep equipment, installations, and other physical assets in the desired operating condition or restore them to this condition [33,267,268]. Maintenance Engineering Society of Australia (MESA) indicates that maintenance is about achieving the required asset capabilities within an economic or business context [212]. To Tsang et al. [298], maintenance consists of engineering decisions and associated actions necessary and sufficient for the optimization of specified equipment "capability," where capability is the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality, safety, and responsiveness. Similarly, Kelly states that the objective of maintenance is to achieve the agreed-upon output level and operating pattern at minimum resource cost within the constraints of system condition and safety [166]. The desired production output is achieved through high availability, which, in turn, is influenced by equipment reliability, maintainability, and maintenance supportability [93].

Maintenance is also partly responsible for technical systems' safety and ensuring the plant is kept in good condition [362]. We can summarize the maintenance objectives under the following categories [169]: ensuring plant functions (availability, reliability, product quality, etc.); ensuring design life; ensuring plant and environmental safety; ensuring cost-effectiveness in maintenance; and ensuring efficient use of resources (energy and raw materials). For production equipment, ensuring the system functions as it should is the prime maintenance objective. Maintenance must provide the required reliability, availability, efficiency, and capability of production systems. Ensuring system life refers to keeping the equipment in good condition to achieve or prolong its designed life. In this case, cost has to be optimized to achieve the desired plant condition [65]. Plant safety is very important as failures can have catastrophic consequences. The cost of maintenance has to be minimized, while keeping the risks within strict limits and meeting the statutory requirements.

For a long time, maintenance was carried out by the workers themselves, in a more loosely organized style of maintenance with no haste for the machinery or tools to be operational again. However, things have changed.

- First, there is a need for higher plant availability. With scale economies dominating the global map, the demand for products is increasing. However, companies suffer financially from the costs of expansion, purchase of industrial buildings, production equipment, acquisitions of companies in the same sector, and so on. Productive capacities must be kept at a maximum, and organizations are beginning to worry about keeping track of the parameters that may affect the availability of their plants and machinery.
- The second concern follows from the first. When organizations begin to optimize their production costs and create cost models attributable to the finished product, they start to question maintenance cost. This function has grown to include assets, personnel, and so on, consuming a significant percentage of the organization's overall budget [59,65]. Therefore, when companies establish policies to streamline costs, the question of the maintenance budget arises, followed by questions about the success of this budget. The companies also start to consider availability and quality parameters.

A question that has haunted maintenance throughout history is, How do we maximize availability at the lowest cost? To answer this question, various methodologies, technologies, and batteries of indicators are being developed to observe the impacts of improvements, as noted by Al-Najjar [7].

1.2 The Need to Measure Maintenance Performance

Organizations are under pressure to continually enhance their ability to create value for their customers and improve the cost-effectiveness of their operations [336]. In this regard, the maintenance of large-investment equipment, once thought to be a necessary evil, is now considered a key function for improving the cost-effectiveness of operations and creating additional value by delivering better and more innovative services to customers.

With the change in strategic thinking of organizations, the increasing amount of outsourcing, and the separation of OEMs and asset owners, it is crucial to measure, control, and improve asset maintenance performance [263]. Today, with the advances in technology, various maintenance strategies have evolved, including condition-based maintenance, predictive maintenance, remote maintenance, preventive maintenance, and e-maintenance. One of the main challenges faced by most organizations is choosing the most efficient and effective strategies to enhance and continually improve operational capabilities, reduce maintenance costs, and achieve competitiveness in the industry. Therefore, in addition to formulating maintenance policies and strategies for asset maintenance, it is equally important to evaluate the efficiency and effectiveness of these maintenance strategies by measuring their performance.

Maintenance performance measurement (MPM) is defined as "the multidisciplinary process of measuring and justifying the value created by maintenance investment and taking care of the organization's stockholders' requirements viewed strategically from the overall business perspective" [262]. It is considered an important element in understanding the value created by maintenance, reevaluating and revising the maintenance policies and techniques, justifying investments in the adaption of new trends

and techniques in providing maintenance services, revising resource allocations, understanding the effect of maintenance on other functions and stakeholders as well as on health and safety, and so on.

Unfortunately, these maintenance metrics have been often misinterpreted and are incorrectly used in many companies. The metrics should not be used to show the workers are not doing their jobs. They should not be used to satisfy anyone's ego, that is, to show that the company is working well. PM_ms, when used properly, should highlight opportunities for improvement, while also detecting problems and, ultimately, helping to find a solution [375].

Mata and Aller [205] have provided an overview of the state of maintenance, its current problems, and the need for adequate metrics for its quantification. In their view, maintenance is seen in the industry as a necessary evil, an expense or loss the organization must incur to keep its production process operative. Because of this, the priorities of many companies do not typically focus on maintenance of assets but on production. The use of objective indicators that allow these processes to be evaluated can help to correct deficiencies and increase the production of an industrial plant. Many of these indicators may relate the costs of maintaining equipment to production or sales; others make it possible to determine whether the availability is adequate and/or what factors should be modified to achieve its increase.

This historical maintenance view mixed with traditional issues of PM_m creates problems in developing and implementing a comprehensive package of maintenance performance management [380]. These problems include the human factor in selecting a measurement metric, the application of the metric, and the later use of the produced measurement, not to mention the need for a delineation of responsibilities in the process.

1.2.1 Too Much Data and Too Little Information

Data acquisition has become relatively simple and cheap through the introduction of modern, powerful hardware systems and software. However, the enormous amount of data, that is, data overload, is a problem in itself. If data collection is simple and inexpensive, there is no reason not to gather data, but sophisticated data mining algorithms are required to get useful information, as Charnes et al. [50] have argued. We need to decide whether the value to the overall company and a specific hierarchical level justifies the effort and cost. This is accomplished by establishing what is important for different levels, that is, analyzing objectives tailored to each organizational level that emanate from the corporate objectives. Once user needs are fully understood, it is possible to decide on the maintenance strategy, as well as the organization, resources, and systems needed to fulfill this strategy.

1.2.2 Number of Performance Indicators, Ownership of the Data, and Aspects to Be Covered

The number of indicators used for each figure or department should be limited by identifying key features or "key factors." Scorecards with large numbers of indicators without defined users or responsible personnel actually hinder the work for which they are developed.

To control the scorecard, it is important to approach the issue of data ownership and the need for collaboration with the rest of the organization. The maintenance department is frequently overwhelmed by its duties, so data cannot be collected. Moreover, there is often

a lack of historical data, making it impossible to create certain indicators. In a multifunctional organization, other departments are likely to collect some data critical to the generation of these parameters and can share them. For example, it may be relatively simple for the production department to collect data on availability or reliability. Occupational Safety and Health people are aware of the safety equipment, making them an ideal source to understand the rates of accidents or surveillance, as studied in EN 15341 [356].

1.2.3 Objectives and Measures

There are situations where different departments within the same company have conflicting interests in relation to the maintenance of their equipment. The purpose of creating objectives is to ensure departmental efforts are aligned with business needs, as explained by Gelders et al. [103]. These should be tangible goals tailored to the users and free from ambiguity. Problems arise when members of the management of a company set goals only at the highest level or fail to ensure their objectives are correctly translated into subgoals at lower levels. When management ensures higher level objectives are translated into objectives at lower levels and are associated with their measurement, not left to the free interpretation of middle management, ambiguities disappear, along with the friction between conflicting departments that may have erroneously interpreted the objectives.

The objectives should be transmitted in a downward cascade, including all company departments; subsequent steps are taken according to the determined measures, with everyone going in the same direction.

1.2.4 Time Lag between Action and Monitoring Results

There is sometimes a delay between policy change and the realization of benefits associated with that change. A second delay can be found between the appearance of results and the time the measurement was taken. These problems must be treated individually against each objective, taking into account that technical levels can expect faster changes in their indicators than corporate levels, where their key performance indicators (KPIs), measurers of strategy, can experience more delay in getting visible results. Once a measure has been identified for a goal and level and is implemented, the method and frequency of data collection have to be specifically tailored to the factors involved: physical, human, financial, organizational, and so on.

1.2.5 Cost and the Reasons for Data Collection

The success of any measurement system is based on the method used for data collection. Poor or incorrect data entered into a reporting system will result in poor data with little value. Human factors involved in the collection of data are more reliable as these data are more closely related to the indicators of ownership and responsibility. However, technicians and operators will collect data only if they believe it is worthwhile. Finally, the results should be made available for free consultation and use.

If there is a risk that the indicators derived from the reported data are used against people, it is almost certain that they will not be collected in an appropriate way. Also, if time passes and the data have not been used for anything, people will inevitably feel it was a waste of time. They will only be motivated to collect data representing a source of information at the collection level, especially if they understand the purpose of this action.

Massive data collection generates unknown indicators for the collector and may impose a punitive burden; this will produce distrust of and fear in the collected data.

Measurements should cover both the internal functioning and the interaction with external actors, particularly with the client, who, in the case of maintenance, will be the machinery to maintain. All of this should follow the objectives of the management who, in turn, will propose improvements following the reading of these indicators.

1.3 Measurement: Sensors and Their Placement

Measurement is the act of assigning numbers to properties or characteristics. The measurement objective is to quantify a situation or to understand the effects observed about things [331]. Measuring performance is essential in managing any business. Continuous improvement is the process of not accepting the status quo [375]. Levitt [186] agreed with Wireman; a prerequisite for the maintenance function is continuous improvement.

More studies are being carried out to ascertain the relationship between maintenance performance and reliability of the productive or operative system. For Kutucuoglu et al. [180] and Atkinson et al. [18], the measurement objectives are planning, selection, monitoring, and diagnosis. According to Mitchell [220], measurements are needed to determine the scope for competition, prioritize resources, and determine the progress and effectiveness of improvement initiatives. PM_ms are ways to control maintenance to reduce costs, increase productivity, ensure process safety, and meet environmental standards [15]. A PM_m provides a base for improvement as without measurement there can be no certainty of improvement [259]. PM_m is a powerful methodology; it allows engineers and managers to plan, monitor, and control their operation/business. The purpose of measuring maintenance performance is to help predict future action and to improve performance based on past data. Appropriate metrics have to be chosen; otherwise, performance results can be misleading.

According to Training Resources and Data Exchange (TRADE) [332], a performance measure is a number and a unit of measurement. The number gives the magnitude, and the unit gives it a meaning. Implementing measures may also be represented by multiple units. These are expressed as ratios of two or more fundamental units, giving a new unit [332]. A PM_m indicator is developed in some applications. An indicator, therefore, is a combination of a set of PM_ms. KPIs identify the key objectives in performance; these consist of several indicators and metrics and are used to streamline the process. To determine the performance level of maintenance, both strengths and weaknesses must be considered; accordingly, the KPIs cover those areas in which management is interested.

An important aspect of MPM is to formulate maintenance performance indicators (MPIs) to link the maintenance strategies with the overall organizational strategy [5]. Users try to derive an index showing the overall performance of a process. The end user wants to concentrate all enforcement activities in the fewest possible indicators to monitor the entire system in a few variables, no matter how complex it may be. A review of the literature reveals many attempts have been made to classify maintenance performance measures as a means of developing an effective and efficient MPM system. The major issue in measuring maintenance performance is related to the formulation and selection of the MPIs; these must be in line with the organizational strategy and be able to give maintenance

management quantitative information on the performance of the maintenance strategy and its ability to achieve organizational goals [16,283].

Hernandez [118] proposes a battery of indicators mainly from system reliability and functional safety. The author defines an indicator or index as a numerical parameter that provides information about a critical factor identified within the organization, processes, or people, or expectations of customer perception in terms of cost, quality, and deadlines. These indices should be few, easy to understand, and measurable; it should be easy to know quickly how things are going and why. In addition, they must identify the key factors of maintenance, establish records of data allowing periodic calculation to set standard values for these indicators, mark targets based on those standards, and take appropriate actions and decisions for the deviations detected [15]. Hernandez gives special emphasis to the ranking of these indicators, a relevant concern when creating a large set of indicators.

Many authors agree the first step is to develop an appropriate MPI; that is, numerical parameters on critical factors associated with measurable physical characteristics must be identified. Besterfield et al. [23] list seven basic characteristics that can be used to measure performance: quantity, price, speed, accuracy, function, service, and aesthetics.

1.4 Type of Indicators: Leading versus Lagging and Hard versus Soft

PIs are used to measure the performance of any system or process. A PI is a product of several measures (metrics). When used to measure maintenance performance in an area or activity, it is called an MPI [259]. PIs are applied to find ways to reduce downtime, costs, and waste, to operate more efficiently, and to gain more capacity in the operational lines. A PI compares actual conditions with a specific set of reference conditions (requirements) by measuring the distances between the current situation and the desired situation (target), the so-called "distance to target" assessment [89].

The list of PIs is long, and each organization's selection of performance indicators will vary as per their corporate strategy objectives and requirements. PIs can broadly be classified as leading or lagging indicators. A leading indicator warns the user about the nonachievement of objectives beforehand. In economic terms, it is one of the statistical series that fairly reliably turns up or down before the general economy does. A leading indicator, thus, works as a performance driver and supports the relevant head of an organizational unit to ascertain the present status in comparison to a referential one. To know how likely it is for something to occur tomorrow or next year, we need soft or perceptual measures, like stakeholder satisfaction and employee commitments. Perceptual measures are often leading indicators in the sense that they are highly predictive of financial performance. When such measures are tracked today, we worry less about tomorrow's budget [44].

A lagging indicator normally changes direction after the economy does, making it useless for prediction. The value of completed construction, for example, is outdated as it would indicate the condition after the performance has taken place. The maintenance cost per unit or return on investment (ROI) calculation is an example of a lagging indicator.

The establishment of a link between the lagging and the leading indicator makes it possible to control the performance of the process. Remember that indicators are to be chosen in line with the chosen maintenance strategy [178].

The complexity of some measures is an obstacle for their implementation. This, in turn, will decrease the frequency of their use—if they are used at all. In maintenance, many processes can be measured directly. Time or costs are quantities whose measurement and systematization are relatively easy. However, many processes only can be measured using the most complicating methods, such as the adequacy of repairs shop, the size and type of the maintenance team or the investment in tools. This difference suggests that the indicators fall into two broad groups: "hard" and "soft."

"Hard" indicators include those measurable through the extraction and exploitation of simple databases, like computer maintenance management system (CMMS) and enterprise resource planning (ERP), purchase orders, energy consumption by area, and so on. Arts et al. [16] explain the development of an MPM system using CMMS [14]. Using the operational view of the maintenance function, they define a number of indices for PM. However, these indices do not take into account the tactical and strategic aspects related to maintenance performance. In this case, the data collection and the calculation of the indicator are rapid, and the measurement of these processes does not interfere in the daily work of the maintenance team. For this purpose, a common database can be an important instrument for decision-making in relation to maintenance management [151].

"Soft" indicators include those that are interesting but have a problem in their measurement either because of a lack of sources or their hard objectivity and unreliability. Apart from the sizing of staff and workshops, this group includes all measures relating to elements with a strong human factor, such as the impact of a training activity on the quality of repairs, or the time for diagnosis and improvement, usually not quantified in any record. It follows from this distinction that the choice of measures to be undertaken and indicators derived from them will be conditioned by the accessibility and reliability of the documentary sources, with the soft indicators affected by human factors that are especially relevant.

The people who operate the equipment are, therefore, a source of information, a determinant in some respects. The human element is configured as an indispensable element in the measurement of maintenance because of the influence it has on repairs. Thus, the data reported by people constitute a major source to be audited. But to assess the overall status of the maintenance system and to correct some critical points, we need more objective tools. For example, mathematical models and some indicators may assess both the probability that a team is inspecting, maintaining, or repairing equipment, and the average time for this equipment to fail after a maintenance intervention.

Therefore, two actors are involved in MPM: people and the mathematical models of the process. On the one hand, people will provide information about their links to the company, including their morale, training, skills, and confidence; on the other hand, the effectiveness and efficiency related to cost or time will be obtained from the models. When these two measures are combined, a company can meet the three objectives of excellence noted by Katsllometes [160], that is, efficiency, effectiveness, and staff involvement.

Different categories of maintenance performance measures/indicators can be identified from the literature. The total productive maintenance (TPM) concept [234], launched in the 1980s, provides a quantitative metric called overall equipment effectiveness (OEE) to measure the productivity of manufacturing equipment. It identifies and measures the loss of important aspects of manufacturing, namely availability, performance/speed, and quality rate. This supports the improvement of equipment effectiveness and, thereby, its productivity. The OEE concept has become increasingly popular and is widely used as

a quantitative tool essential to measure equipment performance in industries [125,227]. Arts et al. [16] use the time horizon to classify maintenance control and performance indicators into three levels: strategic, tactical, and operational. Indicators proposed for operational control include planned hours over hours worked, work orders (WOs) executed over WOs scheduled, and preventive maintenance (PM) hours over total maintenance hours, among others.

Parida proposes a multicriteria hierarchical framework for MPM that consists of multicriteria indicators for each level of management, that is, strategic, tactical, and operational. These multicriteria indicators are categorized as equipment/process related (e.g., capacity utilization, OEE, availability, etc.), cost related (e.g., maintenance cost per unit production cost), maintenance task related (e.g., ratio of planned and total maintenance tasks), customer and employee satisfaction related, and health, safety, and environment (HSE) related. Indicators are suggested for each level of management in each category.

Campbell [40] classifies the commonly used measures of maintenance performance into three categories based on their focus: measures of equipment performance (e.g., availability, reliability, etc.), measures of cost performance (e.g., maintenance, labor, and material cost), and measures of process performance (e.g., ratio of planned and unplanned work, schedule compliance, etc.). For his part, Coetzee [54] outlines four categories of maintenance performance measures with detailed indicators for each category. These categories are: maintenance results, measured by availability, mean time to failure (MTTF), breakdown frequency, mean time to repair (MTTR) and production rate; maintenance productivity, measured by manpower utilization, manpower efficiency and maintenance cost component over total production cost; maintenance operational purposefulness, measured by scheduling intensity (scheduled tasks time over clocked time), breakdown intensity (time spent on breakdown over clocked time), breakdown severity (breakdown cost over total maintenance cost), WO turnover, schedule compliance and task backlog; and maintenance cost justification, measured by maintenance cost intensity (maintenance cost per unit production), stock turnover and maintenance cost over replacement value.

Ivara Corporation has developed a framework for defining KPIs for managing the maintenance function based on the requirements of physical asset management and asset reliability process [368]. They propose 26 key MPIs and classify them into two broad categories, leading and lagging indicators. Leading indicators monitor the tasks that when performed will "lead" to results (e.g., if the planning takes place or if the scheduled work is completed on time), while lagging indicators monitor the results or outcomes that have been achieved (e.g., the number of equipment failures and downtime). Leading indicators are classified as work identification (e.g., percentage of proactive work done), work planning (e.g., percentage of planned work), work scheduling, and work execution (e.g., schedule compliance). Lagging indicators are classified as equipment performance (number of functional failures, safety and environmental incidents, and maintenance-related downtime) and cost-related measures (e.g., maintenance cost per unit output, maintenance cost over replacement value, and maintenance cost over production cost).

Dwight [84,85] classifies performance measures into a hierarchy according to their implicit assumptions on the impact of the maintenance system on the business [71]. He defines five levels in the hierarchy: overt (visible) bottom-line impact (e.g., direct maintenance cost); profit-loss and visible cost impact performance (e.g., total failure/down time cost); instantaneous effectiveness measures (e.g., availability, OEE); system audit

approach (e.g., percentage of planned work and work backlogs); and time-related PM (e.g., life cycle costing and value-based PM). The main finding of Dwight's work is the variation in lag between an action and its outcome.

As the maintenance performance literature shows, different authors have different ways of classifying maintenance indicators. We also see differences in their choice of indicators. However, some indicators and categories of indicators are recognized by all authors as vital for the management of the maintenance function. For example, much emphasis has been placed on equipment performance in terms of number/frequency of breakdowns, MTTF, availability, and OEE. Similarly, maintenance cost-related measures are deemed important. Measures of maintenance efforts are considered important by many authors, though they often use different terminologies to describe them (e.g., maintenance productivity and operational purpose fullness [54], maintenance efforts [40], or maintenance work management [368]). Although many writers propose lists of KPIs, they often fail to offer a methodological approach to select or derive them. As a result, users are left to decide relevant KPIs for their own situation. Therefore, one of our objectives is to investigate how maintenance KPIs are sourced and chosen.

Based on the literature, the commonly used MPIs can be summarized into two major categories. The maintenance process or effort indicators are defined as leading indicators and the maintenance results indicators as lagging indicators (as shown in Figure 1.1). Using the definition of Weber and Thomas [368], leading indicators monitor whether the

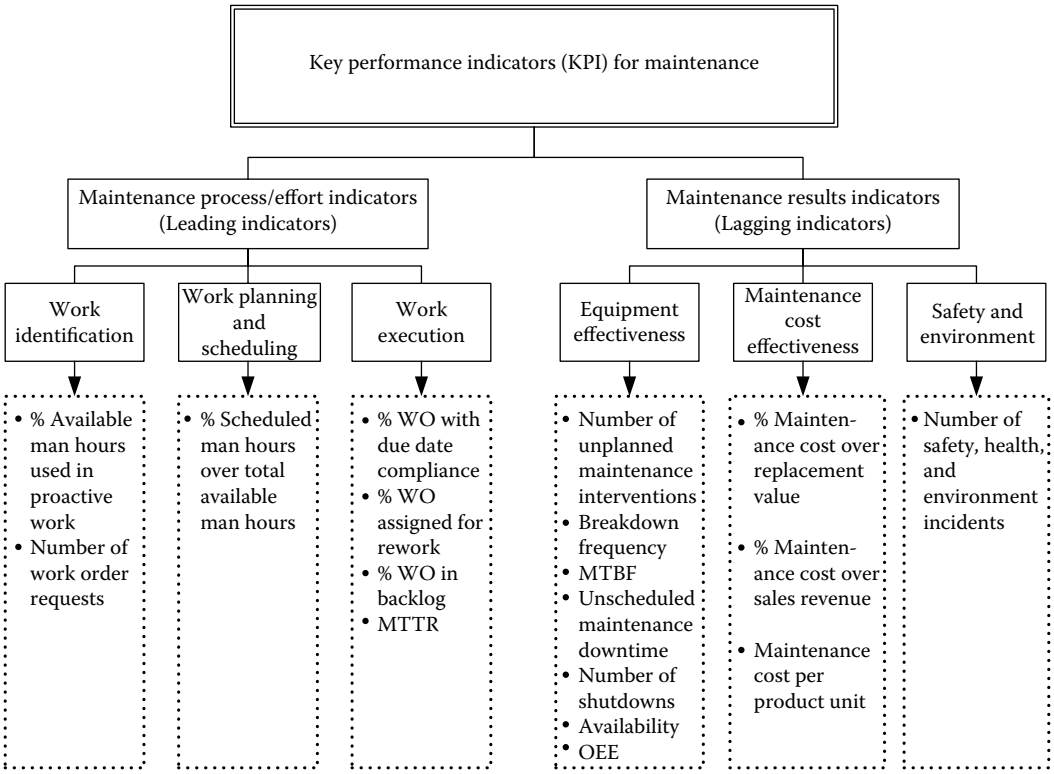

FIGURE 1.1
Key performance indicators for maintenance found in the literature.

tasks are being performed that will lead to the expected output, while lagging indicators monitor the outputs that have been achieved. Under maintenance process indicators and according to Muchiri et al. [228], there are three categories of indicators: work identification, work planning and scheduling, and work execution. For maintenance results, there are three categories of indicators: equipment performance, maintenance costs, and safety and environment indicators. This is shown in Figure 1.1, along with suggested performance indicators for each category.

A survey can be used to investigate the extent to which these indicators are used in industries, establish the most frequently used, and investigate how effectively they are used in maintenance management.

1.5 Grouping of Indicators: Frameworks and Scorecards

The focus here is on performance measuring systems rather than individual performance indicators. An overview of the most currently used PM systems, with their respective advantages and disadvantages, is given in this section. The systems differ by the choice of indicators and the manner of representation.

- *Global PIs*: In practice, maintenance performance is often judged based on one indicator. A complex ratio, in which a number of relevant factors are combined, is commonly used, sometimes with different weights. The ratio yearly costs for materials, labor, and subcontracting/yearly budget is typical. This is a very popular concept because of its compactness. It is fairly tricky to use because of the strong aggregation, which may cause cancellation of some effects (e.g., an increase in labor cost and a comparable decrease in materials cost will never be apparent in the indicator) and makes it difficult to know what exactly happened (did all costs increase, or only one, or some, etc.?).
- *Set of PIs*: Here, a number of PIs are used, each highlighting another aspect of the maintenance activities (a detailed discussion of such a set of PIs is found in De Groote [63]). For example, for the maintenance store, the following indicators are often used: inventory value, number of items in stock, turnover, number of new/obsolete items, and number of in/out movements. This certainly gives a more complete view of the maintenance performance but does not always allow a clear evaluation because of the lack of a structured framework.
- *Structured list of PIs*: Different aspects of maintenance activities are evaluated at the same time, and for each aspect, a set of indicators is used. The TPM measures, evaluating the well-known "six big losses" in equipment performance, may be considered a special type in this class [271,308].

The most popular set or list of indicators is a scorecard. Specifically, a balanced scorecard (BSC) has been adopted by many authors to group maintenance KPIs and show different faces of the maintenance function [334]. The BSC is a holistic approach, grouping both financial and nonfinancial measures to measure performance [152,155,156]. In any organization, the corporate objective is formulated keeping the corporate vision and mission

statement in view. A corporate strategy is formulated as the way and means to achieve corporate objectives. A corporate BSC is part of the corporate strategy to measure performance and compare it with the corporate objectives. These BSCs of the corporate strategy are translated to different divisions, departments, and down to the employee level so that it can be judged and evaluated at various levels.

Similarly, MPIs can be translated from different BSC perspectives down to the division, department, section, and employee levels. Maintenance objectives are linked to critical success factors (CSFs), key result areas, and KPIs. The CSFs provide support to achieve the maintenance objectives. The key result areas are the success areas, where key factors can be used to achieve the maintenance objectives.

Mather [207] coined the term "maintenance scorecard" (MSC), adapting it from the original BSC for asset-centric industries, such as electricity generation and distribution, water treatment, oil and gas, mining, rail, and heavy manufacturing. Based on RCMII by John Moubray [226], in particular, his interpretation of functional measurement and monitoring machine performance and the BSC traditional approach by Kaplan and Norton, MSC identifies a need for strategic initiatives and determining how to define better what form of intervention is required. Breaking down indicators from the corporate levels of management is a common practice and can be applied effectively on the frontlines of the maintenance activity.

Mather [208] proposes building a scorecard to apply in maintenance management and monitor the effectiveness of the maintenance. The MSC is used to develop and implement a strategy in the area of asset management. It also serves to identify strategic improvement initiatives, along with the areas they focus on, early in the process. The MSC is a methodology based on the measurement of performance, built around the use of management indicators, to develop and implement a strategy.

A different approach to measuring is given by Lehtinen and Wahlström [184]. They argue that the use of scorecards to measure performance can focus on safety and the environment as a necessary part of maintenance activities. According to the authors, quality management systems, risk prevention, and environmental concerns require the implementation of a metric in the maintenance department.

1.6 Hierarchy of Indicators

It is common to formulate the indicators at different levels. Each level serves certain purposes and various users. Users at the highest level of the management traditionally refer to aspects that affect the firm's overall performance, whereas those at the functional level deal with the physical condition of assets. The use of multiple performance measures at the level of systems and subsystems helps to solve problems. If a corporate indicator shows a problem, indicators on the next (lower) level should define and clarify the weakness causing the problem [375].

According to Mitchell et al. [221], a hierarchy of different parameters, all linked to business goals, is vital for the success of a program managing corporate physical assets.

Many authors agree on multifaceted maintenance and the need for metrics to value the maintenance relationship with the company strategy; these metrics should serve specific levels of existing organizational hierarchies. TRADE [332] suggests the levels of

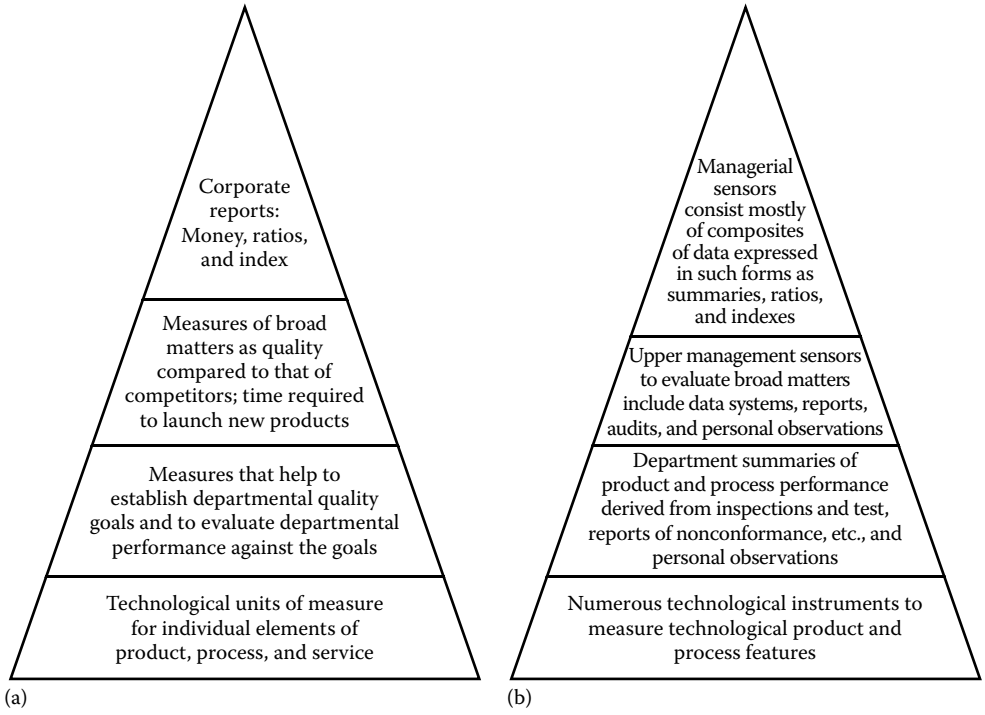

FIGURE 1.2
Pyramid used in all levels of the company. (a) Units of measure and (b) sensors. (Adapted from Training Resources and Data Exchange [TRADE] and Performance-Based Management Special Interest Group, How to measure performance: A handbook of techniques and tools, Prepared for the Special Project Group, Assistant Secretary for Defense Programs and the U.S. Department of Energy, Washington, DC, 1995.)

performance indicators in a typical organization, as shown in Figure 1.2. Different organizations have different hierarchies of PMs.

Grenčík and Legat [109], like TRADE [332], performed a complete analysis of the consistency of the indicators and their classification levels. The first step in selecting relevant indicators for maintenance measurement is to define the objectives to be achieved at each level of the company. At the company level, the requirement is to determine how to manage maintenance in order to improve the overall performance (profits, market shares, competition, etc.). At the production level, objectives will respond to performance factors identified through prior analysis, such as improved availability, improved intervention costs, safety, environmental preservation, improvements in the costs of maintenance inventory, contracted service control, and so on.

Kahn [145] speaks about KPIs for maintenance, suggesting a hierarchical methodology to quantify innovation improvements in the maintenance function. To visualize the expected benefits, he says the process variations and trends should be monitored. The KPIs should be controlled and an adequate program for continuous improvement established. For Kahn, a KPI is a traceable process metric that allows decision-making to achieve established business objectives; maintenance KPIs should include indicators from the corporate level, such as OEE, or financial indicators, such as the overall maintenance budget compared to replacement cost, and so on. These financial indicators should ensure the support of the organization for maintenance improvement projects. The author, like TRADE [331],

proposes five levels of KPIs, each with its own requirements and target audience, thus consolidating the division of indicators by the level of the organization using them: maintenance costs, availability of equipment, OEE, production costs, and performance.

Campbell [40] classifies performance measures into three categories: equipment performance measures, cost measures, and process performance measures. Kutucuoglu et al. [180] suggest another general classification for a balanced performance measure by listing five categories: equipment-related performance measures; task-related performance measures; cost-related performance measures; immediate customer impact-related performance measures; and learning and growth-related measures.

Wireman [375] also defines a set of indicators divided into groups: corporate, financial, efficiency and effectiveness, tactical, and functional performance; see Figure 1.3. The indicators should be properly connected to the levels of corporate vision and company mission.

A hierarchy like the one shown in Figure 1.3 can condemn lower levels to work with operational and functional indicators, while raising economic indicators to top management, thereby causing a rupture and putting indicators into first and second categories. That is why authors have traditionally associated maintenance metrics with RAMS parameters as these are part of the performance to be measured. Few authors have included cost and even fewer have integrated corporate indicators into the maintenance function.

These groups and hierarchies of PIs are ambiguous and nonuser defined. In fact, they confuse groups with organizational levels that lack end user identification and with no responsible persons involved in continuous improvement actions. Therefore, in implementation, there should be multilevel indicators. According to Wireman [375], the first layer is the corporate strategic level, and the supporting level is the financial PI; the third level consists of the efficiency and effectiveness indicators, with the fourth and fifth levels being tactical PIs and functional PIs, respectively. These five levels of the pyramid show the hierarchical relationship of the PIs. It should be noted that the indicators are always determined from top down, and corporate indicators measure what top management feel will satisfy the needs of all stakeholders/shareholders.

For Parida and Kumar [261], indicators on three levels should be considered from a multihierarchical perspective. The first hierarchical level corresponds to the corporate or strategic level, the second to the tactical or managerial level, and the third to the

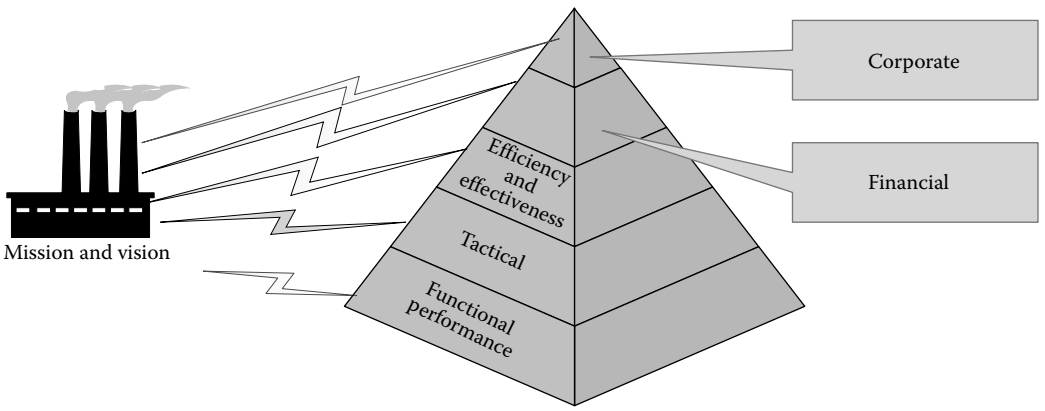

FIGURE 1.3
Hierarchy of indicators in maintenance according to Wireman. (Adapted from Wireman, T., *Developing Performance Indicators for Managing Maintenance*, 1st edn., Industrial Press, New York, 1998.)

functional/operational level. There may be more than three hierarchical levels depending on the organizational structure [261].

Corporate PIs will vary from company to company, depending on the current market conditions, business life cycle, the company's financial standing, and so on. The first rule is that all PIs must be tied to long-range corporate business objectives. If the selection is effective, the PIs will meet the needs of the operations and maintenance processes. The critical strategic areas vary from company to company and from sector to sector but generally include areas such as financial or cost-related issues, health safety and environment-related issues, processes-related issues, maintenance task-related issues, and learning and growth and innovation-related issues. In other words, they comprise both the internal and external aspects of the company.

The measurement system should cover all processes in the organization. There must be a logical interconnection between different indicators so that the numbers can be interpreted and good conclusions reached. This implies a hierarchy of indicators addressed in a dual way [35]. On the one hand, maintenance indicators must be divided according to the areas of influence in the rest of the organization; the maintenance department interacts with finance, human resources, purchasing, and, of course, production in a united attempt to achieve the corporate objectives. On the other hand, these indicators correspond to different levels in the organizational structure, so they will be targeted to the levels.

For Cáceres [35], PM must be comprehensive and requires an appropriate scorecard. Management should be measured holistically, not just from a financial perspective as has traditionally been done [10]. Maintenance should be based simply on the maintenance parameters of availability, reliability, mean time to repair; rather, all perspectives within maintenance should be integrated, covering the organizational and technological aspects, as well as internal processes, customer and company perspectives, and financial perspectives.

Bivona and Montemaggiore [25] agree with Cáceres [35] and argue that there is a lack of linkage between the objectives of general maintenance and the business strategy adopted because of PM systems. In particular, the most common performance indicators oversee operational management and the unique perspective of the maintenance activity, ignoring the effects of maintenance policies on the performance of the company and their impact on other departments. Other authors indicate a PM system based on relations between different departments of a company facilitates communication of the corporate strategy to the various hierarchies of the maintenance organization.

To align business objectives and maintenance, most authors suggest adopting the BSC approach to the formulation of maintenance strategies, not only to group indicators but also to set up a hierarchy. The systemic perspective of the BSC, in fact, supports management in analyzing the various relationships between subsystem maintenance and other business areas, helping to prevent the gains or losses in the performance of maintenance management that are included in the execution costs of other departments.

The BSC method was first developed by Kaplan and Norton [152] and later adapted by Tsang et al. [335] for measuring maintenance performance. It is an effective approach to measuring maintenance performance from four perspectives:

1. Financial (the investor's view)
2. Customers (the performance attributes valued by customers)
3. Internal processes (the long-term and short-term means to achieve financial and customer objectives)
4. Learning and growth

This technique is able to link the maintenance strategy with the overall business strategy and develop performance measures for maintenance that are linked to organizational success [334,335].

Alsyouf [8] criticizes the BSC technique proposed by Tsang et al. [335] because, based on the four nonhierarchized perspectives, it focuses on a top-down PM which does not take into account the extended value chain, that is, it ignores the suppliers, employees, and other stakeholders. The extended BSC presented by Alsyouf [8] incorporates performance measures based on seven perspectives: corporate business (financial), society, consumer, production, support functions, human resources, and supplier perspectives, as shown in Figure 1.4.

There are several alternatives for any planning and development activity, and we have to choose the best fit. Normally, the objectives of the decision maker are expressed in terms of various criteria. If there are many criteria, multicriteria choice problems arise; we can solve this issue if we have information on the relative importance of the criteria [238]. The selection of factors or variables constituting various performance criteria, such as productivity, effectiveness, efficiency, and so on, is an important step in developing a PM system in an organization and is conceived essentially as multicriteria decision-making [278].

An MPM system has a number of criteria or goal functions that need to be considered from the point of view of different stakeholders. These criteria can be broken down into maintenance indicators, such as mean time between failure, downtime, maintenance costs, planned maintenance tasks, and unplanned maintenance tasks.

These maintenance indicators need to be integrated from the operational level to the strategic level. The development and identification of MPIs for an organization is undertaken from the vision, objectives, and strategy points of view and on the basis of the requirements of both the external and the internal stakeholders, as given in Figure 1.5.

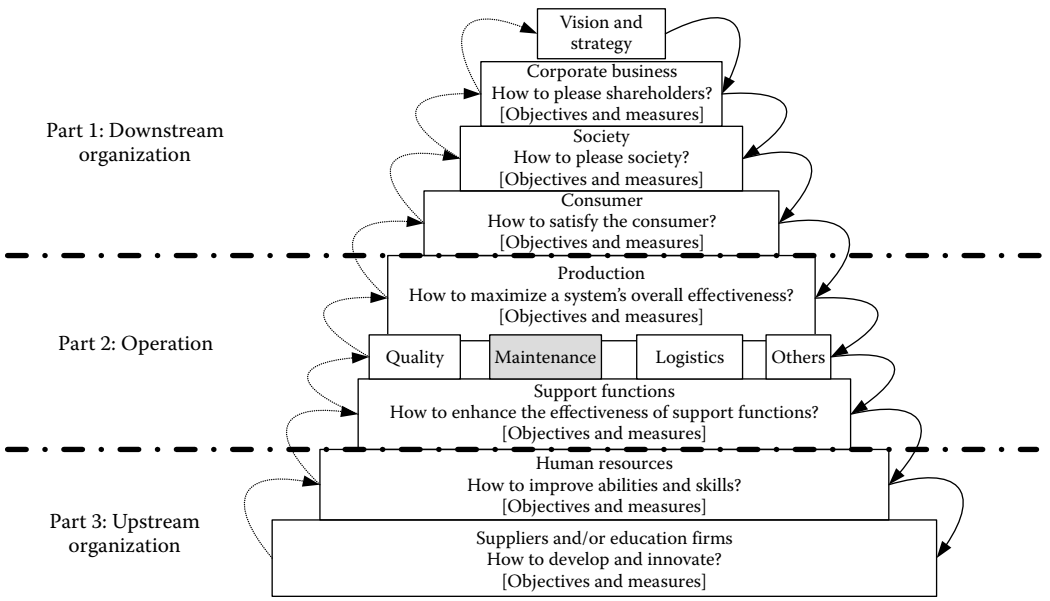

FIGURE 1.4
The extended balance scorecard. (Adapted from Alsyouf, I., *J. Qual. Maint. Eng.*, 12(2), 133, 2006.)



FIGURE 1.5
Developing performance measurement indicators from vision, objectives, and strategy. (Adapted from Parida, A. and Kumar, U., *J. Qual. Maint. Eng.*, 12(3), 239, 2006.)

In our process of developing an MPM framework, we must consider the four basic perspectives of Kaplan and Norton's BSC in addition to the maintenance criteria. We also need to consider health, safety, security and environment (HSSE), and employee satisfaction to make this MPM system balanced and holistic from the organizational point of view.

1.6.1 Multihierarchical Levels

MPIs must consider the multihierarchical levels of the organization. The first hierarchical level corresponds to the corporate or strategic level, the second to the tactical or managerial level, and the third to the functional/operational level. Depending on the organizational structure, there could be more than three hierarchical levels. The maintenance indicators of the functional level are integrated and linked to the tactical or middle level to help the management analyze and make decisions at the strategic or tactical level. It can be challenging to integrate MPIs from top-down and bottom-up flows of information.

Another important challenge is ensuring the involvement of all employees in the MPI development process, with everyone speaking the same language. The strategic goals need to be broken down into objective targets for operating maintenance managers, and this may act as performance drivers for the maintenance group. When the objective output from the operating level, in terms of KPIs, is linked to strategic goals, the subjectivity increases as the objective outputs are integrated to obtain KPIs at higher or strategic levels.

The three hierarchical levels are shown in Figure 1.6.

1.6.2 MPM Frameworks

The MPM framework forms a vital and integrated part of the PM_m system. The need to develop and implement an MPM framework is now well established. The MPM framework needs to provide a solution for PMs by linking them directly with the organizational strategy and considering financial and nonfinancial indicators. Little literature currently covers the development of a systematic approach to PM_m in maintenance, one that embraces

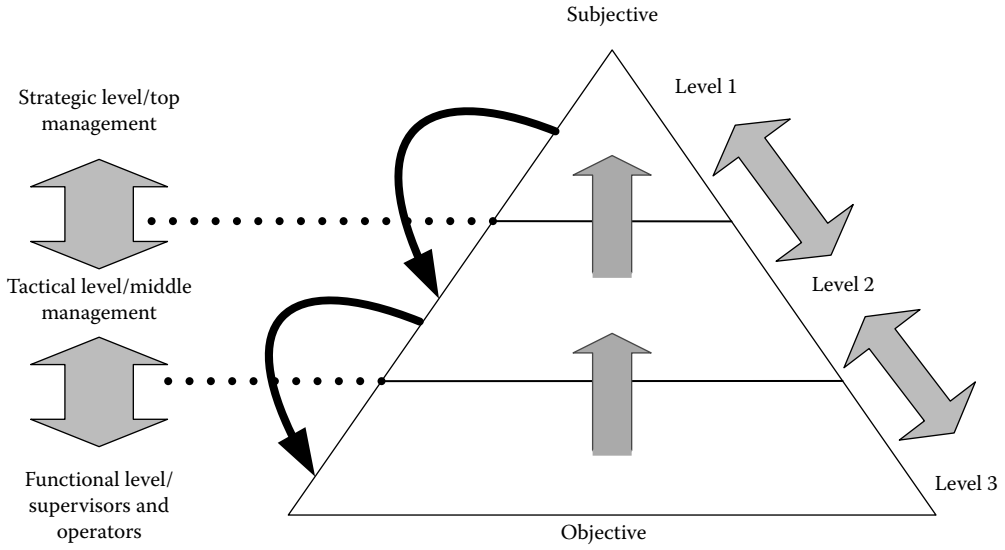

FIGURE 1.6
Hierarchy levels of MPM model.

every level of maintenance, namely strategic, tactical, and operational. An exception is the work by Kutucuoglu et al. [180].

The development of an MPM system is intimately linked with the overall PM_m system and the corporate strategy. Therefore, it is imperative to look into the shortcomings of PM_m systems while taking the MPM framework into consideration, especially systems based on financial measures only [74,140].

Tsang et al. [334] find that a U.S. survey of 200 companies in 1995 concluded that despite a reasonably high level of use nonfinancial measures and targets are frequently treated in isolation from strategic objectives. They are not reviewed regularly, nor are they linked to short-term or action plans. They are largely ignored or studied for interest only.

In another study, Tsang et al. [334] found that the management of a maintenance organization using a structured process to identify measures for its performance was not aware that a PM_m system could achieve vertical alignment and horizontal integration of activities across organizational units; performance measures were primarily used for operational control only.

Coetzee [55] provides a comprehensive list of MPIs and ratios and identifies 21 indices under the four categories of machine/facility maintenance efficiency, task efficiency, organizational efficiency, and profit/cost efficiency. The author fails to identify the specific hierarchical level in the organization where these MPIs would be useful and does not clearly connect them to the corporate strategy. Riis et al. [285] give a framework showing cross-levels and functional integration of maintenance management, which attempts to relate maintenance to manufacturing strategy. However, it does not consider other customers and suppliers, such as design, finance, and top management, and issues like HSSE, employee, and corporate strategy.

Kutucuoglu et al. [180] and Sharp et al. [293] adapt TPM and TQM to improve maintenance performance and identify CSFs linked to maintenance. Dwight [84] explains two other approaches; "the system audit approach" and the "incident evaluation approach,"

which defines performance in terms of changes in value systems. Value is defined here as the probable future earnings of a system.

Tsang [333] and Ahlmann [3] adapt the BSC of Kaplan and Norton [152] to bring a strategic approach to MPM. However, Kaplan and Norton [152] have the limitation of not considering employee, societal, and environmental aspects.

Kutucuoglu et al. [180] developed a PM system for maintenance, using the matrix structure of the quality function deployment (QFD) method.

Murthy et al. [231] propose an approach called the strategic maintenance management (SMM) approach, which has two key concepts:

1. Maintenance management is a vital core business activity, crucial for business survival and success, and as such it must be managed strategically.
2. Effective maintenance management needs to be based on quantitative business models that integrate maintenance with other decisions, such as production, and so on.

The multidisciplinary activity of SMM involves data collection and analysis to assess the performance and state of equipment, building quantitative models to predict maintenance, and operation impact on equipment degradation, and managing maintenance from a strategic perspective. Strictly speaking, this approach is not balanced and integrated as it does not consider all the stakeholders.

Kumar and Ellingsen [178] suggest a PM_m framework based on the BSC model and a list of key indicators for a project for the Norwegian oil and gas industry. The framework considers cost, operation, HSE, and organization perspectives. Maintenance and employee satisfaction are not included, however.

1.7 Categorization of Indicators

1.7.1 Financial Indicators

Financial measures are often considered the top level in the hierarchy of the measurement system used regularly by senior management. This level shows the ability of the organization to achieve good returns on its assets and to create value. The metrics of this level are used for strategic planning and are the backbone of the entire organization. This level of measurement can also be used to compare the performance of different departments and divisions within the parent organization.

Financial figures are lag indicators and are better at measuring the consequences of yesterday's decisions than pointing out tomorrow's performance. To overcome the shortcomings of lag indicators, customer-oriented measures like response time; service commitments, and customer satisfaction have been proposed to serve as lead indicators for the organizations [88]. Examples of such measures are the ROI, return on assets (ROA), the maintenance cost per unit of product, the total maintenance costs in relation to manufacturing costs, and so on.

Vergara [361] proposes the net present value (NPV) for use in maintenance as one of the financial indicators. This consists of learning how much can be gained from an

investment if all income and expenses are estimated immediately. NPV is used to determine whether an investment is appropriate or not; it is used in many sectors and areas of the company but is rarely referred to in the maintenance function. Tsang et al. [335] present a better PM technique first proposed by Dwight [83], which takes into account the impact of maintenance activities on the future values of the organization, instead of concentrating on the short-term values. However, this technique also concentrates on the financial dimensions of PM and is quite laborious to implement.

Hansson [112] proposes using a battery of financial indicators to study the results of the development of the maintenance department. He suggests making a proper benchmarking of the maintenance function, considering such measures as the percentage change in sales, ROA, return on sales, the percentage change in total assets, and the percentage change in the number of employees. These indicators are generally accepted as indicators of financial results and facilitate comparison of results with other studies, for example, Hendricks and Singhal [117]. The correlation of such indicators with more tactical maintenance indicators reveals trends between maintenance and corporate strategy.

Coelo and Brito [53] suggest incorporating the use of financial indicators for maintenance management to support the financial analysis of a corporation. This hypothesis confirms the importance of a system for measuring enterprise performance based on indicators, with special emphasis on maintenance. Coelo and Brito [53] discuss the need for integration and a harmonious balance of financial performance indicators of the organization; they ask how the strategic vision affects the efficiency of the maintenance sector.

Cáceres [35] analyzes the financial outlook of maintenance KPIs. For the author, all planning systems should show the history of strategy and corporate positioning indicated by the financial goals, linking them to the sequence of actions to be undertaken with customers, internal processes, and, finally, with the employees themselves. This perspective is focused on ROI, added value to the organization, and reduced unit costs. In maintenance, the costs of each activity and the incidence rate of maintenance costs per unit of production and maintenance costs on the value of assets are monitored, indicating their global position.

1.7.2 Indicators Related to Human Resources

Measures relating to human resources appear in a separate category. Maintenance organizations depend on the performance of employees to achieve their objectives, but the quality of employees' work in maintenance services cannot be measured directly. Therefore, knowing their experience, education, training, and skills is essential. Few organizations measure the excellence of their human factor in maintenance or the impact of this factor in the performance of the maintenance function. On top of this, measures of organizational performance are often selected on the basis of convenience. Typically, the measures used are either too narrowly or too broadly defined [36].

Examples of measures include using indirect or direct labor, labor in reserve, training measures, and percentage of overtime. To Cáceres [35], the introduction of KPIs relating to human resources in maintenance should cover what the author calls the organizational dynamics perspective, where excellence is focused on the people and the culture of the organization. A cause–effect diagram can be used to identify key skills to support internal targets, thus becoming a true reflection of the company's labor climate in the microclimate of maintenance [282].

The intellectual capital owned by the company is a measure of human resources. In the general area of knowledge management, Fernández and Salvador [98] discuss the importance of intellectual capital (IC) in maintenance teams; they note it is a critical issue for many organizations. They, therefore, incorporate key indicators related to this intangible aspect into their BSC.

In the area of human resources in maintenance, special attention must be paid to the prevention of labor hazards. For this reason, many authors propose an indicator of equipment safety. A large number of operators in maintenance are affected by workplace accidents, far more than production workers [200]. The maintenance staff members are more exposed to high-risk factors, such as electric shocks, heavy components dropping, and contact with chemicals. For production staff, in general, the reason for an accident is the failure of the barriers to prevent accidents or reckless operation by breaking the established procedures. In any case, whatever the origin, an accident has negative effects on employee morale, stops production, and affects the reliability of equipment. Meeting the requirement of safety equipment and the environment, as well as cooperating with regulatory agencies, is one of the responsibilities of maintenance. Maintenance must be rigorous in developing and enforcing security procedures and maintaining good working in barriers to prevent accidents.

1.7.3 Indicators Relating to Internal Processes of the Department

Some authors refer to indicators of internal procedures as functional measures. Traditionally, this category includes processes related to efficiency, and they are measured within maintenance. Examples include work order systems, inventory and purchasing, and management information systems.

For Cáceres [35], one of the four perspectives of KPIs, the internal perspective, or process perspective, is related to the work process, specifically how it can be improved in the pursuit of excellence. The purpose is to understand the processes that add value to the business and identify the levers that drive company objectives. In the specific case of maintenance management, indicators are usually set as repair times, overtime, certified processes, security aspects of activities, and the implementation of plans and programs, among others. This perspective is, therefore, related to the measurement of the internal mechanics used to develop other perspectives.

1.7.4 Technical Indicators

Some authors refer to this category as the technical level of performance indicators. The first objective of this set of indicators is to measure the equipment (assets) performance, that is, the customers of the maintenance function. Mitchell [221] says, "At the technical level, the figures are used to monitor the performance of certain processes, systems, equipment and components." In other words, this level is concerned with the effectiveness of the maintenance work.

1.7.4.1 Functional Safety as a Key Indicator for the Client

Cea [47] proposes the overall indicator of functional safety as a KPI for the customer; it is what he or she expects from the assets. For Cea [47], functional safety is the goal to be achieved to deliver the user the service that he or she expects from the system, with quality and safety according to what is admissible.

According to Blanchard et al. [26], functional safety is "the probability of the system to complete its mission, since the system was available at the beginning of the mission." Functional safety is a measure of the system condition at one or more points; its value is strongly influenced by the system reliability and the maintainability and quality of the project [24,175]. Reliability is associated with the compliance function over time and system performance. Maintainability is also associated with the condition of the equipment to recover function when it stops [46,172,177]. Therefore, according to Blanchard, direct and indirect indices of functional safety are availability, reliability, maintainability, and safety of a production system. This system must have an information subsystem based on indicators of efficiency and feedback, so it is a valid tool operationally, where the user can fully appreciate the benefits of having a "safe operating system."

To assess whether direct indices provide values within the limits defined as acceptable, they are reflected in the operational performance of assets and quality of the products produced. For Cea [47], RAMS parameters are the basic components of the key indicator, that is, the functional safety. Söderholm [303], as well as Cea [47], refers to functional safety as the basis of the whole system of indicators for maintenance and RAMS parameters as the primary indicators on which to build the entire scorecard.

1.7.4.2 Changing Role of RAMS Parameters

For a long time, RAMS parameters were the only indicators adopted for measuring the performance of maintenance, based on the purely technical or operational aspect given to this function. The current trend assigns them a privileged role, albeit limited to the quality of the service that the maintenance function gives its customer as the technical basis on which to build service indicators.

Killet [170] emphasizes the use of MPIs focused exclusively on operational aspects. Without underestimating these indicators, Killet notes the need to develop corporate indicators, a concern that has been growing in recent years because of the deviation of maintenance indicators and scorecards toward simply operational aspects [104]. These are important for the client, but they lose the global vision of maintenance within companies.

According to Martorell et al. [202] and coinciding with Blanchard, there are two main categories of indicators. The first includes the direct or basic indicators directly linked to the collection of operational data, such as the number of maintenance actions, the type of maintenance activities, and the cost. The second category is indirect indicators, such as reliability and availability. For Martorell et al. [202], the direct indicators can be linked to functional requirements, while the indirect indicators may be related to nonfunctional ones.

The recently published standard EN 15341 [94] classifies maintenance indicators into three categories, as do most of the authors mentioned before: technical, economic, and organizational indicators. EN 15341 [94] proposes more than 70 indicators, divided into three types, with these, in turn, divided into three different levels. These levels do not correspond to organizational hierarchies but, rather, a progressive decomposition of higher level indicators into more specific indicators.

The classification into technical, financial, and organizational indicators basically refers to aspects of effectiveness (time-consuming tasks) and efficiency (costs and manpower). Effectiveness falls within the technical indicators, while efficiency is financial and organizational. Organizational indices, due to the high importance of human factors in the maintenance function, play an independent role, but some authors consider them attached to costs.

All authors agree that RAMS parameters are raw materials for creating more complex indicators of effectiveness, providing the MSC with more indicators of efficiency.

1.8 Presentation of Performance Measures

One of the most important factors of a successful PM system is a good introduction of these indicators. If they are not well presented and carefully explained to users, the indicators may be used inappropriately. Mitchell [221] writes, "To fully exploit the benefits of metrics, the metrics must be clearly visible." Seeing the figures often has a positive effect, encouraging everyone to achieve the objectives in the functional area being measured.

Kaydos [161] states that having the performance measures visible to everyone has two advantages. First, everyone can be proud of what has been achieved. Second, where nothing has been achieved, the pressure exerted by the workers in other departments has a positive impact on meeting the objectives. There are a variety of ways to present a performance indicator. Depending on the type of information needed and the type of user, the presentation is different. Charts, graphs, figures, or just numbers are all used to deliver a performance indicator [23].

Lehtinen and Wahlström [184] emphasize the visual aspect and simplicity of the indicators, also key to developing a metric. The indicator should stand out in reports and notices with proper quantification and calibration of the problem. This environment is an important part of continuous learning from which excellence is achieved. Lehtinen and Wahlström [184] show the different nature of the indicators and the need to present them in a visually attractive and powerful way for workers involved in maintenance and production processes.

Another issue associated with the presentation of performance indicators is the frequency of their presentation. Some indicators require continuous data collection; others may have a monthly frequency. There is no advantage in measuring more frequently than needed; it only increases costs [161].

Technology now allows the use of an online graphical user interface (GUI) to present and monitor indicators, tailored for each person's personal needs, making it possible to use the same system for presentation regardless of the hierarchical position. Notices sent automatically to mobile devices or mailboxes for the user's knowledge can further increase information efficiency.

1.9 Efficiency of Performance Measures

Metrics must be understandable, addressed to the needs of users, and controllable by managers through work activities [221].

According to Kutucuoglu et al. [180], in order to develop an efficient and effective system of PM, the need for indicators, what to measure, how to do it, the timing, and who should implement the measurement should be clear. In fact, for Manoochehri [199], the three

obstacles to the effective development of metrics are a misidentification of indicators, a less rigorous data collection, and a bad use of indices by the company managers.

According to Besterfield et al. [23], for measurements to be useful, they should be simple, understandable, and few in number.

1.9.1 Number of Indicators to Be Included and Their Origin in the Metrics Adopted

Killet [170] reflects on the number of indicators to include and the property of each, based on Woodhouse [379] and in line with Besterfield et al. [23]. Woodhouse argues the human brain can only handle four to eight measurements intended to quantify one aspect, suggesting it would be reasonable to target a maximum of six measurements for each supervisor/manager. To achieve this objective, he proposes measuring only key characteristics, thereby limiting the amount of information used and the sources from which to extract this information. In a multifunctional organization, it is likely that other departments may collect and share some of the same data. For example, the collection of data on availability and reliability can be relatively simple for the production department. The department of labor risk prevention is ideal for monitoring injury rates, and the human resources staff is better placed to provide data on trends in absenteeism. This supports Besterfield's thesis on ownership of data, that is, looking to the responsible departments for data instead of calculating them externally.

Shreve [41], in line with Woodhouse [379], and with respect to specific indicators of condition-based monitoring (CBM), proposes the selection of six to eight indicators of high-level performance to analyze the effects of a CBM program in a factory. The performance indicators can be used in both production and maintenance to display the program's progress. Of course, the parameters for monitoring the results of the CBM should be established before implementing the CBM program.

The author emphasizes that measurements should be directed toward areas with the greatest impact on improvement, ignoring those with a small ROI. Furthermore, without constant reminders of performance, programs can start strong then rest on their initial achievements and not reach maturity. Really proactive measurements should be the goal of the monitoring program. This level of maturity is based on the desire to find any problems before they appear and negatively affect production rates and product quality. Shreve [41] and Woodhouse [379] agree on the need to find those indicators with the highest ratio of implementation impact at each level instead of short-term results.

1.9.2 Data Accuracy

A good performance model will give the correct output if the right data are fed into it. The correct input data will yield the correct output at all times. The model must be relied upon to be accurate and consistent when processing the input data. The processing capability of the model must be strong enough to accept the necessary data input and then release the information required to achieve a particular task.

It is clear that "garbage in, garbage out" holds good for any sequential-factored data system model. For the result of model evaluation to be correct, the input data must—as a matter of necessity—be correct. To avoid error right from the start, the model user must ensure the correctness of the data input and, therefore, of data computed. The values must be checked for homogeneity in units, readings, computations, and so on.

The introduction of incorrect or corrupt data into the PM system is very harmful. It simply leads to wrong decisions and losses.

Thus, indicators for data accuracy monitoring are necessary. However, a good PM system does not require high precision [161]. In most cases, we need to know how to identify problems. Very accurate PM is not required; it is more important to know if the trend is up or down and how its value is evolving compared to historical measures. It is crucial to overlap how an indicator is calculated to avoid losing the trend. In addition, Kaydos [161] stresses the importance of trust and credibility: if users do not trust the organization to generate the measures, the whole system is useless.

Barringer and Weber [19] say the data to exploit are often sparse, poorly collected, or of dubious veracity. They suggest that understanding how to manage the reliability of data is the first step toward solving the problems. For Tavares [323], indicators like MTBF or MTTR are particularly sensitive with respect to their accuracy because of their nature. More specifically, their accuracy is linked to the number of items observed and the observation period. The more records available, the greater the accuracy of the values expected. In the absence of many items, or if we wish to obtain the average time between failures of each item separately, according to Tavares, fairly extensive work with longer observation periods (5 years or more) is advisable to ensure reliable results.

1.9.3 Users' Understanding of Metrics

Users must be able to evaluate the performance of the MPM system in terms of its operation and results. More importantly, the user must know how to assess, analyze, and interpret the end result of computations to discover knowledge embedded in the operation of the MPM system. That is why training the user is important. By this we mean the level of knowledge needed to enable proper use of a PM system. It is assumed that the user has taken courses in areas such as mathematics, physics, programming, statistics, and so on to understand the procedure and application of the model, and the user must have had this training in an organized training environment. As part of the training, the user must have been assessed to determine the level of competence attained.

In the opinion of Manoochehri [199], the effective use of performance measures requires user education, especially as a misunderstanding can lead to wrong decisions. Some of the major problems possibly leading to a failure in the measurement of system performance are a lack of real management commitment, a lack of attention to business goals and objectives, and an incorrect updating of performance measures.

The failure to properly use PMs in an organization may be the result of not overcoming the challenges associated with the implementation of a new set of performance indicators. To ensure success, it is very important for the implementation team to persist, especially when starting to use a battery of indicators. Without persistence and determination, the team will lose hope in the new system and voluntary participation in its development will dwindle.

The performance measures of the system must be designed to serve the purpose of the organization. According to Wireman [375], there should be multiple indicators associated with different levels. One layer of indicators could be at the corporate level. Another one could be at the departmental level. Obviously, the levels may vary depending on company size.

Furthermore, to achieve the implementation success of a PM system, measurements should not be numerous. Dispersion into too many areas simultaneously can lead to information overload, increasing the difficulty of directing limited resources to higher value activities [221].

The challenge that most PM systems face is change, simply because it is part of the manufacturing business. The measurement system should not be affected by changes in production characteristics, but it must be adapted to them. Simply stated, the indicators may become dated and require change [161].

1.10 Benchmarks

Two categories of measures fall under reference numbers, that is, benchmarks: "checklists" and "surveys." Each is quantitative in nature. Checklists are widely used by consultants. They are "quick and dirty" performance indicators, for example, the percentage of MRO items (maintenance, repair, and operation/overhaul items) that have not moved during the past 2 years, should not be higher than 3%. Each indicator has an "ideal" value or a range. The checklist approach provides a quick but rough insight into the information sought. In searching for "ideal" values, users encounter a great deal of difficulty. The second class of benchmarks is "surveys." It is common to find the results of maintenance surveys published in specific industrial sectors, such as steel, aluminum, glass, plastics, ceramics, and furniture, and to find academic research groups engaged in their use. Pintelon and Van Puyvelde [268] point out that the result of a maintenance survey may typically include maintenance cost as percentage of cost. Specifically, according to Woodhouse, a range of 10%–15% is given to technical research in industries, while pharmaceutical industries typically record 2%. Research allows for low key benchmarking in specific sectors of the economy. However, a large deviation from the average may not necessarily mean performance is bad. In order to judge, a more detailed evaluation is needed [268].

Benchmarks must be developed to provide the measurement system with the highest possible meaning; positive or negative variations of the indicators must make sense to the operator. Benchmarks represent the targets or limits of each indicator. They are used as a reference for users to determine how close they are to various performance levels. The benchmarks can be internal, in order to compare units of the same plant for an improvement, or external, to compare with other organizations.

Applying the concept of indicators and the appropriate selection of actions to perform, based on continuous improvement, will help achieve excellence in maintenance [160]. Therefore, according to Katsllometes, a metric that follows world class standards is necessary.

That said, new trends derived from world class manufacturing (WCM_f) or lean manufacturing do not give the full answer. It sounds challenging to aim for world class maintenance (WCM, or world class reliability [WCR]), but this level has not yet been defined properly by any source. In the majority of cases, qualitative statements are used, such as the following: a WCM_f organization delivers consistent uptime week to week, minimizes impact on production, delivers its work as planned, and has "spot on" budgeting. Although the organization may be very positive that this will stimulate a much more professional attitude toward the maintenance process, it still does not know how far it is from this level and when it will be reached, if ever. What is the business (economic) impact of low equipment uptime? How much cheaper would maintenance be if the organization accepted 90% weekly schedule compliance instead of aiming for 100%? These and other common questions remain unanswered. Even a highly rewarded quantitative method like Six Sigma has not brought breakthrough results in the maintenance arena, mainly because maintenance data are too poor to apply these kinds of statistical techniques.

Lean maintenance is another popular maintenance management framework that has been developed after a number of successful implementations of lean manufacturing. The goal is to eliminate waste and, therefore, to distinguish between value adding and non-value-adding maintenance activities. But in contradiction to the detailed description in lean manufacturing of how to eliminate nonvalue-adding production activities, in lean maintenance, definitions about which activities to eliminate and which to keep are missing. Some attempts to apply business process reengineering (BPR), pioneered by Hammer and Champy [111], have been made to streamline maintenance processes, eliminate waste, and produce breakthrough performance in areas valued by customers.

Among the methods mentioned earlier, only world class maintenance has been widely developed. Maskell [203] provides a set of guidelines to design MPMs for world class manufacturing systems that lead to excellent performance in today's highly turbulent and competitive business environment. World class maintenance ensures almost 100% capacity for 100% of the time of operation. The metric is at an elementary stage, but it points out some of the indicators considered key, as well as some of the basic benchmarks for improvement. It comes from world class manufacturing, and its main contribution is the proposal of six indicators globally accepted by organizations in both definition and calculation: MTBF, MTTF, MTTR, availability, maintenance cost divided by turnover, and maintenance cost divided by replacement cost. This last indicator is the most popular in small medium companies (SME) according to De Jong [64].

Another contribution is the proposal of reference values for some indicators. These are typically ambitious values, but a company wanting to be considered "world class" has to achieve some high goals. In the maintenance area, these references are usually the result of benchmarking among organizations with good practices and results.

Benchmarks to identify world class maintenance management have been accepted ever since a landmark study conducted in the 1980s by A.T. Kearney Company [162]. The groundbreaking research produced "a mountain of maintenance and operational data." Many researchers have now adopted benchmark data into programs designed to assess maintenance activities and assist organizations in their drive for excellence. According to Kearney, one immediate conclusion of the early research was that there is a high correlation between maintenance operational "style" and overall plant performance. Facilities that rank worst in overall efficiency also tend to have a "reactive" character or a "fix and repair" approach. At the other end of the spectrum, the world's best manufacturers, those enjoying the highest productivity and output quality, invariably display well-planned, fully integrated, and proactive maintenance.

Superiority in maintenance is also characterized by a high level of preventive maintenance (PM) and planned maintenance as percentages of the total work. In the best plants, at least 80% of all maintenance tasks are preplanned a day or more in advance, meaning they can be prestaged with the correct materials, skills, tools, and parts for the most appropriate timing.

Lemos [66] proposes sources of benchmarks for the indicators. According to Lemos, values of indices should be

- Produced using similar equipment available in the market
- Arising from experience in operating similar equipment
- Recommended by the manufacturer
- Standard equipment for the operation of performing the same operation

Kahn and Olver [147] see the need for the comparison of indicators, both within companies and in similar factories or sectors. When a company wants to compare the performance and reliability of internal or external maintenance, it needs a common platform in terms of predefined indicators, so it can compare identical variables and means of production units.

This task has been tackled, in part, by the European Federation of National Maintenance Societies (EFNMS) and the Society for Maintenance and Reliability Professionals (SMRP). In recent years, these two organizations have been working on harmonization, comparing the similarities and differences between existing indicators for maintenance and availability supported by both agencies. For example, they compare the SMRP metrics and the European standardized indicators EN 15341 [94]. The aim is to bring about a systematic and widespread use of shared indicators as a basis for improving asset performance. This harmonization project is promoting the distribution of reference values for guidance in companies that adopt these metrics.

Svantesson [316] is one of the leading experts involved in the harmonization project. The author proposes some indicators based on numerous practical cases in various industries and sectors, using extensive surveys, normally conducted at firms within the same sector, in this case, food and pharmaceutical industries.

It is important that performance measures have meaningful benchmarks. In fact, the metrics are useless without them. As mentioned, the benchmarks can be a goal that the processes must continually focus on and target, or they can be limits these processes must not exceed. The limits can be either maximum or minimum ones. In some cases, the target of an indicator will be zero or one if it belongs to an efficiency or inefficiency group. Specific indicators, such as the MTBF, are more complex, and we have to resort to similar experiences in machinery or refer to the manufacturer's data, along with the expertise of the maintenance technicians.

Benchmarks will always depend on both conventions or business types and the ranking of indicators in each sector. For example, it is particularly interesting to observe how Silter [296] presents the risk asset management model (RIAM); it quantifies the performance indicators to support decision-making at the plant, not only to implement investment options in the best possible way but also to better prioritize the use of certain plant resources and maximize the safety of the process. With the RIAM approach, these performance indicators incorporate "cost-averse" thinking, basically seeking to keep a safe profit. Indicators of availability, maintainability, and technical levels like vibrations or temperature will not have the same reference value in some companies as in others. Therefore, the hierarchy will change; instead of leading economic indicators, the RIAM methodology will provide safety performance indicators at the top of the pyramid.

It is essential to obtain adequate thresholds and targets associated with each indicator; otherwise, the MPM team that measures performance will be faced with a battery of meaningless numbers, with swings upward or downward, but without any objectives and no knowledge of their critical condition. Benchmark points are now included in industry demands; industrial sectors, such as automotive, aeronautics, and energy, request quality parameters from suppliers, but overall indicators of efficiency close to the world class maintenance are required too.

The standard EN 15341 [94] "Maintenance Key Performance Indicators," released in March 2007, was designed and developed from September 2003 to February 2007 by CEN Technical Committee 319 Working Group 6 (WG6), set up by European experts in maintenance management, with the aim of achieving a system and an architecture of indicators able to become a common basis to measure maintenance performance in a shared and

significant way at a worldwide level. In fact, WG6 looked at all the maintenance indicators available in the literature, guidelines, procedures, and experiences of many multinational industrial companies and selected three groups of KPIs: economic, technical, and organizational.

Standard EN15341 is a reliable and fundamental reference in the achievement of an SMRP and EFNMS harmonized document, a worldwide standard to measure and develop maintenance performance in an equal way, considering and managing the external and internal influencing factors.

When an organization wants to compare maintenance and availability performance internally or externally, it needs a common platform in terms of predefined indicators or metrics so that it can compare apples to apples. Comparison of metrics, when the bases of calculation are not the same, is a frustrating, non-value-added activity. Essentially, this challenge has been met by SMRP and EFNMS [313,314]. Their joint effort compares and documents standard indicators for maintenance and reliability performance.

The value to an organization if it uses standardized indicators or metrics, such as the indicators from the standard EN 15341 [94] or the SMRP metrics, includes the following:

- Maintenance managers can rely on a single set of predefined indicators supported by a glossary of terms and definitions.
- The use of predefined indicators makes it easier to compare maintenance and reliability performance across borders.
- When a company constructs a set of company indicators or a scorecard, the development process based on predefined indicators is simplified.
- The predefined indicators can be incorporated into various CMMS software and reports.
- The predefined metrics can be adopted and/or modified to fit the company's or the branch's specific requirements.
- The need for discussion and debate on indicator definitions is ended and uncertainties are eliminated.

SMRP has defined 70 best practice metrics to measure maintenance and reliability performance. The process started in 2004 and is ongoing. In 2000, EFNMS defined a set of indicators to measure maintenance performance. These indicators are now incorporated in the European Standard EN 15341 [94] "Maintenance Key Performance Indicators" released in May 2007. As noted before, the joint EFNMS-SMRP harmonization effort, which began in 2006 [146], had the objective of documenting the similarities and the differences in the SMRP metrics and the EN 15341 [94] standards (Figure 1.7).

With increased globalization and with companies producing goods and supplying services on an international scale, the need for a common understanding of the indicators to measure maintenance and availability performance is paramount. There is no doubt that this activity will eventually play a part in creating a global standard guideline for maintenance indicators.

1.10.1 Objective of the Harmonized Indicator Document

The objective of the harmonization document, deriving from the harmonization project, is to offer the maintenance community a set of predefined indicators to be used by organizations with a need to measure maintenance and reliability performance on a global basis.

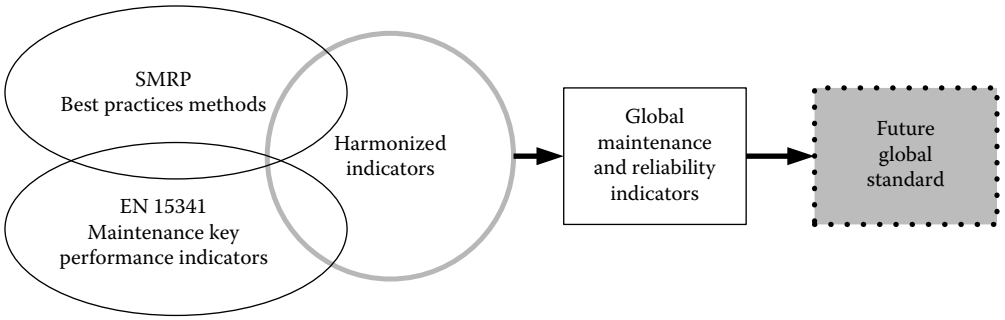

FIGURE 1.7
The process of the harmonized indicator project.

The indicators can be used by all organizations with a need to measure, track, report, and compare maintenance and reliability performance.

A further objective is to give the scale to measure maintenance or reliability performance. It is outside the scope of this document to give any recommended values and thresholds for the indicators, however. The indicators or metrics are supported by a set of guidelines and examples of calculations. This provides maintenance professionals with an easy-to-use guide for understanding the indicators, along with the components included in or excluded from the calculation of each indicator.

The target group for the harmonized indicators document is comprised of maintenance managers, asset managers, plant managers, operations managers, reliability engineers, technical managers, general managers, and, in general, any personnel involved with benchmarking or maintenance and reliability performance measurement.

The two organizations agreed to form a joint EFNMS-SMRP working group to resolve differences between the EN 15341 [94] indicators and those being developed by the SMRP best practices committee. They made side-by-side comparisons of the indicator formulas and the definitions of terms. The basis for the European terms is the standard EN 13306:2001 [93] "Maintenance Terminology" and the standard IEC 60050-191:1990 "Dependability and Quality of Service." The SMRP definitions are contained within each indicator (metric) description and are compiled in a SMRP glossary of terms [301]. This has resulted in two extensive lists as many terms and formulas are common to both.

An indicator is determined to be common if it has the same basic formula or could be universally applied. For these common indicators, it was first determined whether any differences could be eliminated without sacrificing the objective of the indicator. If differences could not be eliminated, the differences were qualified or explained. This is the essence of the harmonization process, graphically depicted in Figure 1.8. It should be noted that the grouping of indicators is different. In EN 15341 [94], the indicators are grouped into economic, technical, and organizational sets. The SMRP indicators are categorized in accordance with the five pillars of the SMRP maintenance and reliability body of knowledge: business and management, manufacturing process reliability, equipment reliability, organization and leadership, and work management [300].

The joint working group made good progress, announcing the first harmonization results in January 2007 and publishing the original edition of *Global Maintenance and Reliability Indicators* in April 2008 [302]. To date, 29 metrics have been targeted for harmonization. When an indicator is harmonized, a statement to this effect is added to the SMRP metric description. Furthermore, the SMRP metric is recommended by EFNMS for use as a guideline for calculating the EN 15341 [94] indicators.

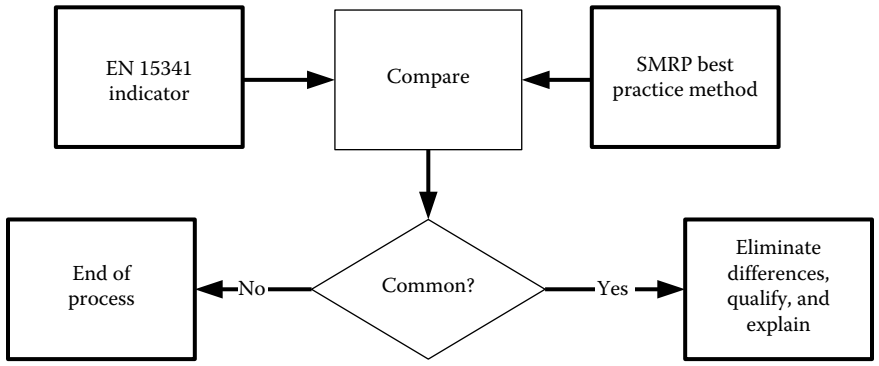

FIGURE 1.8
The harmonization process. (Adapted from Svantesson, T., Benchmarking in Europe, *EFMS Workshops 2004–2005*, Basel, Switzerland, 2008.)

The harmonization work will continue until the complete list of SMRP indicators currently under development has been exhausted. Similar harmonization efforts with other international maintenance organizations, such as Technical Committee on Maintenance of the Pan American Federation of Engineering Societies (COPIMAN) or Maintenance Engineering Society of Australia (MESA) [212] are also desired. Finally, there are tentative plans to promulgate the use of these indicators as international standards; discussions are ongoing with CEN/TC 319 to consider proposing the harmonized metrics as global standards or guidelines.

However, the goals of this harmonization process do not include finding proper benchmark values as thresholds or targets. Many maintenance managers read EN 15341 or SMRP good practices and extract valuable information to calculate parameters, but they do not know the exact desired values as they apply, either partially or fully, to their respective fields. This is a good reason for developing world class maintenance; many figures have been proposed for many industries as a result of individual company experience. WCM_f must not only propose common methods for parameter calculation but also provide real numbers as targets to be reached in companies.

1.11 Maintenance Audit

Converting forecasts into concrete real numeric values requires extraordinary effort. As an alternative, the principles can be addressed by focusing on the system and its attributes rather than specific outcomes. This is the "system audit approach." A maintenance audit is an examination of the maintenance system to verify that maintenance management is carrying out its mission, meeting its goals and objectives, following proper procedures, and managing resources effectively and efficiently (Figure 1.9).

This indicates a concentration on the maintenance system itself, as opposed to the quantification of its inputs and outputs. It is anticipated that using such an approach will yield a level of accuracy compatible with the information normally available on real performance. Subjectivity in performance measurement will not be overcome, but such subjectivity will become more visible.

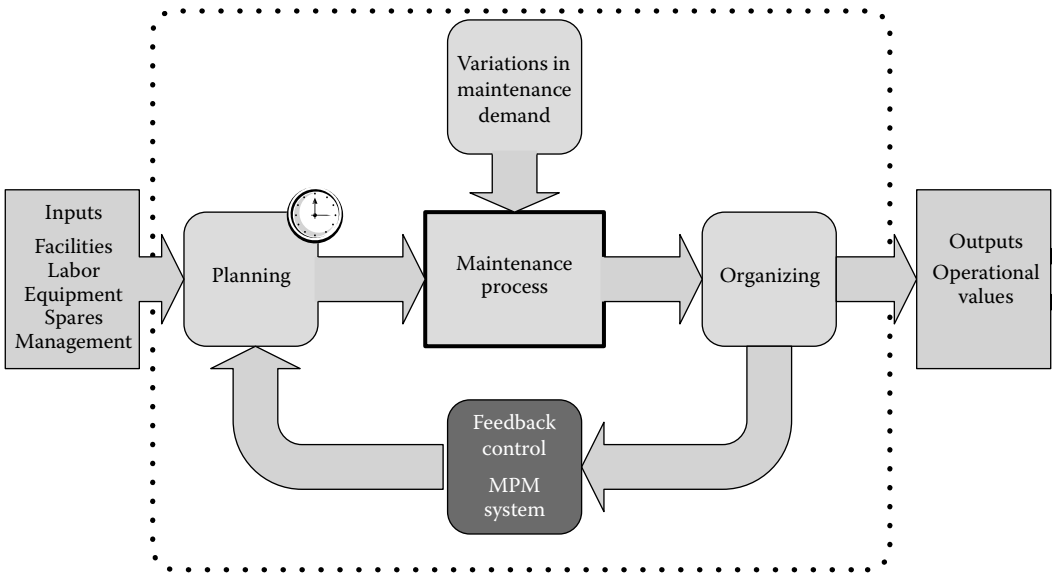

FIGURE 1.9
Input–output of the maintenance transformation. (Adapted from Duffua, S.O. et al., *Planning and Control of Maintenance Systems: Modeling and Analysis*, 1998.)

Auditing, as a general technique, can be divided into two categories. The first utilizes general audits based on a common assumed standard, designating what constitutes a "good system." This is a popular tool for consultants as it allows them to have a consistent standard of what a good maintenance system should be. Although this is normally in isolation from a deep understanding of the organization's business, it permits the insertion of important attributes about which they have good knowledge but whose importance varies, in fact, from one organization to another. This kind of audit is a thorough and comprehensive review of the various dimensions in the maintenance system, such as organization, personnel training, planning and scheduling, data collection and analysis, control mechanisms, measurements, reward systems, and so on. To get unbiased findings, the reviewer should have no direct responsibility or accountability for the performance of the system under review.

The audit is usually conducted by using a questionnaire designed to provide a profile of the maintenance system. Typically, the questionnaire is structured to address key areas in the system to be audited. Responses to these questionnaires may take one of these forms:

- Selecting either "yes" or "no"
- Choosing one or more of the available options
- Putting items on a Likert-type scale, for example, from 1 to 5, to indicate different degrees of agreement or lack thereof

Different weights may also be assigned to different questions to reflect their relative contributions to system performance.

Even though they may use sophisticated assessment schemes, the underlying theory of system audits is obscure. Dwight [83] suggests a procedure that relates the state of a system

element, such as "feedback from operations," to its contribution to the system's overall performance. The overall performance of the maintenance system can be determined by aggregating the contributions to the business success of the observed states of all system elements having an influence on relevant asset failures. In this procedure, failure attributes that affect business success have to be identified. The same requirements apply to the system elements having an influence on a failure attribute.

The more typical system audit tends to focus on the issue of conformity to a standard model, both in system design and execution. It is assumed that the standard can be universally applied to achieve superior performance. The maintenance system audit questionnaires by Westerchamp [369] and Wireman [374] are developed on the basis of this concept. This approach to system audits fails to recognize that different organizations operate in different environments. Products, technology, organizational culture, and the external environment are some key variables in an organization's operating environment, and they may be in a state of constant change. Superior performance can be achieved only if the internal states and processes of the organization fit perfectly into the specific operating environment. Sociotechnical systems (STS) analysis provides a methodology to design a system that will achieve this fit [325]. Thus, the basic assumption of a standard reference model implicit in the design of the typical audit questionnaire is problematic.

The second category of audit technique is initially concerned with the analysis of the technology and business constraints. This allows the determination of the relative importance, and required attributes, of the various elements of a system. The actual system attributes can then be analyzed against the ideal system and tempered by the requirements for excellence in the particular activities making up the system. This technique is pursued here. It tends to be qualitative in its methods as it seeks to quantify the judgments of people with knowledge about the maintenance system, the organization's requirements, and the possible system elements in order to measure performance. Although this implies that it falls short of an objective measure, the compromise is forced in order to accommodate the difficulty in a purely objective measure.

Maintenance system audits are necessary for developing an improvement action plan. According to Kaiser [148], De Groote [63], The Institute of Internal Auditors [327], Mann [198], and Duffuaa and Raauf [80], an audit helps management to achieve the following:

1. Ensure maintenance is carrying out its mission and meeting its objectives
2. Establish a good organizational structure
3. Manage and control resources effectively
4. Identify areas of problems and solve them
5. Improve maintenance performance
6. Increase the quality of the work
7. Automate information systems to increase effectiveness and productivity
8. Develop a culture of continuous improvement

The audit process is usually done on site and reviews key elements. It includes the following steps [383]: interviewing key people in the organization; conducting site inspections; reviewing process flows and mapping maintenance functions and control; reviewing relevant documentation; demonstrating system applications; attending key

meetings; obtaining answers to structured questionnaires; and validating plant, equipment, and maintenance performance.

The results of the interviews and the answers to the structured questionnaires are analyzed to formulate action plans for improvement.

Westerkamp [370] has developed an audit scheme that covers 14 factors contributing to maintenance productivity. In his paper, the author advocates automating the auditing process. The factors included in Westerkamp's audit are organization staffing and policy; management training; planner training; craft training; motivation; negotiation; management control; budget and cost; work order planning and scheduling; facilities, store, material, and tool control; preventive maintenance and equipment history; engineering; work measurement; and data processing. He suggests obtaining information using a set of questions about each factor.

Kaiser [148] has developed a maintenance management audit of key factors in the process of maintenance management. The basic components of Kaiser's audit include organization, workload identification, work planning, work accomplishment, and appraisal. Each of these components has six to eight factors. Using structured statements and weights, an overall score is obtained for the maintenance system. Improvements can be identified from the audit process.

Duffuaa and Raauf [80] conducted a study on continuous maintenance productivity improvement using a structured audit and proposed a structured audit approach to improve maintenance systems. The factors in Duffuaa and Raouf's audit are organization and staffing; labor productivity; management training; planner training; craft training; motivation; management and budget control; work order planning and scheduling; facilities; stores, material, and tool control; preventive maintenance and equipment history; engineering and condition monitoring; work measurement, incentives; and information systems. They propose using an analytic hierarchy process (AHP) to determine the factors' weight and compute a maintenance audit index. They also propose root cause analysis to develop an improvement action program.

Duffuaa and Ben-Daya [79] propose the use of statistical process control tools to improve maintenance quality, while Raouf and Ben-Daya [272] suggest a total maintenance management (TMM) framework. An important component of TMM is the structured audit.

De Groote [63] argues for the use of a maintenance performance evaluation approach based on a quality audit and on performance indicators of maintenance. The quality audit should be conducted in four stages: surveying the influencing parameters; analyzing collected data to make conclusions and recommendations; designing an improvement action plan; and justifying the proposed improvement plan based on cost–benefit.

The evaluation should include the following five major factors: production equipment; organization and management of maintenance; material resources; human resources; and work environment.

Price Water House Coopers [269] has developed a questionnaire to evaluate maintenance programs, with the following 10 factors on the questionnaire: maintenance strategy; organization/human resources; employee empowerment; maintenance tactics; reliability analysis; performance measures/benchmarking; information technology; planning and scheduling; material management; and maintenance process reengineering. The questionnaire includes several statements about each factor, with each statement given a score ranging from 0 to 4.

Al-Zaharani [9] reviewed various audit programs and surveyed managers and engineers in government and private organizations in Saudi Arabia to assess the factors affecting maintenance management auditing, with the aim of developing a suitable audit form for facilities maintenance. He proposes a form with six main components: organization and human resources; work identification and performance measures; work planning and scheduling; work accomplishment; information technology and appraisal; and material management. Each component has six to eight factors relevant to the performance of the maintenance system.

Five structured audit programs for maintenance systems are identified in the literature. These audits were developed by Westerkamp [370], Kaiser [148], Duffuaa and Raauf [80], and Al-Zaharani [9]. An audit program consists of key elements in the maintenance systems that are examined through a set of statements or questions. Each statement or question has a score and a weight. Then based on the audit, a total weighted score is compiled and compared to an ideal score. Based on these scores, an action plan for improvement is formulated. The process is repeated periodically to ensure continuous improvement.

In addition to the BSC technique, Tsang et al. [335] present a "systems audit" technique, based on STS analysis to predict future maintenance performance, and data envelopment analysis (DEA), a nonparametric quantitative approach to benchmarking the organization's maintenance performance compared to its competitors. By defining the performance indicators in terms of ratios rather than in absolute terms, De Groote [63] developed a system for determining maintenance performance, using the four-stage quality audit approach.

Many authors argue the necessity of obtaining both qualitative and quantitative results. Clarke [52] suggests an audit must contribute a maintenance radar (graphic of spider Bells-Manson type) in which all the economic and human aspects of maintenance are imagined. He also proposes that a product of the audit must be good operative and technical practices in maintenance. Tavares [321] makes use of the radar of maintenance in audits, like many authors, to represent the different areas of influence and dependency of the maintenance function. Many authors agree on generating these radars from massive surveys. In spite of their reliability, numeric data on the systems are not included in the radars; rather, there is a strong human factor [258].

More recently, Galar-Pascual et al. [101] have developed an audit in the latter category. This model proposes a mixture of qualitative aspects (from questionnaires) and different weights obtained by maintenance KPIs. The KPIs should be strongly correlated with the answers of the questionnaires. This model shows the relationship between trends in questionnaires and indicators that validate the correlations or highlight the divergences, merging qualitative measures with quantitative ones.

1.12 Benefits of a Performance Measurement System

Kutucuoglu et al. [180] take the advantages inherent in the QFD technique, such as ease of implementation, alignment of performance indicators with the corporate strategy, and the ability to hold both subjective and objective measures and use them to develop an effective performance measurement system for the maintenance function. Such an MPM system can incorporate all the key features necessary for effective maintenance

performance measurement, that is, a balanced view of a maintenance system, cross-functional structure, vertical alignment of performance indicators, and so on. Introducing performance indicators can

- Clarify strategic objectives
- Link maintenance department objectives to core business processes
- Focus actions on CSFs
- Keep track of trends in development
- Identify possible solutions to problems

Varied industrial sectors have benefited from the introduction of indicators in their maintenance departments [95]. In his work on the aluminum industry in England, Espinoza says that in an effort to gain a competitive advantage over its rivals, this industry is using a series of MPIs through which effectiveness can be monitored continuously (reliability, availability, and use of equipment). The purpose of effective maintenance, according to the author, is to vary the ratio between unplanned and planned activities. Espinoza says in this industry, an increase in the number of scheduled jobs is a sign that the maintenance strategy is effective. Other authors, like Racoceanu and Zerhouni [270], have developed specific scorecards, with sets of indicators to increase competitiveness in the machine tool sector.

Once indicators have been embedded in the organizational hierarchy, the benefits accruing to the organization, according to Wireman [375], include the proper development, evolution, and progression of the maintenance model. The author proposes a sequential implementation of steps to ensure the proper management of maintenance: (1) preventive maintenance, (2) inventory and procurement, (3) the work order system, (4) the CMMS system, (5) technical training and staff relationships, (6) staff involvement in operations, (7) predictive maintenance, (8) RCM, (9) TPM, (10) statistical optimization, and finally (11) continuous improvement. Wireman [375] considers each of these activities represents a section in the maintenance management process, as expressed in the pyramid of Figure 1.10. The figure illustrates Wireman's [375] suggestion that a preventive maintenance program should be implemented before moving to the next level of the pyramid. Before considering the application of RCM, predictive maintenance programs and the involvement of staff in the maintenance functions, appropriate work order systems, and well-managed maintenance resources are required. The involvement of operators and employees, in general, belongs in the stage of TPM programs. Finally, the use of optimization techniques will finish setting up the organizational structure necessary for continuous improvement.

It is a mistake to think the reorganization of a department is based on a particular technique, and it is advisable to ignore consultants and companies advocating a single technology as a solution to a problem. When a department is in a state of "stagnation" of ratios or indicators, we should be aware of the need for a drastic change in maintenance philosophy. Reengineering may be a possible solution, but we need to realize that while moving up in the maturity pyramid of maintenance evolution, the change to the next level may be complex. Zaldívar [382] shows that when employees and managers perform functions in a process-oriented environment, organizations can measure their performance and determine their pay based on the value they create. In organizations that have undergone a major renovation on the basis of reengineering, employee contribution and performance become the main bases for compensation and, in most cases, they are a success.

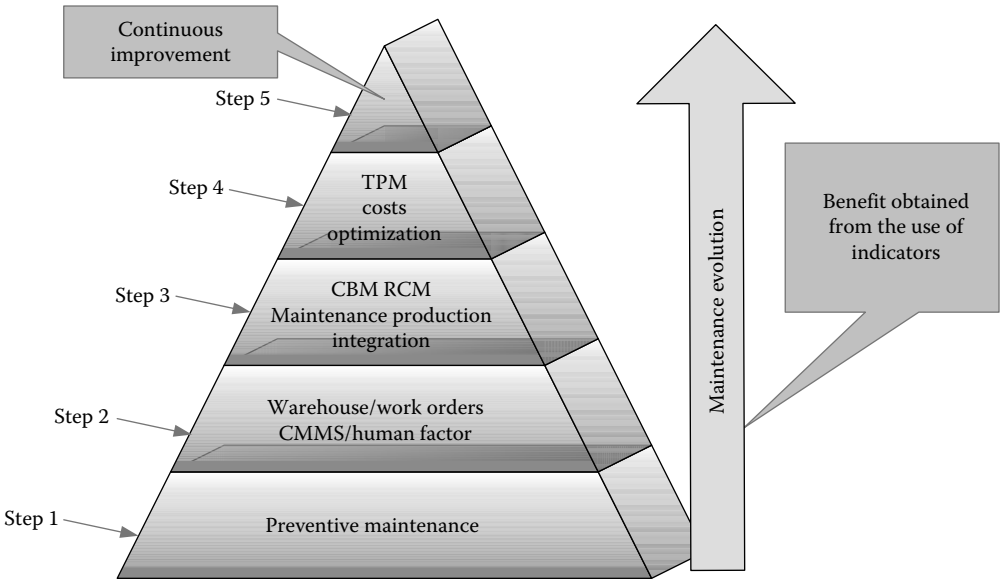

FIGURE 1.10
Construction of the maintenance management process by Wireman. (Adapted from Tsang, A. et al., *Int. J. Oper. Prod. Manag.*, 19(7), 691, 1999.)

Those concerned with quality guarantees and product reliability focus their decisions on the efficiency and quality of maintenance management. When the process of reengineering is applied in maintenance, and it affects other processes of the organization, not many people are needed to ensure quality and efficiency. Zaldívar [382] implies that with fewer managers, fewer administrative levels, and, consequently, a predominance of flat structures, stable performance, and a qualitative jump in each of the technical–economic indicators are achieved as never before, leading to a position closer to the top of the pyramid (Figure 1.10) with continuous improvement.

All this sequential development is achieved on the basis of appropriate indicators associated with each level, from the operations performed by each team, to the strategies of the organization at the top of the pyramid. The proper measurement of the state of maturity at each level will help to develop measurements at the next level. Unsystematic CBM implementations or isolated and uncoordinated strategies do not usually give good results, as stated by González [107]. A development in the reorganization of pyramidal maintenance is essential, and an organization cannot jump steps or ignore the proper order. We emphasize the analogy between the sequential development pyramid of comprehensive maintenance program and the proposed hierarchy of KPIs as noted by the authors reviewed here.

Schneidewind [291] analyzes the need for stability in a maintenance process to ensure product quality. For this purpose, he investigates the ability of a maintenance process to reach maturity after its implementation that is the process of climbing the pyramid mentioned before. The use of metrics in the maintenance process can predict reliability and risk and, therefore, serves to achieve the desired stability. Schneidewind [291] stresses the need for strengthening each layer of the organization, moving toward a maturity that allows the jump to the next level. The evolution of the maintenance process should not be precipitated or accelerated without achieving the necessary accomplishments associated with each level of the process.

1.13 e-Maintenance

Today's competitive manufacturing depends on the manufacturer's ability to provide customers with lean services and life cycle costs (LCCs) for sustainable values at all times. e-Maintenance is transforming the maintenance function to a service business to support customers anywhere and anytime, with the use of Internet, web-enabled wireless communication, and technology. e-Maintenance enables the companies with predictive intelligent/embedded sensors to monitor their assets through web-based wireless communication to prevent them from unexpected breakdown. Such systems can compare the performance of the product through a global network system to focus on degradation monitoring and prognostics.

These kinds of information will provide management with the support required to make business decisions [173]. The main problem with performance measurement for decision-making is the unavailability of relevant data and information. The recent application of information and communication technology (ICT) and other emerging technologies facilitates easy and effective collection of data and information [260]. The two most important applications of the measurement are identifying opportunities to improve existing equipment and plants before new investments are made and promoting improved supplier performance. MPM has become part of the decision-making process for the mining industry, with condition monitoring playing an important role.

e-Maintenance is a maintenance management concept, whereby plants and machinery are monitored and managed through computer software, involving intelligent sensors, databases, wireless communication, Internet, online GUI, and so on. Levrat et al. [187], Muller et al. [230], Thun [330], Campos [42], Cao et al. [43], Jantunen et al. [136], Jeong et al. [138], and Jun et al. [142] have all presented studies investigating the monitoring of manufacturing performance using wireless communication technologies and noting the impact on maintenance performance. Today, with the availability of unique e-maintenance solutions, the production and process industry can benefit from server-based software applications, the latest embedded Internet interface devices, and state-of-the-art data security. e-Maintenance creates a virtual knowledge center with users, technicians/experts, and manufacturers, specializing in operation and maintenance of the process industry, for example, mining, among others. e-Maintenance provides a solution for those in the process industry who want to reduce the overall costs, save resources through OEE, and make maximum returns on maintenance investment (ROMI).

Some existing e-maintenance solutions provide server-based software, equipment-embedded Internet interface devices (health management card). These solutions provide 24/7 real-time monitoring, controls, and alerts at the operating centre. They convert data into information, available to all concerned with decision-making and predicting the performance condition of the plant and machinery on a real-time basis. This enables the system to match with e-business and supply chain requirements.

1.14 Summary and Discussion

Many attempts have been made to deal with issues related to the development and implementation of an effective MPM system to create value for organizations. As the literature shows, authors have considered how to align the organizational strategy to the strategies

of the maintenance function, how to link the maintenance performance measures to the different hierarchies of the organization and establish effective communication between them, and how to translate the MPIs at the operational level to the corporate level, to create value for the whole organization and its customer [263]. While most researchers have developed frameworks based on financial (tangible) measures to provide answers, others have used nonfinancial (nontangible) measures to formulate their frameworks.

In the beginning of the previous section, we discussed some key features required for an effective and efficient MPM system, as proposed by Kutucuoglu et al. [180]. Similarly, Alsyouf [8] has noted the characteristics of a holistic performance measurement system:

- It is able to assess the contribution of the maintenance function to the strategic business objectives.
- It can identify the weaknesses and strengths of the implemented maintenance strategy.
- It can establish a sound foundation for a comprehensive maintenance improvement strategy using qualitative and quantitative data.
- It can reevaluate the criteria employed in benchmarking.

An effective MPM system should focus on measuring total maintenance effectiveness, that is, internal and external effectiveness [261].

When we judge previous frameworks using these criteria, we discover that frameworks focusing on measuring maintenance performance using only financial impacts may help to improve the internal processes of the maintenance function but will fail to account for the impact of maintenance strategies on functions external to the maintenance function, such as production, logistics, customers, employees, and organizational goals.

Similarly, other frameworks, like the value-based framework using BSC proposed by Liyanage and Kumar [190] and frameworks using QFD, may account for financial and nonfinancial impacts of maintenance strategies but fail to ensure improved maintenance performance at a tactical and strategic level and do not take into account the impact of maintenance strategies on the extended value chain, that is, suppliers, and so on.

In contrast, the framework using the extended BSC is more complete, in the sense that it provides both qualitative and quantitative impacts of maintenance strategies, offers control over different hierarchies of the organization, and strives for both internal and external effectiveness. The multicriteria multihierarchical framework for MPM is also quite effective and efficient for MPM as it incorporates the total maintenance effectiveness concept, as well as the characterization described by Alsyouf [8] and Kutucuoglu et al. [180]. Finally, it shows the causal relationship between performance indicators at different organizational levels, and the PIs that are based on both financial and nonfinancial aspects.

Based on the value propositions of the frameworks identified in the literature review, we consider the extended BSC framework and the multicriteria multihierarchical framework effective tools for evaluating and measuring the performance of CBM and predictive maintenance, while the BETUS tool can be considered as an efficient tool for e-maintenance and remote maintenance performance evaluation.

Evaluating the performance of maintenance strategies using effective financial and nonfinancial measures has been a major concern in maintenance operations literature. Different techniques and frameworks have been developed to measure the performance of maintenance strategies. However, few studies have applied these frameworks in a real-world environment, for example, a company, to validate them in a more practical setting.

In this chapter, we have identified various techniques for formulating performance indicators to measure maintenance performance. However, as discussed previously, MPM techniques are general techniques that help to determine the right set of performance indicators and are independent of the maintenance strategy. Therefore, we cannot determine the optimal technique for evaluating CBM, remote maintenance, RCM, or e-maintenance.

We have also identified different frameworks and models showing how MPM systems should be implemented and how they can create value, both financial and nonfinancial, for organizations. The review of the literature showed what value is created when different frameworks are used. The case studies discussed in the literature demonstrate what value is created and how it is created when MPM frameworks are used in organizations with condition-based, vibration-based maintenance, and reliability-centered maintenance. However, the review failed to identify how and what value is created when these frameworks are used in an organization relying on e-maintenance or remote maintenance.

As the literature review suggests, no attempt has been made to design a framework or model to consider two different maintenance strategies. Nor has any study compared the effectiveness and efficiency of different strategies. Finally, no one has tried to link MPM frameworks with a particular maintenance strategy, like CBM, remote maintenance, and predictive maintenance.

Based on these gaps in existing knowledge, the following represent potential future research directions:

- Find an optimal MPM framework for a particular maintenance strategy like CBM, remote maintenance, and e-maintenance.
- Compare the effectiveness of different maintenance strategies (like CBM, remote maintenance, and e-maintenance), using a particular framework like the one based on an extended BSC [8], or a multicriteria multihierarchical framework [262].
- Combine the multihierarchical multicriteria framework with the extended BSC framework to consolidate the features of multiple perspectives and multiple criteria and multiple hierarchies.
- Apply the multicriteria multihierarchical framework to evaluate the effectiveness of e-maintenance.

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2

Introducing Metrics in Maintenance and Associated Problems

2.1 Introduction

2.1.1 Performance-Based Industry: A New Era

Interest in the performance of manufacturing companies has grown at an increasingly rapid pace, especially in the field of asset management and control. Asset managers are facing increasing pressure to reduce costs while increasing productivity. In some companies, the situation is complicated by the incorporation of more flexible structures. These structures are flat rather than hierarchical, with increasing autonomy of the work "team." The maintenance manager is no longer solely responsible for controlling costs and equipment availability; rather, responsibility is shared.

Trends such as "self-managed teams" and "teamwork" have changed the concept of "property and ownership" at the plant level. Managers are moving into the role of trustees, allowing workers higher autonomy in the day-to-day work.

To meet the demand for autonomy and entrench the concept, we need a scorecard that shows clearly what is happening throughout the organization. Its construction in asset management uses three main approaches as described by Jones and Rosenthal [141]:

1. *Consultations and audits using surveys*: These are usually presented as an official report and are generated specifically for use by the management team. The auditors often perform this type of analysis with the use of questionnaires that have been further refined by many similar audits.
2. *Benchmarking* to quantify and compare data with other plants: This type of analysis is usually more specific than the external audit and can be carried out in-house or between several plants from the same manufacturing sector or business group. A study by Dunn [82] shows that 42% of companies have formal processes for benchmarking. The methodology consists of obtaining a "picture" or current state of "as it is now" and compare "like for like" those items equivalent of the plants of comparison, to the processes or services in production to highlight strengths or weaknesses.
3. *Internal measures or measures "in house"* (cost, availability, etc.): This is a set of performance indicators or measures intended to reflect the plant as a set of processes with inputs and outputs of product resources. It is present in all levels in an organization; its quality lies in the accuracy of the data provided by the relevant departments on indicators related to their specific activity.

Each approach is useful in different scenarios and situations. The external audit presents an impartial snapshot of a point in time to an auditor with particular expertise in many other companies. Unfortunately, these reports tend to be expensive and are drawn up specifically for the senior management of the company, that is, documentation for the exclusive use of higher levels and not the subordinates, much less those within walking distance of machines. Such a document is very useful to assess the overall picture of the maintenance department at a particular time; in fact, it is often performed when large structural changes are mandatory.

Benchmarking is very powerful as a tool of comparison between similar companies. It can be used to analyze any level of detail and can be carried out internally in companies with several plants or locations of equal productive nature, or as a "like for like" comparison of companies. An example of benchmarking in the maintenance field is a joint venture between Toyota and General Motors plants in California, where there was transfer of knowledge and good practices in the field of total productive maintenance (TPM); see Keller [164]. The idea behind the exercise was to take methods that, in the opinion of the auditors, are considered "good practices" and adopt them in the appropriate zones, similar to those that have had success in the company's origin. The key point when using this technique is the expression "like for like." To extrapolate measures and methodologies, we must be sure that the comparison areas and assets are similar across companies. Some functionally comparable measures may be useful in one area and useless in another.

The two approaches outlined earlier are valuable tools to evaluate strengths or weaknesses in the strategy of the organization, that is, the maintenance policy function, but are not suitable to establish monitoring or the frequency of reporting data. The third approach incorporates the establishment and maintenance of a complete set of measures to display the current position and status of the organization and to establish trends.

There are hundreds of performance measures and indices of almost all sectors of all industries, as explained in Wireman [375] or Woodhouse [379]. Many authors propose scorecards to promote the dynamic control of organizations, in particular, the maintenance departments. Unfortunately, much of this information is overwhelming and often contradictory.

2.1.2 The Need to Control the Maintenance Department

For technical and economic reasons, it is not possible to have a "maintenance free" plant with zero risk of failure. For example, computers requiring maintenance tend to have a shorter life expectancy than the plant to which they belong and necessarily require replacement or repair on several occasions during the entire useful life of the equipment to which they are attached. A maintenance program for complex equipment can comprise thousands of decisions to repair or replace it. Therefore, to ensure the reliability and availability of the plant, a maintenance organization is necessary. This organization will be made up of the required resources (mainly workers, tools, and spare parts), controlled by an administrator or a manager supporting the direction of the organization.

Until recently, it was common to find large firms with more resources than necessary for the maintenance of their equipment. At the other end of the spectrum, many companies had equipment barely able to cope with the workload because of the scarcity of resources. However, neither scenario says anything about the shortcomings of the company's top management, for example, if they did not understand what was happening in their maintenance department. On the one hand, some chiefs of maintenance accomplished everything; the money was well spent in maintenance resources. On the other

hand, some companies faced revenue losses caused by a manager who did not know the importance of this function within the company. These scenarios have been very common in the industry of processes such as automotive, chemicals, and food.

Fortunately, the situation in modern organizations is changing for the better. The benefits of an effective strategy and an efficient maintenance organization are increasingly accepted and are no longer classified as "necessary evils." The leaders of equipment management are increasingly willing to invest in costly maintenance programs, especially when the benefits demonstrably compensate for the costs.

This chapter defines in a realistic way the package of measures or indicators that can be put in place to provide managers the evidence they need. It uses models and concepts of BCM or "maintenance focused on business" as described by Kelly [168] as well as the methodologies of TPM and "reliability-centered maintenance (RCM)."

2.1.3 Description of a Method for Measuring Performance

First, we need to know the purpose of the maintenance department and the main reasons for wanting its control and measurement. We must find a method to guide this process from start to finish. Throughout this chapter, we propose appropriate models and examples.

Function: Although the function of a maintenance department is relatively generic, that is, the control of the reliability and availability of the plant, this is not always the case. The assertion is well suited to a manufacturing process but does not include, for example, a service company or aerospace equipment. Therefore, the first step in strategy formulation is the elucidation of the "function" of the maintenance department within the company.

Objectives: Using high-level information, that is, the business objectives and trade figures, the management team must define a clear set of maintenance objectives. These are based on the business needs of the maintenance organization and presented in a hierarchical manner to make it understandable to each level of the organization. By establishing what the company expects of management, we can build a strategy to comply with these expectations.

Action: The maintenance strategy will generate the maintenance workload; this will generate the resource requirements and dictate the necessary management structure. Resource efficiency and the effectiveness of the strategy, in turn, will affect the performance of the company (e.g., productivity, security, and environmental control). It follows, therefore, that the implementation of the proper measures will ensure that maintenance objectives are met. To ensure this outcome, companies need to find and use a maintenance metric.

A complex interplay of departments may appear in this process, affecting the whole organization and its systems. Therefore, measurements and "sensors" should be strategically placed to highlight the major relationships affecting maintenance objectives.

Unfortunately, the objectives are rarely carried out in a reasonable manner. As a result, the establishment and communication of clear objectives and targets is crucial to organizations with a strategy based on continuous improvement.

Before describing the complexity of a maintenance organization and the problems related to training and startup, we should consider some problems associated with the measurement of the performance of this department.

2.1.4 Main Problems of Measuring Performance

Woodhouse [379] cites six main problems associated with the development and maintenance of a comprehensive set of performance measures. These should be dealt with separately if a company intends to implement a robust measuring system.

2.1.4.1 Too Much Data and a Lack of Information

The implementation of maintenance software such as CMMS to manage work orders and CBMs as diagnostic tools for vibrations can create serious obstacles to the measurement of performance. They are costly and also inaccessible to the majority of maintenance operators because of their technical complexity. Large amounts of data can be stored in these systems and retrieved with very little effort if we know what to look for and where to look. Many times the problem is neither the acquisition nor the processing of data but the understanding and removal of the necessary and appropriate data.

2.1.4.2 Number of Performance Indicators and Their Influence Area

Woodhouse argues it is inefficient to use large sets of performance indicators for maintenance. The author suggests that the cognitive capacity of humans restricts them to coping with four to eight indicators per item. This implies that it would not be reasonable to exceed a maximum of six measures per level in the hierarchical structure. It is much more important to link all business areas to the maintenance function through the defined metric. The big question is, which indices are best suited to the company profile, ones that are both generic to any service and specific to the business area concerned?

2.1.4.3 Conflicts between Objectives and Measures

> An agenda for efficient maintenance and cash can only be developed by the maintainers and users of the assets working together [226].

John Moubray [226], one of the so-called fathers of TPM, says the establishment of any objective and metric to evaluate maintenance must be agreed upon and supported by the various areas of the company having relations with the maintenance function, especially those providing quality service to customers, that is, the production function.

All departments must be aligned in the same direction. What improves the results of one department may be detrimental to another. If this is the case, the overall impact of individual actions can be detrimental to the overall situation. A commitment to common ideals across departments and the search for clear, properly aligned objectives is vital to the success of a modern company: "one team, one goal."

2.1.4.4 Time That Elapses between Actions and Follow-Up Monitoring for Results

There are two key points associated with this problem. In the first place, by monitoring a process, we discover what is going on at the time. Information is collected for a situation happening in a given time (or just after). It is only possible to make appropriate management decisions if the frequency of monitoring is high enough to detect changes in the process.

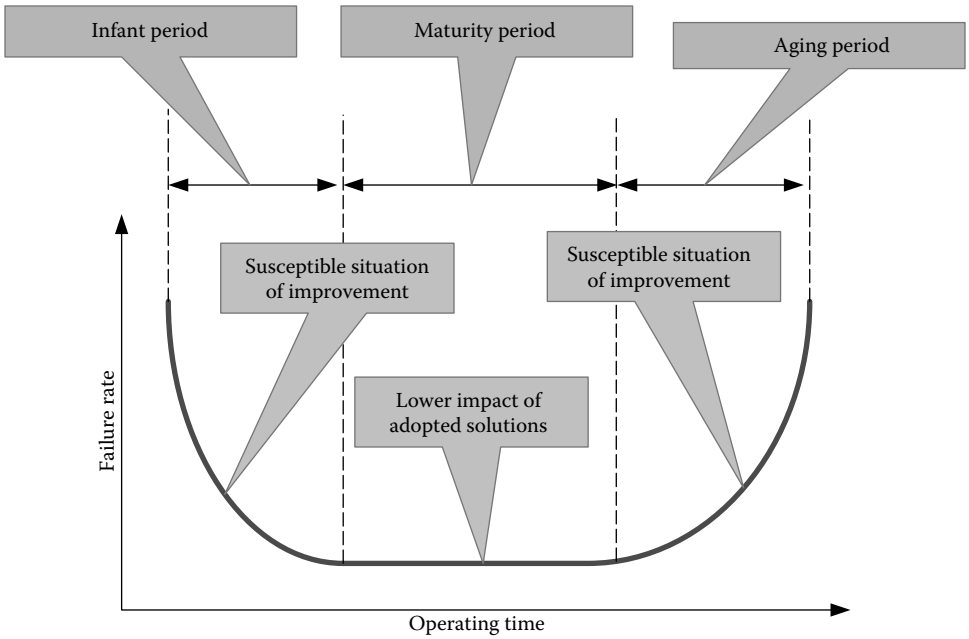

FIGURE 2.1
Bathtub curve.

In the second place, the results of many actions performed as part of a maintenance strategy do not manifest themselves until a later time. In strategies such as TPM, 6 weeks may lapse after the beginning of the plan before there are visible results. This delay must be carefully considered in measurement. It is possible that improvements cannot be fully assessed until many years later, especially in industries such as aeronautics or energy.

As shown in Figure 2.1, when the equipment is in the lower part of the bathtub curve, that is, in early stages of maturity, there is a low rate of faults, making it difficult to appreciate the effect of any changes; overall, there may be huge costs with low impact.

2.1.4.5 Lack of Correlation between Observable Symptoms and the Underlying Risks

The risks involved in a specific job are seldom considered against the actual number of accidents. Studies should be proactive to accumulate sufficient data to prevent and predict points whose measures are associated with insecurities for the process or the individuals working in those processes. At this point, it should be emphasized that the safety of the operators must be ensured during measurement, especially if safety barriers are shut down or physical measures such as vibration and resistance, are involved.

Factors such as the condition of the equipment, the quality of the work done by that equipment, the impression of the client, and the public image of the company can help in the search for information. However, such factors may be difficult to measure, and we may need to search for information in other departments if it cannot be generated by maintenance.

2.1.4.6 Cost and Motivation of Data Collectors

It is often difficult to convince the workshop staff that the collection of good quality data is extremely important. This is even more delicate if a "culture of guilt" has been created

within a company. It is unlikely that service engineers will provide data if they know it will be used against them or their colleagues at a later date. In situations like this, all the returned data are likely to be inadequate or distorted, leaving the true cause of the problem hidden.

The high cost of some forms of data acquisition and the benefits of their employment should also be kept in mind. For example, it is ridiculous to acquire expensive systems to control and monitor the use of lighting, electrical consumption, telephone, etc. in small businesses, when it is most effective and economical to simply set up a regime of good practices.

2.1.5 Responsibility for Plant Performance

The three main factors contributing to lower production and the poor state of a machine are

1. Improper maintenance
2. Poor operation
3. Bad design

This list is not exhaustive, but it suggests maintenance management is not solely responsible for plant performance. All departments must work together to maximize productivity.

2.2 Maintenance Strategy

2.2.1 Introduction

The main tools for decision-making in maintenance, as previously discussed, include RCM, TPM, and BCM methodologies. Figure 2.2 shows the latter process and is what Kelly [168] calls the "strategic thinking process." BCM is based on the establishment of correct principles of administrative management; it provides an appropriate framework to identify, classify, and then audit the elements of any system of maintenance management. Kelly [168] extends this methodology by introducing ideas from other approaches such as RCM and TPM to ensure a global vision.

Anyone who has had experience in the management of a maintenance department knows it is dynamic in nature and interacts with many other departments (production, quality, engineering, etc.). Without a structured approach to analyze these systems within the organization, the task of monitoring is nearly impossible. The companies demonstrating excellence in maintenance management have likely invested resources in methodologies such as TPM, RCM, and BCM. These methodologies can demonstrate the relationships among the departments or systems of an enterprise, in particular, the interplay of maintenance with the rest of the organization.

2.2.2 Maintenance Strategy Formulation

The remainder of this section describes the factors that must be taken into account in the design or improvement of a modern maintenance department. It will explain the decisions

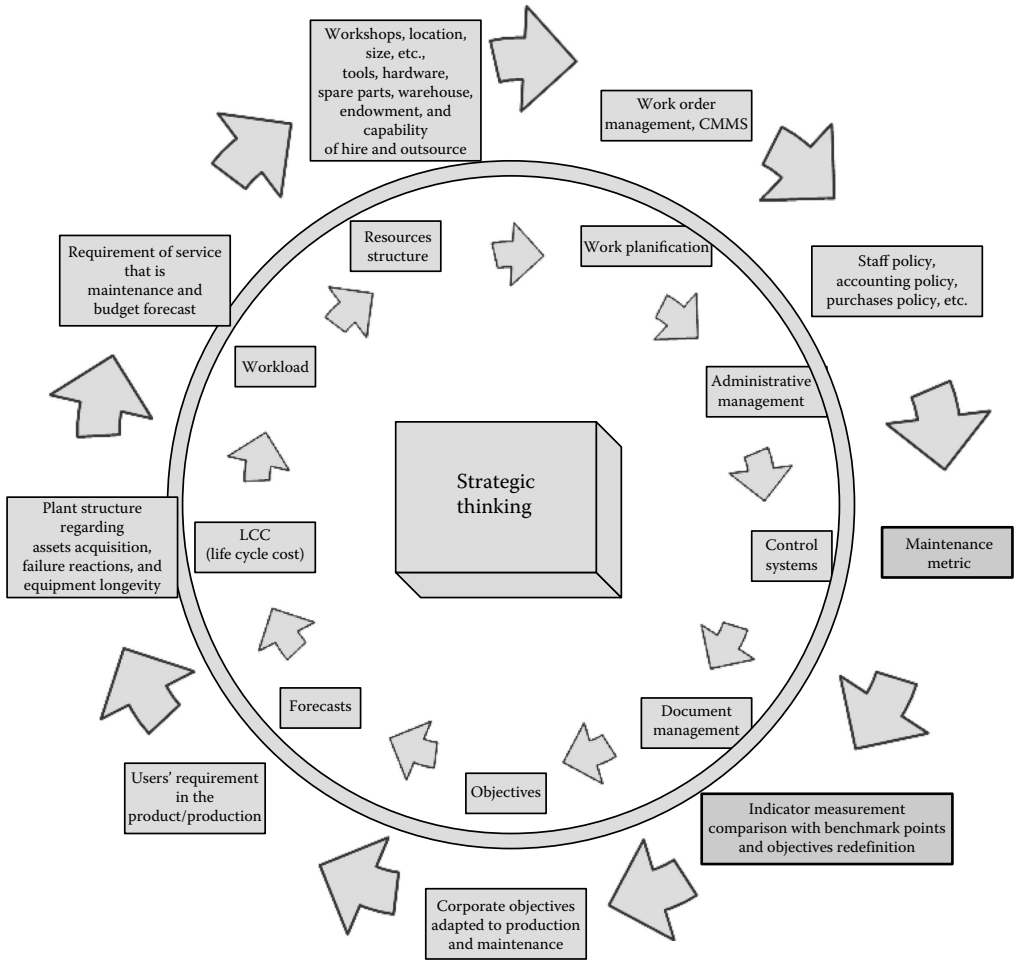

FIGURE 2.2
BCM methodology.

required to formulate an efficient organization with minimum wastage and an effective maintenance strategy. Willmott and McCarthy [372] explain the elimination of waste is one of the first actions, using indicators in the maintenance field. In their search to eliminate waste, the authors speak of KPIs for maintenance; these KPIs are specifically adapted for TPM to study its effectiveness and efficiency (Figure 2.3).

2.2.2.1 Function

As noted before, the first step in the creation of a maintenance department is to define its role within the company. Moubray [226] suggests it is composed of five areas:

1. Preserving the physical assets' functions throughout their lifetime
2. Satisfying and adequately responding to the needs of owners, users, and society as a whole
3. Selecting and applying the most cost-effective techniques

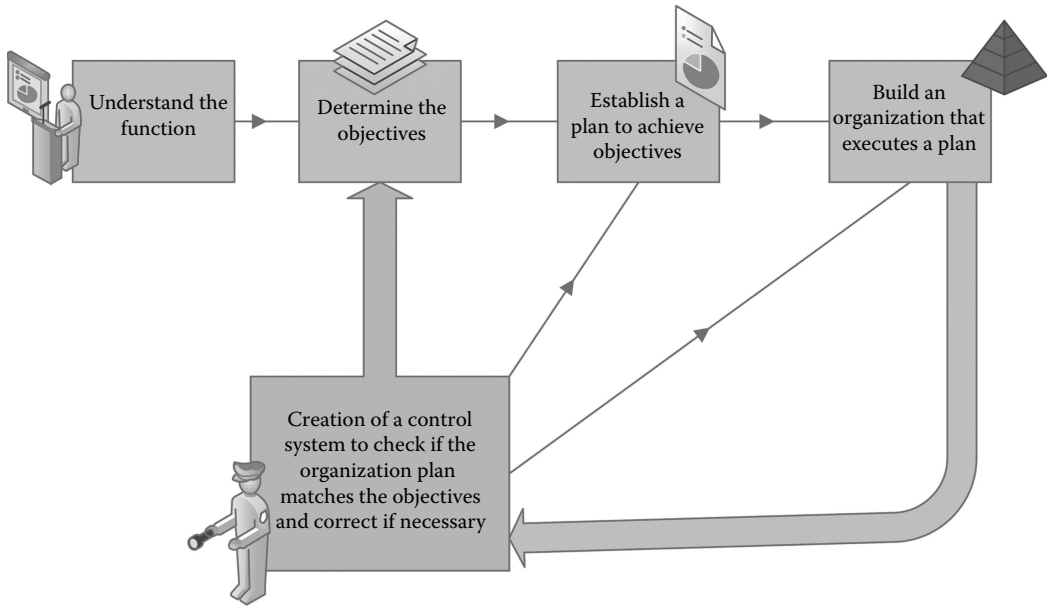

FIGURE 2.3
Basic steps of a management process.

4. Conducting fault management
5. Actively supporting all the people involved with the productive assets

Obviously, the importance of each point can vary from one plant to another. For example, the maintenance function in industry processes might be "to ensure and monitor the availability and quality of the finished product at a minimal cost."

However, some functions of the department can be more dangerous, making safety a specific concern. In such cases, the role of maintenance may be "to ensure the reliability and safety of the plant at a reasonable cost."

2.2.2.2 Objectives

The general objectives of the company can be converted into the overall objectives of the maintenance department, controlled by the direction of the department. This process should be supported using such information as the figures for sales, marketing, and any other key requirement of the plant (e.g., the value of the capital and the longevity of the equipment). The setting of goals will be discussed later since this is a key element in any methodology of maintenance. However, it is important to understand at this point that these objectives should be directly related to the corporate objectives and must be clearly interpreted and understood at all levels. The systematic establishment of goals and targets hierarchically adapted to each of the assets and persons involved will generate a clear image of what is required of the department and its staff.

2.2.2.3 Strategy

When the operational strategy of the plant has been established, the maintenance department can create plans and schedules associated with each element active in the system.

The main task of these plans is to determine the nature and intensity of the preventive work as this will directly affect the amount of corrective work. There are numerous techniques available for this type of analysis; selection of the proper technique depends on many factors, for example, the type of industry in question and the level of detail required.

- BCM incorporates a relatively simple and pragmatic technique: "top down bottom up" (TDBU). As the name suggests, TDBU focuses on understanding the needs of users through a study from top to bottom/bottom to top. This simple analysis aims to identify all the equipment requiring maintenance activity and determine a strategy for each. However, it does not provide the same level of analysis of faults as RCM as the latter method also classifies and prioritizes actions.
- RCM studies each piece of equipment to respond to seven basic questions, the first of which aims to establish how a fault affects the company [229]. It analyzes the failure mode and its effects, commonly called failure mode effects analysis (FMEA). This systematic approach does not have the same objectives as BCM; rather, it seeks to identify the more critical failure modes of the equipment with the ultimate goal of improving reliability, sometimes losing the business perspective in the process.

Both TDBU and RCM provide appropriate methods for evaluating the best way to preserve the equipment and may be combined if necessary. Whatever method is chosen, the result will culminate in a maintenance plan for each asset and the definition of the workload and the necessary resources to ensure it meets the needs of users.

These plans should be introduced into an overall program (in a manual or through a CMMS), which must be negotiated and agreed upon with the production function. Historically, this has been done manually, requiring much labor to control updates. The situation has greatly improved with the introduction of programs of CMMS maintenance management. Even so, an enormous number of work hours are required to update and retrieve information in these computer systems.

At a very basic level, this program must contain information on the proper way to maintain a computer. On a more global level, it must consider all aspects affecting the relationship between the plant and the equipment, for example, patterns of change in production, redundancies in the plant, and windows of opportunity. Compiling this information is almost impossible without the help of senior management as well as any department having contact with the plant.

2.2.2.4 Organization

The maintenance program will affect the level and nature of the workload generated (preventive and corrective maintenance and modifications). This, in conjunction with factors such as plant design, will have a considerable impact on the design of the maintenance organization. The organization depends on three key areas of decision-making, namely, the structure of the available resources (humans and assets), the administrative structure, and the necessary control systems.

The first element is the structure of resources. This includes the geographical location of the labor, parts, and tools, along with information on the equipment, its function, composition, size, and logistics. The second element, the administrative structure, refers to the training and configuration of the decision-making. It can be considered as a hierarchy of

work rules, classified according to the authority and responsibility to decide what, when, and how the maintenance work should be carried out.

There are many theories of how to design a maintenance organization, ranging from strongly hierarchical structures to recent proposals of autonomous teams. An important contribution is the focus of TPM on self-maintenance. TPM uses seven steps that allow operators to take control of maintenance tasks; see Willmott and McCarthy [372]. Like all methodologies, it has both advantages and disadvantages.

- *Advantages*: Removal of departmental barriers and introduction of flexibility into the labor force
- *Disadvantages*: Diluted levels of qualification and expertise for the sake of versatility

2.2.2.5 Control Systems

The third element in the design of a maintenance organization is the formulation of maintenance control systems, or "work system planning." This defines the way the work is planned, scheduled, assigned, and controlled.

The main function of a control system is to ensure the maintenance organization meets its objectives by noting the degree of fulfillment of these objectives. When goals are not being achieved, the system should be able to assist management in the preparation of a plan to improve the situation. Kelly [167] suggests three ways to achieve this:

1. *Controlling the productivity of maintenance*: Ensures budgeted levels of maintenance are met and the required plant productivity is achieved
2. *Monitoring the effectiveness of maintenance*: Ensures expectations of long-term and short-term reliability are achieved, that is, prediction of life is effective
3. *Controlling the organizational efficiency of maintenance*: Controls efficiency in the use of manpower, materials, and tools

The first point (productivity) is often considered the culmination of the other two points as an effective strategy and efficiency will lead inevitably to productivity. This is not always true, however, because to achieve peak production, productivity goals may be met at the expense of a reduction in the life of the assets because of poor repairs or the absence of preventive maintenance; in addition, maintenance costs may be high. This issue will be addressed later in the chapter when we consider the costs of linking effectiveness and efficiency in maintenance.

The fundamental requirement in the design of a system of control is ensuring savings are greater than the cost of implementing and maintaining the system.

The maintenance organization should be considered as being synergistic, that is, a body that is much more than just the sum of its parts. This complex concept involves understanding that maintenance has a vital function within the organization.

2.2.2.6 Papers

The last element of the methodology described in Figure 2.2 is the documentation system. This is the collection, storage, analysis, and presentation of information (schedules, manuals, charts, reports, etc.) necessary to facilitate the operation of all the elements of the maintenance department. Document management, either manual or informatics, plays an important role in the measurement of results as it is the nerve center of the control system.

2.3 Adjustment of Perceptions of Maintenance Objectives and Associated Performance Measures

2.3.1 Common Perceptions of Objectives

Although the main objective of the chapter is directed at the measurement of maintenance performance, the first stage of this process is to identify appropriate measures. This is accomplished by establishing goals.

Industry and academics are unanimous in their belief that objectives are vital for organizations today. They agree all maintenance objectives must be directly related to corporate objectives; further, these objectives should be understandable and credible. Even with this common understanding, however, it is difficult to find a company that excels in setting targets for maintenance.

2.3.2 Classification of Maintenance Goals

There are two main types of maintenance objectives: effectiveness of maintenance and organizational efficiency. These are discussed in more detail later, but the following subsection provides a basic description.

The effectiveness of maintenance refers to the manner in which the plant meets the users' requirements, that is, the proper selection of a strategy; organizational efficiency refers to the optimization of resources to comply with the strategy. The way both fit into a corporate structure is shown in Figure 2.4.

Many companies use these concepts. For example, the automotive sector uses the concept of the effectiveness of services and resources management; see the Rover Group [284].

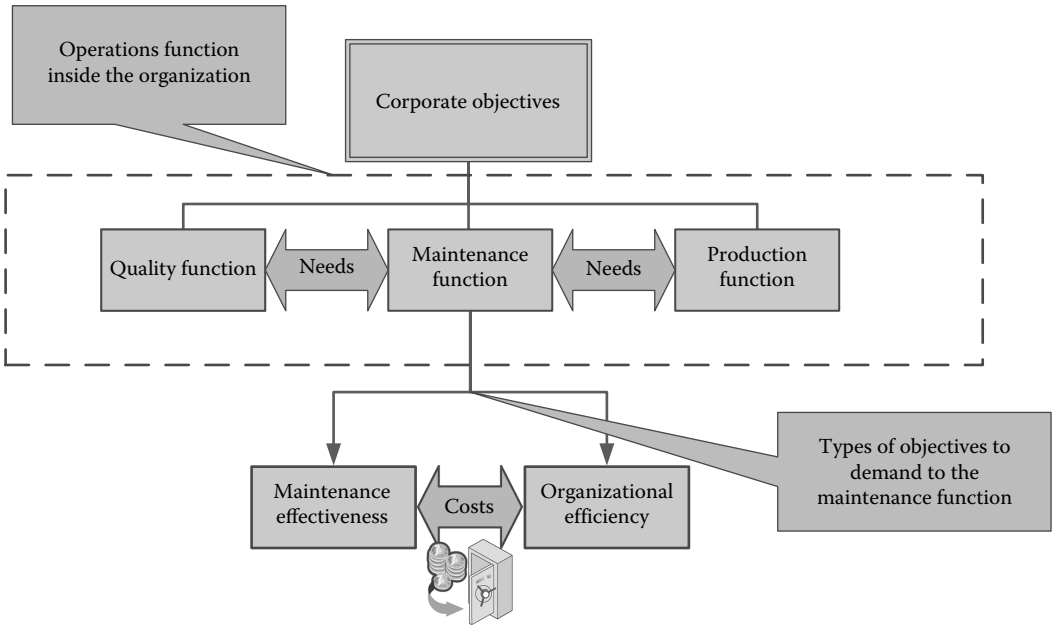

FIGURE 2.4
Structure of general objectives.

Their strategic and action plans, as well as the documents derived from these plans, often refer to these two types of objectives.

Although we begin by discussing the establishment of maintenance objectives and measures of effectiveness before turning to the efficiency of the organization, in reality, the concepts are closely intertwined. Understanding this relationship is important, especially in studies of maintenance costs.

2.3.3 Maintenance Effectiveness: Setting Objectives

2.3.3.1 Users' Needs

We have already indicated the importance of understanding the role of the maintenance department in the company. This could be, for example,

> to ensure and monitor the availability of production equipment and the quality of the finished product at a minimal cost.

Most of the time, we must apply a maintenance strategy to ensure requirements are met. The function of a maintenance strategy is generally to meet the needs of users, that is, the factors of the plant production, safety levels, longevity of the equipment, quality, waste, energy consumption, etc., at a minimum cost. The importance each user attaches to the aforementioned requirements varies from industry to industry and from user to user. For example, in the chemical industry, security will be the *key factor*. Some of these requirements or user needs are

1. *Critical information in relation to the method of operation*: Hours, shifts, staff cuts, vacations, levels of availability, etc.
2. *Quality of products and production*: Internal and external rates of rejection, units produced per hour, minimum and maximum speed, etc.
3. *Condition of the plant*: Longevity of equipment, appearance, status, etc.
4. *Safety standards*: Number of accidents, legal regulations, etc.
5. *Costs*: Budgets, etc.

A generic list of industry needs would be impossible to generate. A company's needs are as unique as the company itself.

2.3.3.2 Business Needs

This information must be transmitted downward to ensure each employee understands the company's needs. For this to take place, the maintenance department should establish and communicate a comprehensive set of hierarchical objectives. Figure 2.4 proposes a top-down approach, as mentioned earlier. Using the five points, the overall objective of a maintenance department could be

> to ensure the operation of the plant according to the established model, keeping the quality of the products and the production within acceptable thresholds and complying with the rules of security, while maintaining the lowest possible cost of resources.

As it stands, this statement is inadequate because it does not indicate the "operational pattern" or how it affects every part of the organization.

More specific objectives for a production facility could be

- Greater availability: For example, 95% per item (world-class measure)
- Number of items produced per hour
- Minimum number of rejections by batch
- Maximum life of the plant
- No accidents
- Maximum budget

Once the objectives have been defined for each area, we must decide if the next level in the hierarchy requires subgoals or objectives applied at that level. It is also useful to highlight where particular emphasis should be placed. Clearly, defining objectives for each unit in a plant with large numbers of human and material resources is a complex task.

2.3.3.3 Key Factors in the Establishment of Objectives

There are two important points to remember when setting objectives:

1. *Commitment of senior management*: Top-level objectives have to be set by the management team and should describe exactly what the company requires from each department to be more competitive in the market. Once this vision is sufficiently clear, the task of defining partial departmental objectives aimed at achieving business objective must begin. This process is driven from the top down. The directors of the departments must not get side-tracked; senior management must ensure that the definition of objectives is carried out in a coherent and understandable manner.
2. *Interdepartmental communication*: The objectives must be formulated based on the input of information from all departments that can affect or are affected by the operation of the plant. A full set of statements must meet the needs of all. For example, the organization of production (the user) is in the best position to set performance targets, while the quality team may suggest a reasonable rejection rate. The maintenance department has the responsibility of assessing the best way to achieve these goals or negotiating relevant amendments.

2.3.4 Measuring the Effectiveness of the Maintenance Strategy

A set of robust measures will enable an organization to monitor its performance either in pursuit of its own objectives or in comparison to a similar organization. Any department may be analyzed in depth to make management decisions or make changes to the current policy. A manager of productive assets must have a clear understanding of what is actually happening; therefore, the measures should be established to provide a realistic vision and a faithful reflection of the plant. Improvement should focus on key areas crucial to the business, not on activities in which the benefit obtained from improvement is reduced.

As discussed, there are two main types of objectives, that is, maintenance effectiveness and organizational efficiency. Therefore, it makes sense that the measures implemented should be classified according to these two categories to ensure their alignment with the objectives.

Maintenance actions relating to effectiveness are easier to measure and tend to be more directly related to production. Key issues such as levels of inactivity, accident rates, and poor product quality are visible in any industry and, therefore, quite easy to identify. Often, the collection of data comes from other departments such as production and quality as they are in direct contact with the plant and are the custodians and official collectors of these data. If the plant is working properly, life is easier for everyone in the company, creating a very positive labor climate. This favors the exchange of interdepartmental data.

Unfortunately, this is not the case for measures of organizational efficiency. Even some of the most basic measures, such as manpower, training, and/or subcontracting data, are difficult to measure and are subject to union negotiations, collective agreements, or corporate policies.

Each goal is directly related to a key aspect of the users' needs. Therefore, the two must be harmonized, making it unfeasible to generate a generic list of independent measures.

2.3.5 Measures of Maintenance Effectiveness

Although the measures must be generated specifically for the objectives, some indices are commonly accepted throughout the industry. These include the following four measures:

2.3.5.1 Reliability

Reliability can be defined as

> The probability that an item meets the function that you require to the desired shape in all relevant conditions, on the occasions that you demand, or during the time intervals, at the request of its users [108].

This is an important step in many sectors, especially in industries where safety is critical, such as aerospace and energy, with special emphasis on nuclear power. Measures of reliability are classified as dependent on or independent of time; that is the basis of projection can be hours of use, starts, routes, etc.

2.3.5.2 Maintainability

In maintainability,

> A feature is intimately linked to the design and installation of the productive assets and less dependent on the operation itself. It is expressed as the probability (%) that an item is maintained or restored to a certain condition in a given period of time, when the maintenance is performed in accordance with the procedures and resources [171].

Maintenance is severely affected by the early stages of equipment life, that is, design and installation. It follows that this will have some impact on time and, therefore, on the costs associated with the complete life cycle. This leads to more emphasis in the design phase on how the machine can be restored to its original specifications in a simple manner. Concepts such as "modularity" and "normalization" are increasingly being adopted to reduce the minimum repair times.

2.3.5.3 Overall Equipment Effectiveness

Overall equipment effectiveness (OEE) can be defined as follows:

> The Overall Equipment Effectiveness or OEE is the main measure associated with the concept of Total Productive Maintenance [214].

OEE not only focuses on the efforts of the maintenance department but also, as its name indicates, on the company's overall strategy for productive assets. The three components of OEE are

- *Availability* (%): Percentage of time the plant is available for production use
- *Performance* (%): Actual performance compared to the performance anticipated by the design
- *Quality* (%): Percentage of acceptable finished products

OEE is a measure that, by itself, cannot assist in the identification of the root causes of problems. It is simply a number whose tendencies through time can be plotted and analyzed. The three components and the information used for their calculation are the main sources of data necessary to understand and diagnose faults.

OEE is a global interdepartmental indicator that can climb the hierarchy of the organization for use by managers as it provides information on production, maintenance, and quality. A drop in the overall OEE will be due to a drop in any of the three components. Wireman [375] says that if an indicator presents an anomaly, the level immediately below in the hierarchy should explain its cause.

2.3.5.4 Availability

Availability is a valuable measure and is frequently used in the industry. It is defined as

> The probability that equipment or a component or a system is ready when it is required during a given period of time [201].

Availability is a time function that characterizes the reliability and the times for the repair, which, in turn, define maintainability.

2.3.6 Objectives of Maintenance Department

The main task of the maintenance department is to balance the necessary resources with the volume of work in order to fulfill its objectives (Figure 2.5). The resources within any organization, mainly labor, tools, and spare parts, are expensive and must be controlled effectively in order to maximize profitability and use.

We have already outlined a method of monitoring the effectiveness of the maintenance strategy to ensure a plant meets the needs of its users. This has to be balanced with the efficiency of the organization in carrying out the work. For example, changing the brake pads on a car every week, regardless of its condition, is one way to guarantee the brakes will not fail because of wear (i.e., effective), but this is not an efficient solution. Even if the pads are changed in a program based on condition, it would still be necessary to evaluate



FIGURE 2.5
Balancing resources with workload.

the time and labor required. This simple example highlights the main elements that interact in a maintenance organization. These elements can be restated as

1. *Structure of resources*: Workers, tools, and spare parts needed to carry out tasks
2. *Administrative structure*: To assign and control the work of the organization
3. *Systems*: Planning job cost, reports, etc.

The form, composition, and location of the structure of resources depend largely on the industry and the consequent workload (proactive, corrective, etc.). In some cases, the structure has to be dynamic and be able to cope with ever-changing demands, while in other cases, it may be relatively stable, for example, a car workshop.

The administrative structure must be designed to suit the company and its current organizational policy. It would be inappropriate to design a multilayer and highly hierarchical structure in a company that believes in flat organizations, with great flexibility and versatility in maintenance.

Structures used to control the organization must be profitable and workable. For example, buying an expensive document management system is not a good idea if there are only a few drawings and manuals of equipment to be stored in that system.

2.3.7 Trends in the Design of a Maintenance Organization

Over the past 40 years, significant changes have affected the traditional structure of the maintenance organization. The issues discussed later provide an overview of the origin and purpose of these organizational changes.

2.3.7.1 Traditional Organization

Until the 1970s, it was common in medium- and large-size companies to find subcontractors located near the plant; these subcontractors took care of any emergency work, as well as certain minor tasks. Such subcontractors were intended for use during peak workloads; their presence ensured that required skills were available at all times. Workshops acted as a central reservation area in charge of major tasks. These two support groups performed specific tasks under strict control. The administrative structure was often centralized and hierarchical with a strict demarcation of the maintenance function; that is, production operated the plant and maintenance managed and ensured production. Organizational efficiency was adversely affected not only by excessive allocation of resources but also by excessive management structure. Many resources were duplicated, and hostility existed horizontally and vertically across the company. Rey [283] says that only companies that struggled to break down these barriers survived the competition coming from Japan.

There were some attempts to improve the situation in the mid-1970s, with the centralization of specific resources and the plant engineering staff. The purpose was to reduce duplication within the plant, reducing the amount of resources required anywhere and anytime. In addition, plant engineers became more dependent on and worked more closely with production staff. Both actions made major improvements in the efficiency of organizations, but neither helped to improve horizontal and vertical friction. In general, the situation tended to worsen.

Since the 1980s, however, three further changes have greatly improved the efficiency of maintenance organizations.

2.3.7.2 Flexibility in the Performance of Tasks: Disappearance of the Trades

The sharp delineation of tasks that existed in the 1970s was slowly disappearing with increased flexibility in the offices of the personnel. For a dynamic workload to be tackled effectively, an equally dynamic resource structure is required.

The multiplicity of skills and abilities, more commonly known as versatility, has played an important role in the philosophy of joint training of the labor force in a wide range of skills. Although people still tend to have individual duties related to union distinctions (e.g., welder, fitter, and electrician), when they are competent, they are also able to work effectively in other disciplines. It is not unusual to find job descriptions for "electromechanical engineers" who are expected to act as electricians, fitters, engineers, or controllers depending on the workload. Keep in mind that the boundaries between mechanical, hydraulic, electrical, electronic, or computer fields are not evident in compact machines; versatility is imperative to avoid difficulties in diagnosing failures in these machines, as Monchy says [224].

This has greatly influenced the training centers related to the maintenance function. The classical disciplines of electrical, electronic, and mechanical engineers have given way to mixed engineers in specialties such as mechatronics. Industrial organizations now seek to give engineers wider scope to handle a more flexible technical and organizational vision. Not surprisingly, the new commitment to flexibility has been to the detriment of the classic, highly specialized disciplines and areas of knowledge.

Another aspect that has improved the utilization of the workforce is increased flexibility in the hours and places of work of operators. Many companies now have numerous shifts or ask their engineers and technicians to accept flexibility and mobility within the plant, with occasional transfers to other plants.

2.3.7.3 Merger of Production Equipment and Maintenance

TPM has been adopted in the last 20–30 years in many companies around the world as a philosophy of improving the productivity of their equipment. Although companies obviously differ in their needs, there are some common concepts and associated benefits regardless of industry application. These include the use of "multitaskers" and "autonomous maintenance"; see Smith and Hawkins [297].

The concepts work together in the interaction between departments at the lowest level of a company. Those closest to the plant and machinery have the most responsibility and require time and training if the factory is to perform to the maximum capability. This concept has been further developed in some companies under the heading "operator–maintainer."

Simply stated, in TPM, production workers are given the necessary training to carry out the day-to-day maintenance of the plant when they are not performing functions of production.

2.3.7.4 Use of Contracts

Using contractors to help with peak workloads or specialized tasks is not a new concept. However, the use of maintenance contracting is becoming more common and more comprehensive. Some companies now use contracts for 100% of maintenance for their customers, enabling them to focus on their core business concerns. This type of "turnkey" agreement puts all the responsibilities for the maintenance of facilities and production under external control. The loss of income due to unavailability or lack of reliability will result in heavy fines levied on contractors; good service is linked to substantial economic benefits established in the contract. Clearly, it is in the client's and the contractor's interest to maximize the profitability of the maintenance department and equipment.

2.4 Objectives and Organizational Actions

2.4.1 The Need for Objectives and Organizational Actions

Even if we have inaugurated a strategy for proper maintenance and plant performance in meeting the objectives of maintenance, it is still necessary to maximize efficiency. The amount of effort required to do so varies across companies, depending on many factors. For example, in a nuclear installation, it is much more important to perform certain security checks, regardless of the cost, while other industries prioritize speedy completion of tests to maximize production. Nuclear power facilities must stress the quality of the work and the robustness of all control systems. Plant management should have information on the time and resources required, but any safety aspect outweighs a possible loss of efficiency.

The main reason to optimize organizational efficiency is to maximize departmental productivity (and, ultimately, company productivity). This is achieved through the implementation of the maintenance strategy that requires the least cost. In many cases, the efficiency of the maintenance strategy is likely to be more important than the efficiency of the

organization. However, the reduction of waste through better control remains an important part of the objectives and tasks of maintenance management.

This section examines how to set goals using principles similar to those described in maintenance effectiveness.

2.4.2 Human Factors

Human factors play an important role in the operation of a dynamic organization. Human factors can be described as emotions and relationships integrated into any group of people working together.

A more formal definition appears in EASA [86]:

> Human factors are trying to optimize the relationship between people and their activities through the systematic application of science like psychology or physiology, all it integrated within a framework of systems engineering.

There is no default list (Table 2.1) of factors, and every person, department, or company will vary in any attempt to compare and extract a closed group of factors.

The list in Table 2.2 defines the drivers of such emotions and relationships.

It should be noted that although we have divided the drivers of the emotions and relationships, in reality, there is no such division. For example, communication is a driver and also a relationship and can be found in either list.

2.4.2.1 Human Factors in Maintenance

All factors listed earlier affect the operation of a maintenance organization to some extent. However, the most common trends directly affecting a maintenance department are the following:

1. *Education and training*: An individual or a team lacking the necessary skills will inevitably generate a lack of confidence and must be retrained. A good team of trained professionals will earn the respect of other departments.
2. *Possession*: Plant specialization will allow technicians or operators to feel responsible for any machine under their jurisdiction. They will also feel empowered to propose improvements and modifications.

TABLE 2.1

Emotions in a Typical Organization

Morale	Friendship	Honesty	Goodwill
Respect	Confidence	Flexibility	Membership
Inspiration	Commitment	Enthusiasm	Pride

TABLE 2.2

Generators and Stimulators of Emotions in an Organization

Salary	Job satisfaction	Religion	Stability
Leadership	Discipline	Training	Communication
Involvement	Security	Culture	Promotion

3. *Participation*: Maintenance workers should understand the processes and systems that make up the plant; if so, they will feel valued and will suggest improvements.
4. *Communication*: This is an essential component in any system, especially when human beings are involved.
5. *Flexibility*: This will improve organizational efficiency and promote teamwork and camaraderie.

Many of the factors and drivers are not limited to the maintenance organization. This issue will be discussed in due course.

2.4.3 Organizational Interrelationships

In all organizational levels, the existing relationships can either hamper or improve the function of the various departments in one form or another. In the case of a productive system, the roles adopted are as follows. Operators (by definition) operate in the plant and manufacture the product, which, in turn, provides income for the company. A maintenance worker is employed to keep the factory running at a default performance level; the company considers this a negative but essential element. Engineers write the specifications and requirements to purchase new equipment or make modifications to existing ones. Staff concerned with quality keep track of the product to ensure that it meets the requirements of the customer.

Several areas of possible friction are immediately apparent and are enumerated later.

2.4.3.1 Factory Level

Pay: Pay scales and benefits are rarely uniform throughout a company. Production operators tend to be lower paid than those in other departments and, in general, have more tasks requiring physical effort. This gives rise to resentment. Normally, the difference in wages is explained by the level of training: those working in production generally have less training than those in departments such as quality control, finance, purchasing, engineering, or maintenance. In fact, training in companies commonly focus on these areas, rarely on production.

Conflict of interest: Although it seems logical that all departments within a company have the same interests and objectives, it is not always that simple. In many cases, maintenance technicians need time to work on the computer but cannot obtain their release from production. This is especially delicate for manufacturers working with a "just in time" (JIT) policy. Often, maintenance personnel blame production or plant directors for not letting them stop the plant to perform maintenance. This gets worse when nobody on either side communicates the reasons. This conflict of seemingly contradictory goals between production and maintenance would be lessened if both functions were aligned with the strategy of the organization.

Vertical polarization: The two areas of friction mentioned earlier are horizontal between departments, but friction can also be found among officers, supervisors, and managers in a vertical form. Problems arise when the "wrong" person is promoted to a senior post or others do not like the attitude of a certain official or group of officers. This is especially visible in the creation of TPM; the election of the group leader often leads to vertical frictions.

2.4.3.2 Management Level (Supervisors and Managers)

The problems encountered at the factory level may extend through the entire hierarchy. Some of the most relevant causes of frictions are

Accountability: In traditional structures with a "culture of blame," departmental supervisors and managers or directors may distrust each other. When problems occur, there is always a temptation to pass the blame to another person.

Status: The production managers may not have formal qualifications and thus feel inferior to the engineers and technicians on the same level. Conversely, the engineers may feel they are better than the production staff because of their training. This type of friction often appears between maintenance supervisors and highly qualified engineers.

The aforementioned points inevitably have an adverse effect on the performance of individuals or groups within a company if left uncontrolled. A metric must be designed for managers to control these factors with precision and confidence. The only way to address the issue is to counteract negative situations with positive ones, remembering there is no one way to assess conflicts due to emotions.

Common practices such as small team activities, autonomy, or flexibility help to eliminate obstacles and reduce friction. Major Japanese companies (such as Toyota and Honda) use concepts such as "kaizen" (continuous improvement) and "self-maintenance" for this reason. The Japanese companies boast that they offer the same decision-making opportunities to all employees equally, thus reducing friction in the workplace. However, surveys conducted by research centers such as Nikko indicate something completely different. According to these surveys, the much-vaunted Japanese system is an illusion; decisions are made by the direction or triggered by the pressure of teammates, thereby maximizing frictions instead of minimizing them; see Sakiya [290].

2.4.4 Key Components of a Maintenance Organization

The components of a maintenance organization, of course, vary from one industry to another and even between companies within the same sector. As noted, plants require a model for their maintenance. The same logic applies to the department or organization required to carry out this maintenance. Figure 2.6 maps the typical components of a traditional organization.

The model shows how information and work flow through the plant. It is very simplistic but indicates the magnitude and complexity of a typical organization and its functioning. Feedback and interrelationships are not shown because, of course, there is no such thing in a traditional organization. The information in such an organization only flows from top to bottom, never from the bottom upward. These relationships (i.e., feedback and interrelationships) and their importance must be assessed in the same way as the performance of the plant, as discussed in previous paragraphs. In addition, the model must be evaluated for each plant and its critical components studied (e.g., poor feedback).

In other words, what the problem was or whether it did not exist (e.g., the contribution of information from lower levels to higher levels) is now an advantage and a "key factor" of the success of the production and maintenance team.

Unfortunately, many of these links are hidden, and many factors do not appear in this model (e.g., human factors). In addition, each element (e.g., the information system) will generate a complex model itself.

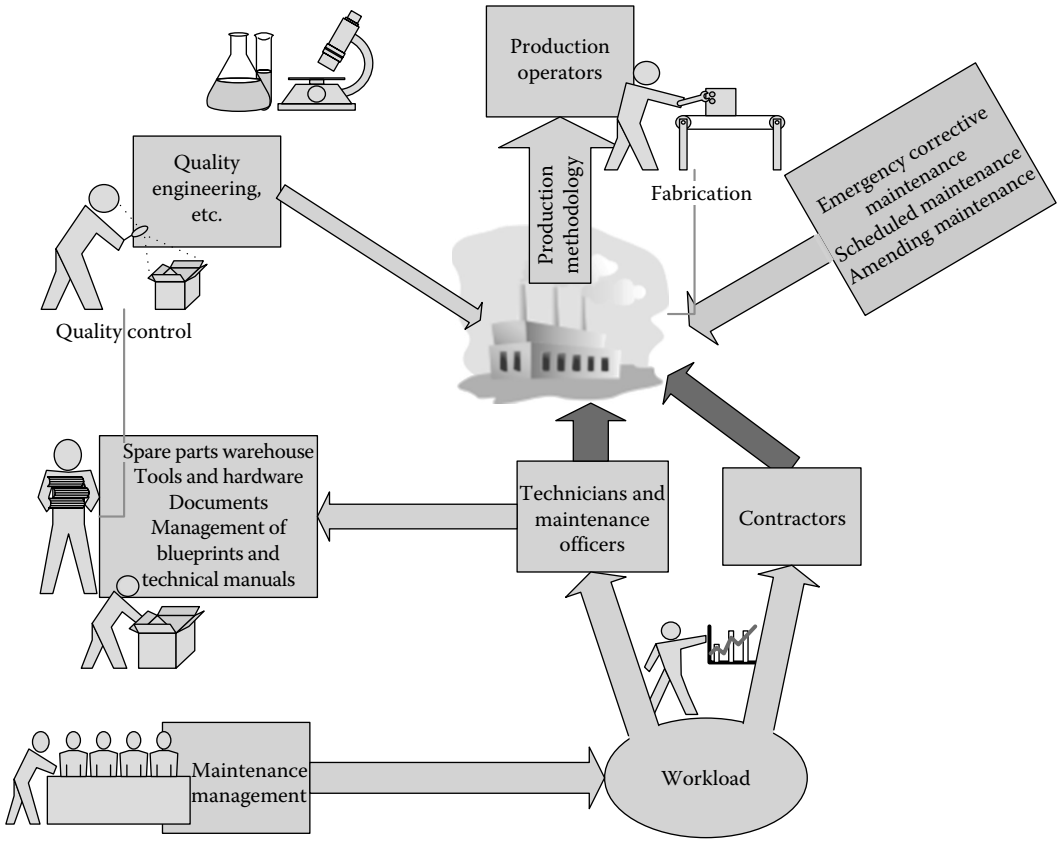

FIGURE 2.6
Traditional organization.

2.4.5 Adjustment of Objectives and Measures of Organizational Efficiency

The objectives of maintenance should be set specifically to measure and improve the efficiency of the organization in order to maximize its contribution to productivity. This must be carried out in conjunction with meeting the objectives of effectiveness of maintenance and should consider any objective specified by the company. This optimizes efficiency in selecting a metric, eliminating waste, and duplication in measures of performance. For example, the majority of companies measure generic indices such as absenteeism and wages as a function of the global values of the company; calculating these indices in the maintenance department would be redundant.

Figure 2.7 shows the optimization of an organization from a management point of view. As mentioned earlier, maintenance management seeks to maintain the parameters of effectiveness and efficiency:

- *Efficacy of maintenance*: It should be possible to meet the objectives of maintenance without wasting resources.
- *Efficiency of the organization*: The aim is to maximize efficiency, but it is much more important not to impede the effectiveness of maintenance.

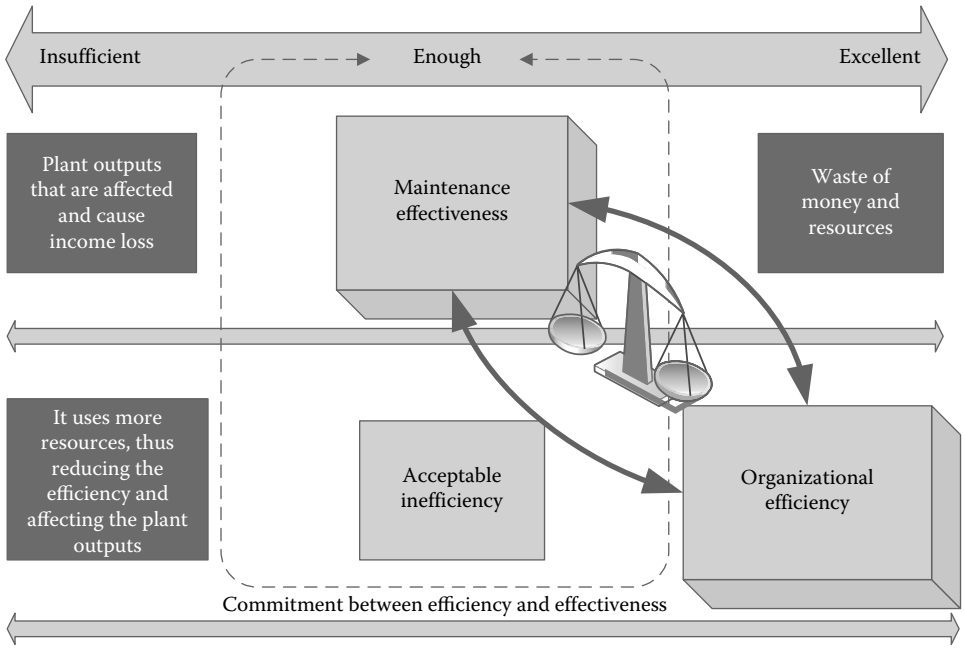

FIGURE 2.7
Optimization of maintenance organization.

For effective maintenance, we previously argued that user needs can be met using a hierarchical goals and measures structure. This is not the case with organizational efficiency. The management should seek to maximize the utilization of resources without hindering the effectiveness of maintenance. This can be achieved by identifying components and systems with the greatest impact on the organization, for example,

- *Cost of human resources*: Absenteeism, overtime, training, etc.
- *Contractors*: Percentage of work carried out by contractors
- *Stores*: Inventory value, the cost of the inventory, cost of obsolescence, delivery times, and rates of use
- *Administrative structure*: Indices of direct to indirect labor
- *Information and tools*: Uses, costs, updates, and losses
- *Work planning and control*: Delays in the work, mean time to repair (MTTR), and staff performance

The last point is by far one of the most controversial objectives. The time required for tremendously repetitive tasks may be easy to calculate, but such calculations are very subjective and sometimes impossible in the maintenance area.

MTM and other methods of measurement and timing in production are relatively simple and have given excellent results; see Arenas [14]. In repetitive tasks, such as determining the compactness of terminals or making visual inspections (i.e., preventive maintenance tasks) or performing predictive analysis of vibrations, the measurement often dictates

what will happen; in other words, a reliable prediction will be developed, affecting corrective maintenance tasks.

If workers are penalized by using a metric that is not proven, relations can deteriorate very rapidly. As explained earlier, it is vital that the staff collecting data feel their job is in the best interest of everyone in the organization. Otherwise, these data will become corrupt or useless.

Peer pressure, combined with a few basic principles of effective management, can improve the performance of an individual or a group. The most modern software of management training, for example, TQM, supports this. Ultimately, an efficient policy can be created by giving "ownership and responsibility" to the lower levels of the organization to promote a culture of teamwork and labor flexibility.

2.5 Combining the Organization's Objectives and Strategy

2.5.1 Matching Strategy and Targets

The methodology proposed here suggests that there is a gap between the effectiveness of maintenance and organizational efficiency. The minimum threshold of the costs associated with the effectiveness of the maintenance function is a crucial consideration as the overall costs are, in reality, a combination of the two sets of objectives (efficiency and effectiveness), as shown in Figure 2.8.

The total maintenance cost is, in fact, the sum of the effectiveness of maintenance and the costs caused by inefficiency. Therefore, it follows that the cost is a vital link that includes the two objectives.

A maintenance department should obviously seek to minimize the total cost associated with the function (Figure 2.9). Or to be more specific, it should meet all goals and objectives at a minimal cost, as Mitchell [220] points out, to maximize productivity.

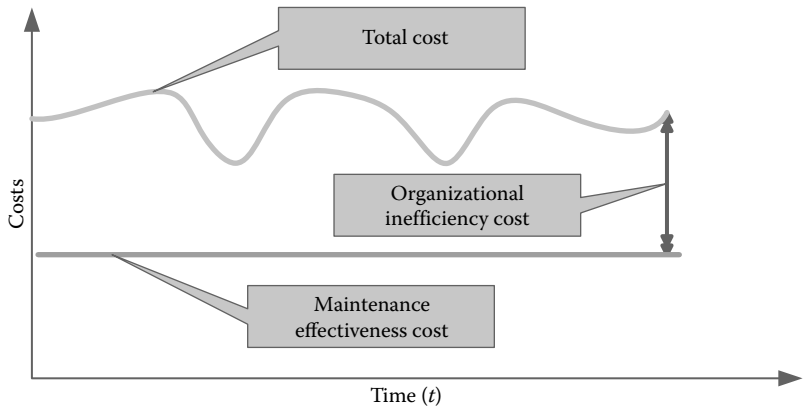

FIGURE 2.8
Total maintenance cost.

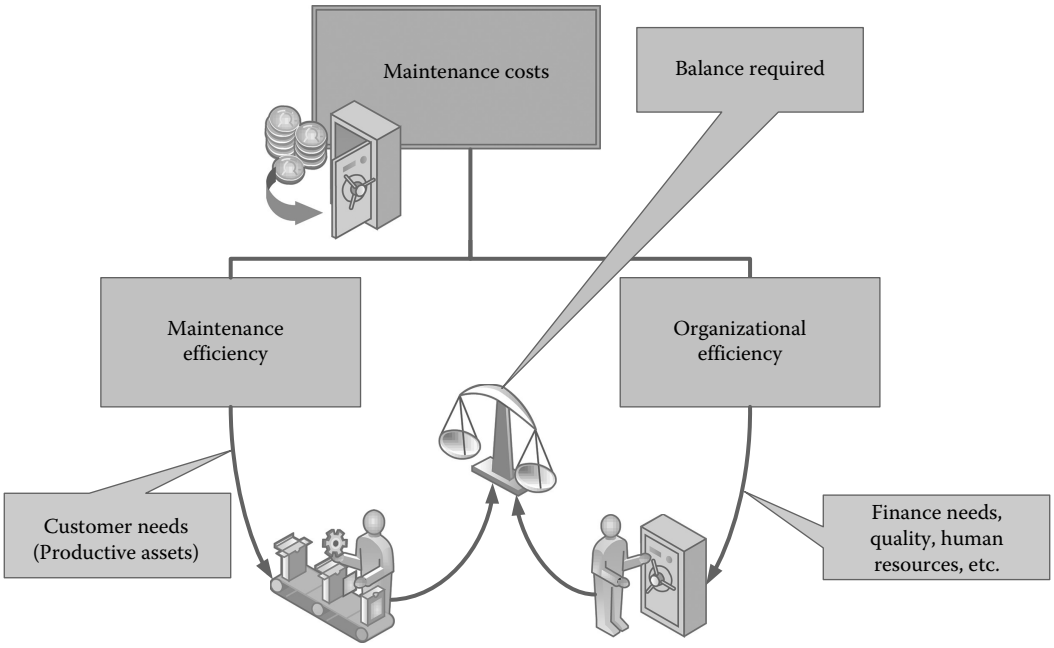

FIGURE 2.9
Overall maintenance cost as an objective.

2.5.2 Cost of Maintenance

The previous objective can only be controlled if the company has a robust system of data collection through the creation of hierarchical cost centers. These centers can be grouped according to certain characteristics, such as machinery, projects, or departments (or combinations of these). Once this structure has been created (usually proposed by the Department of Finance), it is easy to identify and represent all costs within each one.

Cost centers do not usually cascade down to specific assets or people. Although certain key individuals or teams may have an accounting center, it is much more common to stop downward decentralization or to have work teams composed of several people.

The needs of maintenance management often cause it to focus attention on the lowest level of a system of this type to determine exactly how the costs are distributed, but this entails the management of a wealth of data with large dimensions and a complex documentary system. This process has been improved in recent years through the introduction of asset management software (CMMS), widely disseminated in the industry, designed to capture, store, and process huge amounts of data. The implementation of this type of system allows companies to build up large amounts of information for a multitude of characteristics associated with the assets, for example, the cost of each component or resource.

The energy and petrochemical industry has recently developed sophisticated decision support tools to manage assets; see Van Rijn [361]. These systems help the graphic simulation of equipment failures, permitting detailed analysis of simulations of costs and types of failures. This is important as the cost of failure can be directly compared with the cost of repair or replacement. These complex systems of data mining are based on abundant, quality data.

Unfortunately, even with this type of system installed, there are still complications in the evaluation of the actual cost of the maintenance function. Before addressing this question, it is necessary to determine which types of expenditure occur more frequently and have a greater effect on the total cost of a maintenance department.

2.5.2.1 "Hard" and "Soft" Costs

Hard costs are easy to identify and measure; soft costs are far more difficult to locate and identify. Financial managers are more interested in hard costs expressed in the use of resources (i.e., workers, tools, and spare parts) and the loss of income due to inactivity. They are more easily identifiable, making the conversion of the costs of maintenance effectiveness a relatively simple task. This type of information is exactly what a software package is designed to collect.

Avoided costs represent a "soft" cost. To cite one example, the cost savings of vibration analysis are not usually known by the finance department. Among other things, soft costs are associated with a significant technical component and cannot be calculated by finance without the active support of the maintenance department.

2.5.2.2 Maintenance Cost Formulation

As expected, the costs associated with organizational efficiency tend to be more difficult to measure, making them "soft" costs. In addition, some are hidden within "hard" costs, considerably complicating the issue. For example, inadequate training can lead to technical failure in the diagnosis of a fault (causing high outage). The actual costs associated with the slowness of the diagnosis or judgment are very difficult to identify, but the total cost of the failure is relatively simple to calculate.

Another complication is that the total maintenance cost is directly affected by factors outside the control of the organization, such as malfunction and design. A machine with an inherent defect because of its design or erroneously combined production methods (misuse of the equipment by the operator) is inevitably linked to the maintenance department in some way. The use of maintenance resources to identify and resolve problems of this kind is acceptable only if the costs are separated from the regular workload and are not confused with waste.

These types of costs must be distributed among the main factors affecting plant production and maintenance of resources:

- Design
- Operation
- Maintenance

2.5.2.3 The Need to Understand Inefficiency Cost

Unfortunately, the evaluation of "soft" costs in maintenance is complex. As explained earlier, they tend to be interrelated with "hard" costs, making them difficult to distinguish. This raises the question of the accuracy of the inefficiency cost.

If the plant is working according to the established parameters and the total maintenance cost is known, it is likely not necessary to have comprehensive knowledge of the soft costs. Of course, an item can be analyzed separately, if necessary, through procedures or

computer programs. For example, if a plant is very complex and requires comprehensive staff training, it may be necessary to identify all the costs incurred by a shortage of qualified personnel.

2.6 Conclusion

2.6.1 Problems Associated with the Measurement of Maintenance Performance

2.6.1.1 Too Much Data and Too Little Information

Problem: Data acquisition has become relatively simple and inexpensive with the introduction of powerful systems of hardware and software, but the enormous wealth of data is a problem in itself.

Proposed solution: If data collection is simple and cheap, there is no reason not to collect them. This requires the installation of a software package, the choice of fundamental data, and, as far as possible, the automatic filling of fields when work orders are executed. If data can be incorporated automatically into the system through SCADAS, CBM or interfaced with the ERP plant, data storage and processing become inexpensive. This information, even if it does not have an immediate utility, can be used in data mining to identify relationships and trends or provide solutions to problems with a hidden cause.

When data are more difficult to collect, it is necessary to decide if it is worth the effort and cost. To determine this, it is necessary to define what is important to the company, that is, analyze its hierarchy of objectives. Once the needs of the user/company are fully understood, it will be possible to decide on the maintenance strategy, its organization, and the systems to fulfill it. Measures are put in place to ensure the proper functioning of the mechanisms associated with the implementation of strategic objectives. The information necessary to establish relevant measures is the key to the data to be collected. For example, if the production plant is vital to a company, all the factors affecting it have to be monitored. If data are collected only for the output of the plant processes (finished product), the analysis of any deficit detected in the system will be difficult (especially when it involves the temporal evolution of some parameter).

2.6.1.2 The Number of Performance Indicators, Ownership of the Data, and Aspects to Cover

Problem: How many indicators are needed to effectively monitor the performance of a maintenance department? Woodhouse [339] has analyzed scorecards with more than 40 indicators; based on his findings, he suggests 6 indicators for each layer of the organization.

Proposed solution: The identification of the key features or key factors limits the number of indicators. Six measures is only a suggestion; it is more important to do a follow-up of all the key issues for the performance of the department, taking into account the assimilative capacity and management of a limited number of these indicators. That said, scorecards with too many indicators actually hinder the work.

It is important to address ownership of the data and the need for the whole organization to help construct the control panel. The maintenance department is often overwhelmed by the lack of sufficient historical data to create indicators. In a multifunctional organization,

other departments may be collecting crucial data and, thus, may be able to generate shared parameters. For example, it can be relatively simple for the production department to collect data on availability or reliability.

2.6.1.3 Objectives and Measures

Problem: In some cases, departments in the same company have interests that conflict in the maintenance of their equipment. A classic example is the choice of an asset management system in a large company. The finance department, maintenance, and ICT are almost certain to have different needs and views on the type of software, hardware, platform, contract maintenance, upgrades, consultants, etc.

Solution: The purpose of the objectives is to ensure the efforts of a department are aligned with the needs of the company. This requires tangible goals free from ambiguity. There are problems when a company stops setting goals at the highest level or does not ensure objectives are successfully translated into subgoals at lower levels. When the directorate ensures overall company objectives are translated into objectives at lower levels and not left to the interpretation of middle managers, the ambiguities giving rise to interdepartmental frictions disappear.

The objectives should be transmitted downward and internalized by each department. The appropriate measures should ensure everyone is going in the same direction.

2.6.1.4 Time between Actions and Follow-Up

Problem: Sometimes, there is a delay between a change in policy and the emergence of clear results. A second delay can be found between the appearance of the results and the time the measurement is taken.

Solution: These problems must be treated individually; it is unrealistic to suggest a general answer. Once a target has been identified and a measure is put into practice, the method and frequency of data collection must be adapted for the specific factors involved: physical quantities, human factors, organizational, or financial factors.

This problem often occurs with the selection of a measurement system for vibration analysis. A company can opt for measurements using portable collectors or a permanent or continuous monitoring system using sensors and wiring specifically designed for this purpose. The choice of action is determined by two key factors:

1. Safety of the operator in data collection
2. Speed at which a fault is triggered by a vibration that appears abnormal

For each measure and its corresponding sensor, there will be a sound solution depending on the required frequency measurement and the risks for the equipment or the people using it.

2.6.1.5 Lack of Correlation between Observable Symptoms and the Underlying Risks

Problem is unknown: Certain risks may not be acceptable, but they rely on information obtained after events.

Solution: The use of proactive measures to reduce the risks has been suggested. When equipment failure is expensive or dangerous, it is possible to identify countermeasures through

root-cause analysis (RAC) or AMFEs. Even if equipment failure is not a major problem for the company, it is still necessary to evaluate the security of employees. All tasks and situations that involve risk should be identified. This requires proactivity.

For example, in the indicator proposed by the UNE-EN 15341:2008 [356] on accidents, we cannot simply place the sensor and wait to count the number of accidents occurring in a certain period. This indicator, while useful and referred to in all scorecards, implies the use of countermeasures.

2.6.1.6 Cost and Motivation of Data Collectors

Problem: The success of any measurement system is based on the data collection method. Scarce and incorrect data give rise to poor reports. When worker participation is required, it becomes even more difficult.

Solution: Information on human factors should be collected only if it is worth it, and the results are available for free consultation and use. If there is any risk that findings will be used against workers, it is almost certain the workers will not be happy. Similarly, if after a certain period the data have not been used and there has been no well-communicated feedback, the collection of data represents a loss of time.

2.6.2 Model for Measuring Performance

The information on and references to the measurement of maintenance performance are often contradictory and almost always specific to the industry in which they were created. Performance measures must align the overall company objectives with the departmental objectives, as shown in Figure 2.10.

The model is not specified for a particular industry or sector; this ensures its generic nature. With this process, a company should be able to integrate the maintenance function with its business needs. Although the model is designed around the maintenance function, with a certain level of abstraction, it could be adapted to any function within a modern company. The setting of targets in a hierarchical order requires all functions within the company to work together. Williamson [371] says maintenance is not a department but a shared responsibility. This concept will become increasingly common. This conception of maintenance reinforces the idea that all functions within the company, properly aligned and working together, should seek to improve performance and reduce costs, that is, a quantitative improvement of effectiveness and efficiency.

2.6.3 Conclusions

2.6.3.1 Problems of Measuring Performance

Problems of measuring maintenance performances are fairly generic. Although the solutions vary from one plant to another, the causes of complications tend to be similar.

2.6.3.2 Human Factors

Human factors are complex but play an important role in the performance of an organization. Many methodologies, such as TPM and TQM, have recognized the importance of this factor and have tried to resolve the situation.

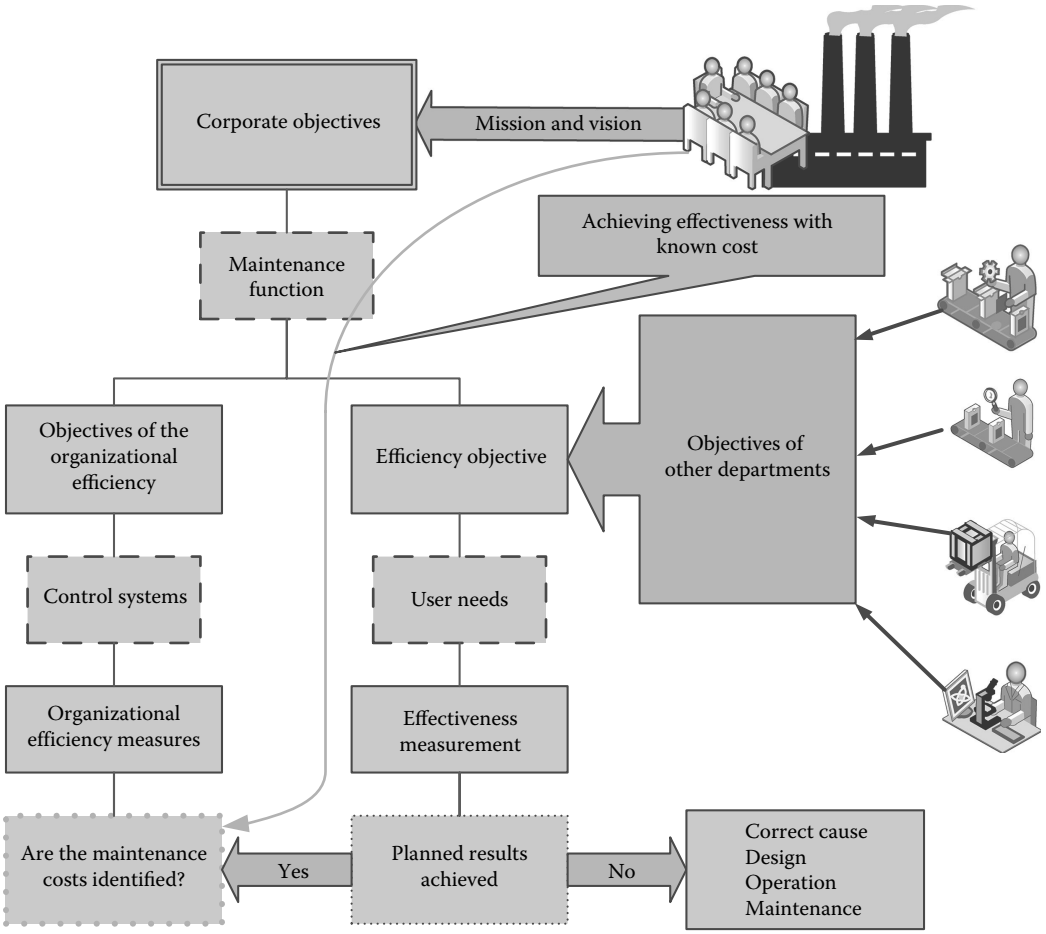

FIGURE 2.10
Model to measure the performance of maintenance.

2.6.3.3 Data

If data are scarce or incorrect, this will generate reports of little interest and less use. It is vital that the data collection systems be designed in such a way that the benefits of their use outweigh any inconvenience. Similarly, the data collectors must be sufficiently motivated to provide only valid information.

2.6.3.4 Function

The understanding of the specific function of a maintenance organization within a company is a vital step toward its proper control. This knowledge will help in the identification of the plant as a user of maintenance and the description of what the company needs from the department.

2.6.3.5 Objectives

A modern organization should be flexible and dynamic.

1. Goals and actions should be constantly evaluated and revised to remain aligned with business needs.
2. Objectives and measures must be transmitted from top to bottom and have the support of all levels in the organization.
3. Each department and each person should have the opportunity to participate in the determination of the needs arising from each objective.

2.6.3.6 Measures

It is important to align the measures with the main objectives. There is no point in setting a goal to improve performance if we are not going to adequately control or measure it.

The indicators related to organizational efficiency tend to be difficult to measure and subjective in nature. That is why the finance staff tends to focus on costs caused by the use of resources (i.e., "hard" costs related to maintenance efficiency). This is much easier to measure with CMMS systems as they are programmed to capture this type of information through the management of the volume of work hours, purchases of spare parts, recruitment, etc. The most commonly used organizational indicators refer to use of staff, extra work hours, and percentages of direct or indirect staff. The measurement of intangible aspects linked to "soft" costs, such as response capabilities, skills, or ease of team work, is more complex.

2.6.3.7 Costs

The total maintenance cost is the sum of the costs associated with maintenance effectiveness and losses due to inefficient organization.

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3

The Human Factor in the Measurement of Maintenance Performance

3.1 Introduction

At present, technological development is within the reach of all companies. Yet, the difference between a good company and an excellent one is not technology but human capital. Although technology is becoming more essential to production, companies still need people to operate and maintain machines. The possibility of error that is inevitably linked to dependency on human beings must be minimized in the shortest possible time.

In the management of assets, multiple factors affect system reliability. Near the top of the list are "human factors." These can be defined as "the physical and psychological capacities of the person, his or her training and experience, and the conditions under which he or she must operate, as these influence the capacity of the system to manage the maintenance of assets so that they fulfill their desired role."

The influence of human factors on maintenance has been studied in areas where safety and reliability are essential. These include such industries as oil, petrochemical, gas, electrical generation, nuclear, cement, aviation, plants, and other fields where an accident entails nonpermissible human and/or economic losses. Safety, hygiene, and the environment must prevail over other factors.

Human factors have become increasingly important in the past 50 years because the fields where they are fundamental (see preceding text) have developed relatively quickly.

This chapter considers the influence of human factors on the measurement of maintenance performance, focusing on the following:

- The human factor in the measurement of the performance of an activity
- The human factor in the management of maintenance and in the maintenance functions more generally

The conjunction of these two factors determines how maintenance should be measured in an organization.

Although it will soon be solidly established in each of them, it should be emphasized. Note that the measurement of performance in organizations is often poorly received by employees because the departure point is usually an attempt to make an improvement (i.e., causing change); that is the assumption is that things can done better than they are done now.

Performance measurements can comprise of

- External evaluations or audits by people outside the organization
- Internal evaluations consisting of three possible elements:
  - Self-evaluation
  - Evaluation by subordinates
  - Evaluation by superiors

The human factor in maintenance is closely related to total productive maintenance (TPM), especially when the history of the maintenance function in a company is sprinkled with organizational changes whereby the maintenance function has acquired more or less importance, thus directly affecting the individuals in the maintenance department. Modifications vary from the integration of the maintenance in production to the externalization of the same function through subcontracting. Depending on the modification, the workers' morale, motivation, and/or sense of ownership can be affected. All this affects the performance measurement of a quite controversial department inside the organizations and normally negatively considered by its costs or by its service perception.

3.1.1 Introduction to Human Factors

Human factors are all those characteristics and qualities inherent to the human species, physical as much as psychological, that influence the capacity to carry out a specific task. The analysis of human factors includes, but is not limited to, the following:

- *Safety culture*: identifying the elements necessary to create a culture of safety
- *Human error*: identifying errors and possible chain of errors
- *Human performance and its limitations*: identifying failures in the senses, perception, memory, and motivation
- *Surroundings*: determining the environmental influence
- *Procedures, information, tools, and practices*: identifying the specifics of daily work
- *Effective communication*: noting the problems in communication that may cause failures in the fulfillment of the tasks
- *Group and/or individual responsibility*: determining the effect of the group, decision making, responsibility, and leadership

3.1.2 Human Factors in Organizations

An organization comprises of a dependent system of human beings who, in turn, affect the organization's structure and operation. The management of human relations requires the consideration of the characteristics and interrelation of individuals and groups within an organization and how these affect the organization's design and administration.

All of the following interrelated aspects must be considered in the study of the human factor in maintenance:

- Human relations between personnel
- Participation of management

- Independent work groups
- Individual behavior
- Modeling the human factor
- Theories of behavior

The following two points are essential:

1. Production systems must be safe. Safety is a priority in many companies, especially energy-producing industries, the chemical industry, hospital services, and aeronautics/aviation.
2. If an employee is conscious of his/her own weaknesses, it will be possible to reduce the possibility of error, saving time and money; at the same time, frustrations can be avoided.

3.1.3 Necessity of Studying Human Factors: The SHELL Model

The objectives of the study of human factors are the following:

- To acquire the capacity to include the theoretical foundations of the complex subject of human factors
- To give general descriptions, making appropriate use of typical examples
- To apply knowledge in a practical way using detailed procedures
- To gain awareness of the situation in which work is done

SHELL (Software, Hardware, Environment, and Liveware) is a model widely used in the study of the human factor is, which was first proposed by Professor Elwyn Edwards in 1972. In 1975, a modified diagram was created by Commander Frank Hawkins to illustrate the model.

The component blocks of the SHELL model are Software, Hardware, Environment, and Liveware. As the names imply, they correspond to procedures, machines, surroundings. and people, respectively. Figure 3.1 shows a graphical representation of the connections between the blocks.

As the figure shows, the human element (L), equipment (H), and software (S) interact in the surroundings (E). This block diagram does not include the interactions that take place outside the human factors, for example, equipment–equipment, equipment–surroundings, or support–equipment.

This model highlights that a large part of the interactions of a human being in a company is with other people, not only with machines; these interactions with others can be a source of innovation, creativity, effectiveness, and efficiency. They can also cause frictions and inefficiency, especially if the importance of the human factor has not been quantified suitably.

The human element "liveware," that is, the person, is at the center of the model. The human being is generally considered the most critical and more flexible component of the system. But people are subject to considerable variations in their performance and have many limitations, most of which are foreseeable, at least in their most general aspects. Thus, the components of the system must be adjusted carefully to avoid creating stress in the set of blocks and causing their possible rupture.

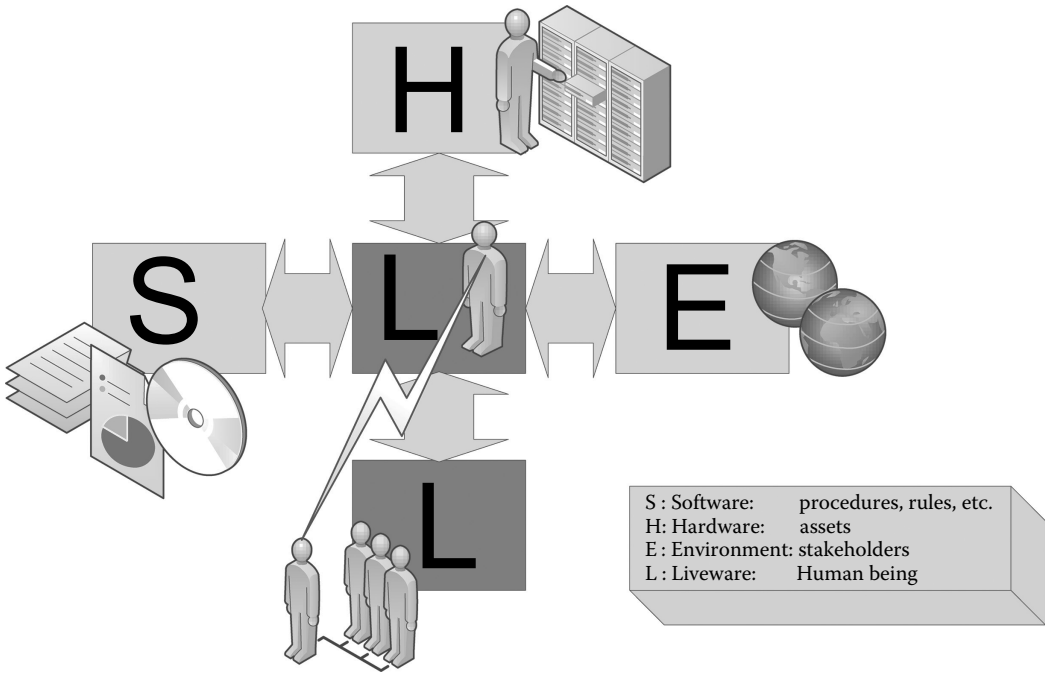

FIGURE 3.1
SHELL model.

In order to create a balanced SHELL model, it is indispensable to understand the following characteristics:

- *Size and physical forms*: In the workplace, especially when using equipment, human performance can vary according to factors such as age, ethnic origin, and gender. These aspects must be determined in one of the first stages of the design process. Information can be found in both sociology and industrial relations.
- *Physical needs*: Basic human needs, such as food, water, and oxygen, are crucial to performance. Information on this comes from human physiology and biology.
- *Contributing characteristics*: Human beings are equipped with diverse sensory systems that allow them to compile information on both the external world and their own internal world. The gathered information helps them to respond to events and to carry out the necessary tasks. But all senses are subject to degradation for one reason or another. Sources of knowledge in this field include psychology and physiology.
- *Data processing*: Here as well, the human functions have limitations. Frequently, the design of instruments and systems of alert is deficient, not taking into account the capacity and the limitations of a human being's ability to process data. This, in turn, influences factors such as stress, motivation, and short- and long-term memory. Psychology and sciences provide basic knowledge.
- *Response to information*: Once information is detected and processed, decisions are made by the individual, and messages are sent to muscles to initiate a response. The response can be a physical movement or a form of communication. Here, biomechanics, physiology, and psychology provide basic knowledge.

- *Environmental range*: Environmental factors, such as temperature, vibrations, pressure, humidity, noise, hour of the day, amount of light, and forces of gravity, can affect performance and well-being. Such factors as heights, enclosed spaces, and boring or tense work can influence the behavior and the performance or operation of a human being. Medicine, psychology, physiology, and biology all offer useful information.

These inherent characteristics of the human body's physical and mental capabilities will affect the measurement of the performance of any activity, including maintenance. Thus, for example, the physical condition of maintenance technicians, including their age and gender or the influence of the surroundings on their health, will influence performance. Because a person's ability to assimilate information, to process it, and to transmit it will affect the function maintenance, good management will consider the human factor.

In SHELL, the most frequently occurring interactions in the maintenance function are discussed in the following.

3.1.3.1 Human–Equipment (L–H)

The quality of the human–machine interface depends on the user's information processing ability. An advantage is that humans are adaptable, but at the same time, users may not recognize a deficiency in the interface, even though it might cause problems—possibly be disastrous. Ergonomics take care of the human–equipment interface to a large extent (i.e., seats designed to fit the characteristics of the seated human body, screens that adjust to sensory characteristics, etc.) but not entirely. As will be seen in due course, maintenance is directly related to the man–machine interface, with consequences for the system's availability and safety. Ultimately, machines that are difficult to repair or uncomfortable or that require great physical effort to use will cause problems.

3.1.3.2 Logical Human–Support (L–S)

This is the interface between the human being and the nonphysical aspects of the system, such as procedures, manuals, verification lists, and computer programs. In this interface, the problems may be less tangible than those in the L–H interface (person–equipment) and, consequently, more difficult to detect and solve (e.g., incorrect interpretation of symbols or verification lists). The interaction of personnel with a CMMS system, the strict fulfillment of safety requirements, and following the internal procedures of the company all affect this connection. In addition, the maintenance personnel manage guarantees, contracts, purchases, and so on, and these require technicians to interact with (interface with) the support system. The measurement of performance is included in this interface and is inevitably a source of conflicts, as will be shown.

3.1.3.3 Human–Surroundings (H–M)

The human–surroundings interface was first examined in the fields of energetics and aviation. Measures include modifications to the environment to accommodate human requirements, for example, air conditioning and soundproofing. Accidents and injuries occur frequently in maintenance departments, but modifying the surroundings so that the work involves fewer risks, creating a breathable atmosphere, and eliminating uncomfortable positions have noticeably reduced dangers for maintenance personnel.

3.1.3.4 Human–Human (L–L)

This is the interface between people. Traditionally, maintenance personnel have been individually evaluated. When each member in a group was suitable, it was assumed that the group was also suitable and efficient. However, a group of human beings is not the sum of its parts, and increasing attention is being paid to how groups operate. Support systems work as groups, and the group determines performance. In this interface, it is necessary to consider leadership aspects, cooperation among group members, their respective tasks, and interactions of personalities. Human–human connections generate a greater number of conflicts and are crucial to the measurement of performance.

3.1.4 Application of Human Factors

The study of human factors in maintenance leads to the design and implementation of programs of action such as the following:

- Designing the enterprise's objectives and incorporating them in the action plans of each level
- Developing internal and external policies in accord with the surroundings
- Evaluating human–human interactions since success or failure depends on human relations
- Elaborating better methodologies to maximize human capital
- Generating changes in common objectives
- Designing safety systems, reliability, and availability to assure well-being and prosperity

The following theories and models consider the relationship between people:

- *Mechanist model*: This model monitors and controls how the work is realized from the lowest level; it includes the method, programming, and direction.
- *Administrative management*: This theory applies the principles and functions of structural management to the design of an organization and its operation.
- *Management of human relations*: This approach includes studies of the characteristics and the relations of individuals and groups within an organization; it applies these to design and administration.
- *Decision making*: Studies of decision making use procedures and quantitative models to solve management problems.
- *Systems of management*: This includes the study of dynamic systems that react with their surroundings. A systemic vision of a company analyzes a system and disturbances in its subsystems, considering both technology and management.
- *Management of contingencies*: The characteristics of an organization must adapt to the internal and external surroundings. Since these surroundings can change, it is important to see the structure of the organization from a dynamic perspective.

The attempt to model people from a systemic or mechanist perspective has had good results in man–machine interactions. For example, a model can be created of an individual based on age, height, or gender to adapt him/her to repetitive work requiring a certain physical effort. Movements can be quantified and predicted, thus optimizing work and avoiding injuries or work inefficiency.

3.2 The Human Factor Considered by Management

The first important development in the study of human relations was Mayo's [209] theory that psychological and social factors were important for both worker satisfaction and productivity. Considerable advances in the understanding of the motivation of workers were made from 1950 to 1970, mainly by Maslow [204], Herzberg [119], and McGregor [210].

Maslow [204] identifies and classifies the needs of the individual in a pyramid form as follows:

Superior needs

- 5. Self-realization
- 4. Autonomy
- 3. Self-esteem

Basic needs

- 2. Sociability
- 1. Security

Herzberg [119] also divides human needs into basic (biological) and more elevated (of personal growth) ones, identifying and quantifying the factors affecting those needs, as shown in Figure 3.2. Herzberg [119] argues that the factors influencing the highest

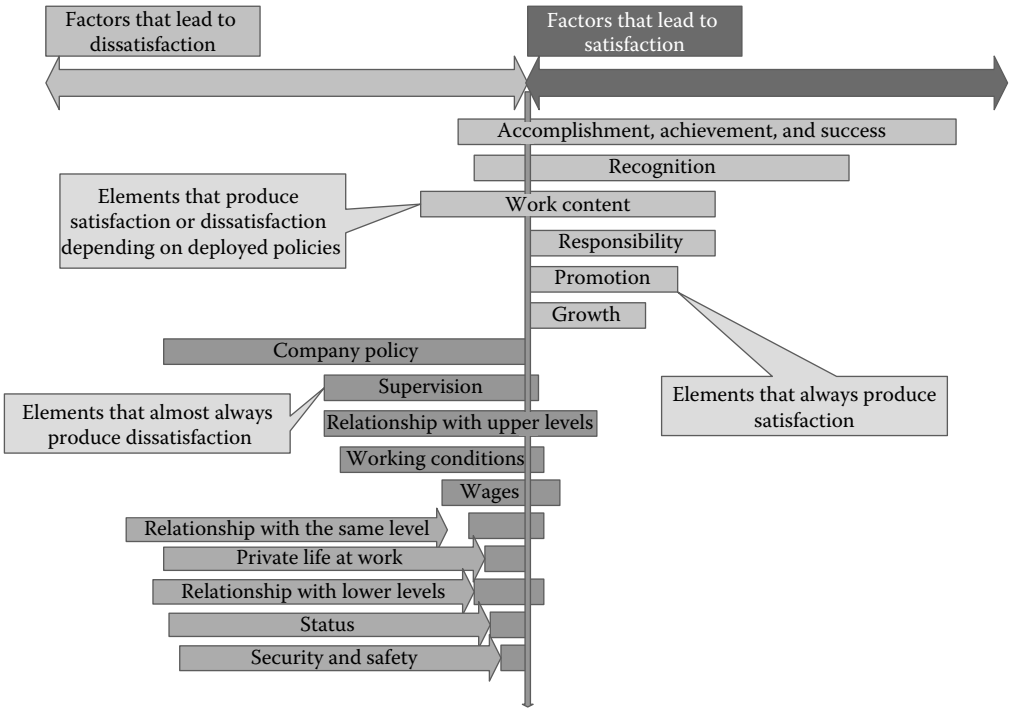

FIGURE 3.2
Factors that affect attitudes in the workplace.

needs, that is, growth, affect work satisfaction and, therefore, have an impact. For example, motivation is an internal stimulus that causes an individual to be satisfied when carrying out work, thus affecting the quality of his/her work and making motivation an important part of the measurement process. In contrast, the factors that influence basic needs affect work dissatisfaction.

McGregor [210] posits two theories. The so-called theory X maintains a traditional point of view, whereby workers must be controlled and directed because of their inherent aversion to work. The second theory postulates that the majority of workers can be remotely controlled if they feel satisfied with their work. These theories were important because they alerted managers to the need to consider the characteristics of the workers when formulating their objectives.

The previous theories, especially McGregor's [210], have undergone numerous applications in maintenance. In fact, TPM is an attempt to apply theory X; the basic idea is that giving workers autonomy will increase productivity.

Maslow's pyramid [204] remains valid in the field of maintenance in three basic aspects:

- It is difficult to foster pride and a sense of ownership when the lower part of the pyramid is not covered, that is, if the worker does not have a living wage. Feelings of ownership/pride become more evident when basic needs are met.
- The use of work groups has given workers more autonomy, adding to their self-esteem and external recognition. However, subcontracting prevents workers from feeling a sense of ownership in the company and also decreases sociability, preventing personal growth.
- In the special case of maintenance, the danger of accidents, as mentioned previously, is elevated with the use of machines lacking adequate safety measures. The implementation of suitable safety practices ensures that the employee feels protected.

Herzberg [119], in line with Maslow [204], has proposed that physical needs should be prioritized over personal development. For maintenance, the physical conditions under which an individual works are important. If maintenance personnel lack suitable tools or logistical support, for example, the performance of maintenance can pose an insurmountable obstacle.

During the early period of analysis, the general opinion of industrial sociologists was that work had become overly controlled and boring. Criticism of the dominant philosophy was voiced by K. Matsushita (Japanese Personnel Management) during a 1982 trip to England:

> For you [the English], the essence of administration consists of taking ideas from the heads of the managers and putting them into the hands of the workers (offices and departments). For us [Japanese], the essence of administration is indeed the art to mobilize the intellectual resources of all the personnel and to put them to the service of the company. Since we have evaluated better than you the economic and technological challenges, we know that the intelligence of a management group, able as it is, is not enough to ensure success.

The feeling that excessively hierarchialized structures lacked a place for innovation ultimately led to the following changes in philosophy:

- Articulating clear objectives instead of providing detailed instructions
- Increasing workers' responsibility, whereby planning, organization, direction, and control become joint functions with other employees
- Studying the organization of jobs in an attempt to better satisfy human needs
- Exchanging controlled activities for a focus on the development of abilities, including the use of mentors, associates, or advisers
- Devising a suitable configuration to construct effective equipment within the skill set of employees

During the past 20 years, there have been multiple industrial applications of this approach. Some of the main ones have concentrated on autonomy, with an emphasis on small, self-sustaining work groups. In Sweden, management and unions have worked together, applying (and modifying through experience) many of the ideas about work on specific equipment; see Swedish Employers Confederation [320].

In the United Kingdom, however, similar exercises in the 1970s that attempted to foster workers' participation in management had limited success, albeit not total failure, mainly because the United Kingdom's industrial surroundings are very different from Nordic countries and the style of traditional management was not compatible with the "new participating fashions," see Johnson [139]. This sociological change took 20 years; in the 1990s, the United Kingdom's industrial policy finally introduced participatory management, with a focus on autonomy and professional growth (reflecting the Japanese concept of the autonomy of the operator-breadwinner of the equipment).

More recently, the industrial climate has changed again with the reduction of personnel and the creation of new types of alliances (especially subcontracting). Thus, the style of management of human factors is evolving. In some aspects of the performance of maintenance, it represents a considerable step back, for example, subcontracts can be misapplied and employees' abilities/versatilities misunderstood.

3.3 Human Factor in Maintenance

The previous section discussed studies on human factors, noting that these have concentrated on identifying those elements that cause the work of an employee to be satisfactory, allowing an organization to more effectively reach its objectives.

This section analyzes human factors from a different point of view, identifying the main factors that allow an organization to achieve its maintenance objectives. One example is a sense of ownership of the equipment being maintained; this factor is linked to both reliability and performance. Another is motivation, a factor affecting the efficient use of resources. It is important to understand that management can take action to modify human factors; for example, creating work parties in a plant can improve the feeling of ownership of the equipment.

When identifying human factors, the following points are central:

- It is important to distinguish between human factors and the measures that influence them.
- Human factors can interact; for example, morale affects motivation.
- Some investigators consider that some human factors, such as goodwill toward the company, are more important than others.
- Some indicators of performance provide a measurement of certain human factors; for example, the absenteeism level is an indicator of morale. This type of indicator is easily calculable, as discussed in Section 2.6.2.1. The absenteeism index is a readily obtainable parameter of the ERP; thus, the degree of absenteeism is easily quantified. Other parameters are not so immediately accessible.

When maintenance departments are audited, auditors try to obtain an idea of how well or how badly the human factors function. It makes little sense to affirm that the strategy, the structure, and the systems are good, without also analyzing the corresponding human factors.

3.3.1 Human Error and Its Influence on RAMS Parameters

RAMS parameters are affected by human factors; this, in turn, affects maintenance interventions. Put otherwise, the human aspect of maintenance (i.e., the technician) influences the incidence of accidents or failures. Many problems of maintenance, and therefore of reliability and safety, are related to the following:

1. Assuming awkward positions due to restricted spaces; when they lack suitable foot support, workers become fatigued and commit errors
2. Moving heavy components that cause damage to the spine
3. Lacking tools or using incorrect tools
4. Lacking clear visibility

Other common factors that cause errors are

- Difficulty in understanding the task (work orders, manuals, etc.)
- Interruptions during the accomplishment of the task; for example, making phone calls or stopping to eat can lead to forgetfulness, with serious consequences
- Incorrect or inadequate lighting
- Machines and/or components that are difficult to handle due to their design

3.3.2 Influence of Human Factors on Maintainability

Certain factors affect safety during maintenance interventions. In addition to safety, reliability and availability are a concern. Repairs and the time taken to perform them will influence the system's reliability and availability. The variable of concern here is maintainability, which, like safety, is a RAMS parameter, where the human factor is very important. By measuring maintainability, it is possible to make accurate predictions, thereby optimizing maintenance times and costs.

The question that arises is, why do different individuals take different amounts of time to execute identical maintenance tasks? To answer this question, it is necessary to analyze all the factors contributing to the KPI of the human factor in maintenance. The following three are the most influential:

1. *Personal factors* represent the influence of the ability, motivation, experience, attitude, physical conditioning, view, self-discipline, formation, responsibility, and other similar characteristics of the personnel involved.
2. *Conditional factors* represent the influence of the operating surroundings and the consequences that a failure in the physical conditions has produced.
3. *Surroundings* include the influence of factors like temperature, humidity, noise, light, vibration, time of day, time of year, and wind on maintenance personnel.

These factors directly affect the time required to complete a maintenance task. Consequently, the nature of the maintenance task also depends on the variability of those parameters.

As a result of the high number of parameters in each group, on the one hand, and their variability, on the otherhand, it is impossible to find a rule to describe this complex relation for maintainability. Rather, the analysis of maintainability must resort to determining probabilities using existing data.

Of the three aspects, the most important one is the human factor and the man–machine interaction in the repair process. This strongly influences the quantification of maintainability, reducing or increasing the reliability of the equipment and affecting availability.

Simply stated, maintenance tasks, whether routine or not, are influenced by human factors, both physical and emotional. When considering the interface of users and maintenance personnel with the system, their physical characteristics must be taken into account. Following Maslow [204] and Herzberg [119], workers must be able to carry out their work in physical conditions that fit into the pyramid of values. Therefore, the primary target of the anthropometric analysis of maintainability is to consider the limitations of human action with respect to the size of the body and its physical force. Access to the system, the location, the setup, the weight, and the repair time must be evaluated, along with the human characteristics as design parameters, as the human factor is a crucial and irreplaceable element of maintenance.

The analysis must verify that the design proposed for the system will allow the maintenance personnel to install and work on equipment effectively, within the limits of the system and the surroundings. An anthropometric evaluation identifies the requirements of the location and the configuration of the equipment to provide sufficient access and adequate work space for maintenance personnel. This type of evaluation identifies the structural characteristics of the equipment that may prevent the accomplishment of tasks by inhibiting or impeding the movements of maintenance personnel. It compares the statistical data on the proportions of the user's body with the work space and the anticipated configuration of the equipment during maintenance. Normally, the evaluations include biomechanical considerations of the force and movements of the personnel. Anthropometric considerations start during the conceptual phase and continue during design and development. Although the systems must be sufficiently detailed and mature before the evaluation can be completed, the evaluation of subsystems begins during the phase of the program's conceptual development. Before a reengineering design is defined, some level of anthropometric evaluation is required to ensure that the anthropometric and biomechanical characteristics of the maintenance personnel have been considered in the design [171].

Evaluations normally consider the following factors:

- Anthropometric characteristics of the population of users
- Setup, location, and weight of the systems
- Procedures for accessing, disassembling, installation, and alignment
- Area, height, congestion, and limitations of the work space
- Characteristics of human engineering that facilitate maintenance (i.e., grips, steps, registries, posters with instructions, etc.)
- Clear areas and angles of view of the maintenance personnel
- Tools, special equipment for support, and devices
- Dangers, precautions, protective clothing, and evacuation areas

An anthropometric evaluation begins with anthropometric descriptions of the population of users, functional descriptions of the subsystems, setup of the engineering design, setup of equipment assembly, and analysis of maintenance tasks.

The measures of the human body are of great importance, both when designing the equipment and when assembling and using it, in order to create the conditions necessary for safe and effective maintenance. In Figure 3.3, Blanchard et al. [26] show the concept of human factors in maintainability, from the design stage and throughout the cycle of operation.

In addition, designers must consider the following typical behaviors of those who repair the equipment:

- People usually execute their assigned tasks while thinking about other things.
- People tend to use their hands.
- People usually are too impatient to take the necessary time to take precautions.

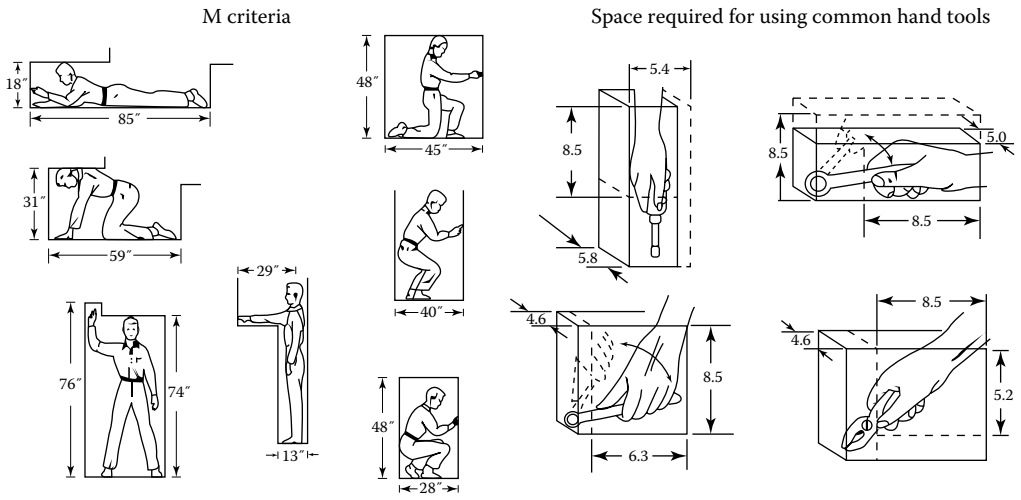

FIGURE 3.3
Maintainability. (Adapted from Blanchard, B. et al., *Maintainability: A Key to Effective Service Ability and Maintenance Management*, John Wiley & Sons Inc., New York, 1995.)

- People usually read instructions and labels incorrectly or too casually.
- After executing a procedure, people normally do not realize how to detect errors.
- People usually respond irrationally in emergency situations.
- People usually are too obstinate to admit errors.
- After manipulating dangerous objects correctly over a long period of time, many people begin to feel too trusting and are less careful.
- People are generally reluctant to admit that they do not see clearly or do not hear well, but both are likely to be the product of an external condition.
- People often do not make good estimations of distance, speed, illumination, or weight.

Of all these data, a mixture of physical and mental factors is inherent to the execution of maintenance tasks, influencing RAMS parameters and safety, because maintenance personnel have greater exposure to risk than the rest of the employees in a plant.

3.3.3 Influence of Behavior and Human Error in RAMS

As explained earlier, maintainability is related to physical human characteristics, including force, design, physical accessibility, or other variables. But nonphysical characteristics, such as behavior, are also important in the determination of RAMS parameters.

Operating reliability is strongly influenced by the human being and his/her errors. A classification of the various processes that occur in industrial tasks has been developed by Rasmussen [274]. This procedure is a useful tool to identify the types of error that usually occur during operation. The system of classification is based on skills, rules, and knowledge (SRK) and is described in numerous publications [273,275,276,279].

The terms skills, rules, and knowledge relate to how the individual carries out his/her activity. Table 3.1 shows two extreme cases.

In knowledge-based activity, the individual carries out the task in a completely conscious manner. This could happen in a situation where a newcomer is executing a task for the first time or when an experienced individual is in a completely new situation. In both cases, the worker must make a considerable mental effort to handle the situation

TABLE 3.1

Ways of Interacting with the World

Way Based on the Knowledge BRINGS BACK TO CONSCIOUSNESS	**Way Based on the AUTOMATIC Ability**
Inexpert or occasional user	Expert user
Novel surroundings	Familiar surroundings
Slow	Express
Much effort	Little effort
Requires considerable feedback	Requires little feedback
Causes of the error:	Causes of the error:
Overload	Consolidated habits
Lack of knowledge or ways of use	Frequently an inadequate rule of use is used
Lack of knowledge of the consequences	Changes in the situation that do not motivate a change in habits

Source: Data from Reason, J., *Human Error*, Cambridge Press, New York, 1990.

and decisions will tend to be slow. After each controlled action, the worker will need to review his/her efforts before carrying out the next action, slowing down the whole process.

The execution of a task based on ability requires very practiced physical actions, with the individual not always conscious of his/her actions. Actions based on ability are generated initially by some specific facts, for example, when an alarm sounds, a certain procedure must be followed; the subsequent operation is realized unconsciously by individuals who are very experienced in performing it and who find it simple.

In Figure 3.4, another category of the information process is identified, in this case, the use of rules to determine the action. Rules can be learned as a result of an interaction with the process, through training or by working with experienced personnel. The level of consciousness is somewhere between actions based on abilities and actions based on knowledge.

The execution of work in maintenance and the behavior while performing it will have an impact on RAMS parameters. Work with a component of stress creates what has been called an index of mental load, whereby an increase in the difficulty of a task will produce an increase in its demands, reducing performance [60].

Figure 3.5 shows the relationship between the mental load and the performance of a worker, distinguishing three possible situations.

The first situation, shown in level A, includes levels of load between low and moderate and is characterized by the presence of a high level of performance. In this region, the increased complexity of the task will not produce variations in the level of performance of the worker since it has a residual capacity sufficient to compensate for the increased load. In level B, high levels of mental load exceed the capacity of the worker, thus reducing his/her performance. Finally, in level C, the load is excessively high and the performance stays at a very low level.

Dalmau [60] distinguishes between simple and multiple tasks. In the former, the mental load of a task is evaluated on the basis of the performance of a unique task. In the latter, the analysis focuses on the mental load created for a single task when it is carried out simultaneously with others of equal or different characteristics. When the subject must carry out two tasks simultaneously, the situation is called a dual task or a double task. The task being

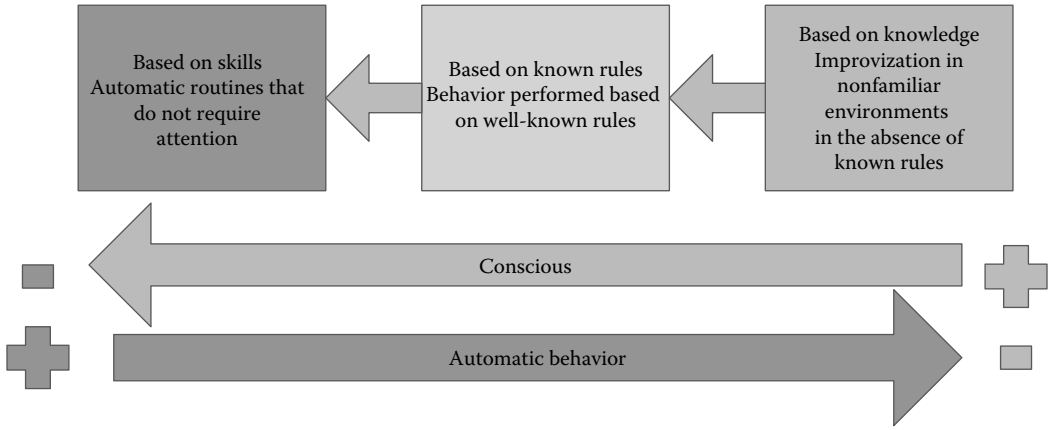

FIGURE 3.4
Continuity between conscious and automatic behavior. (Adapted from Reason, J., *Human Error*, Cambridge Press, New York, 1990.)

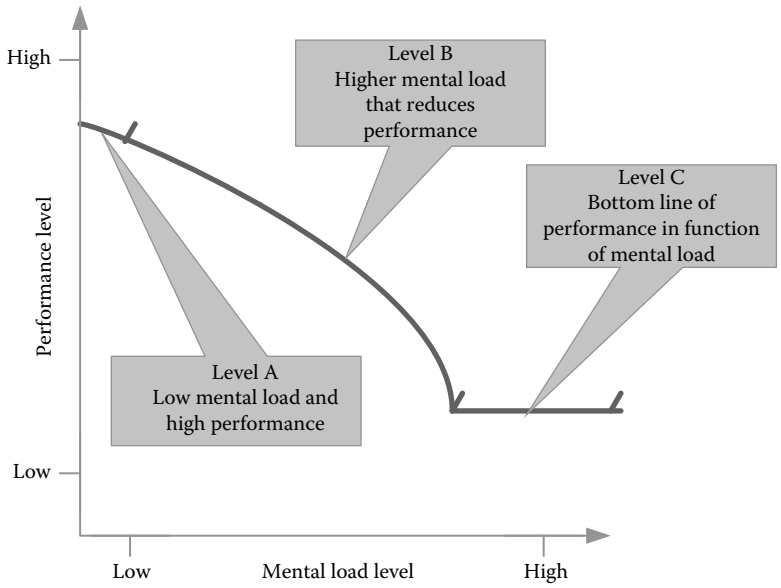

FIGURE 3.5
Hypothetical relationship between mental load and performance.

evaluated is the primary task. Additional tasks that are not being evaluated are secondary tasks. This could be an excellent indicator for the maintenance function, but its use is limited to certain jobs, such as air traffic controllers, and to certain sectors, such as the nuclear and aeronautical sectors.

3.3.4 Model of Human Reliability

To evaluate the reliability of a system, it is important to remember that the person not only plays a negative role as the source of errors but he/she is also able to anticipate problems, handle nonpredicted deviations of the system and incidents related to technical failures, and identify and rectify his/her own and other people's errors. In fact, the human being surpasses the majority of technical devices [185] in the following ways:

- Superior capacity to adapt in nonforeseeable situations and flexibility to modify strategies to reach the determined objective
- Ability to learn in new situations, constructing possible resolution strategies and adapting them to future circumstances
- Ability, mainly in dynamic surroundings, to anticipate events and, therefore, to modify initial strategies to avoid unfortunate consequences and correct errors

When the operation security studies are often based on the quantitative aspects of the human activity, human reliability can be difficult to define quantitatively [137]. Only a close analysis of the activity of the person in a system reveals the characteristics of this activity and allows one to search solutions to diminish the sources of unreliability without harming the reliability activities.

In the analysis of the safety of systems, it may be tempting to apply the methods of study of technical reliability to the study of human reliability but doing so would ignore certain

characteristics of the human being, such as the capacity to learn and adapt, as well as the ability to correct or to recover from human errors and technical failures.

At the same time, it is necessary to consider the variability of a person's conduct (based on such things as fatigue, physical strength, psychological, affective and mental characteristics, attitudes, training, and experience) and interpersonal variability; it can manifest as an unreliability element hardly controllable through the selection and formation of personnel. To this, we can add "extreme" environmental situations (radioactivity, great depths/heights, climatic conditions, etc.).

In short, the possibilities of transferring the techniques used in the analysis of technical reliability to the analysis of human reliability are limited. It is necessary to design methods to analyze human reliability that consider both human error and human contributions. The application of a model of human reliability depends to a great extent on the strategy formulated.

Figure 3.6 shows an application of human reliability based on managing knowledge. It attempts to implement proactive operational reliability, creating a strategic map to diagnose and mitigate failures from both the operational and human points of view.

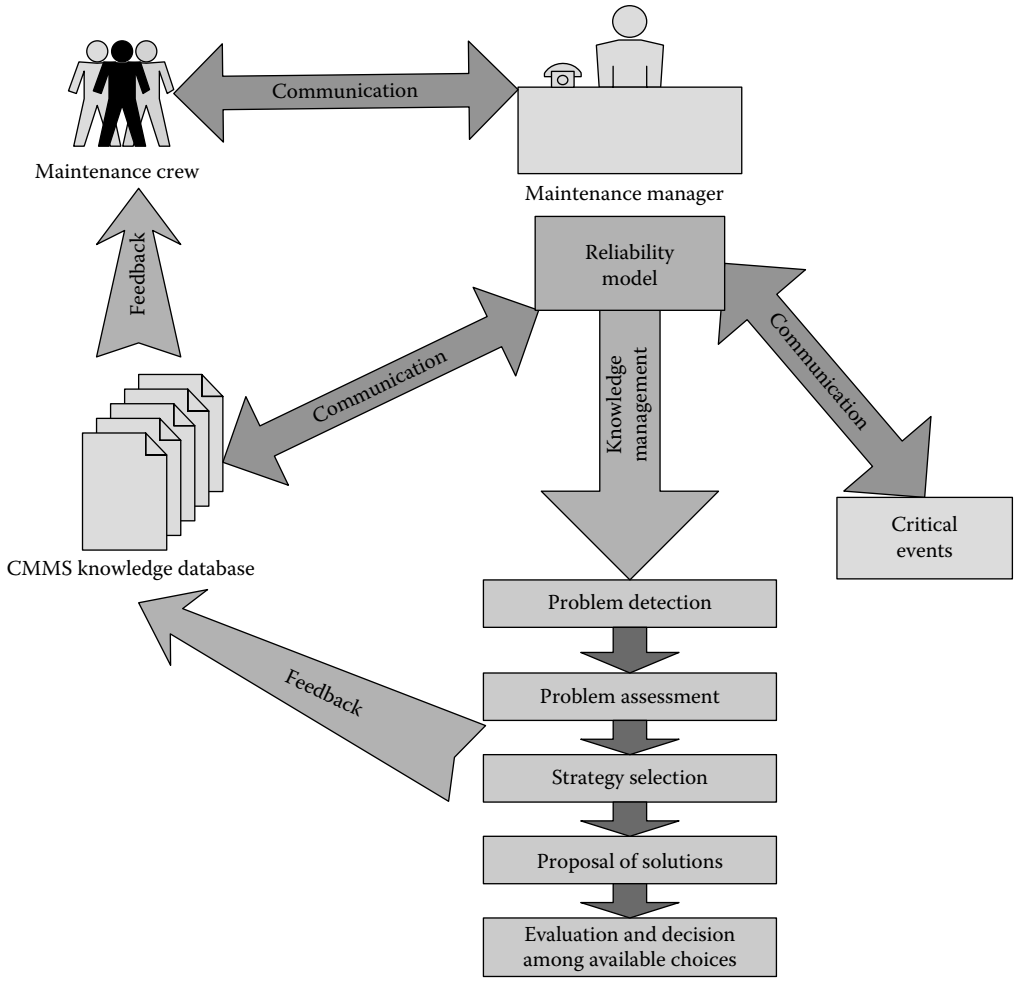

FIGURE 3.6
Model of human reliability.

The objective is to determine the causes of problems in each sphere. All work parties take part in this exercise. Data are gathered from events, various databases, and the work parties, with the aim of clarifying the causes of problems. Data comprise of flow charts, methods, attempts to balance load and capacity, balance sheets and financial statements, behavior of the defects, power consumption by areas, processes, and so on.

Group integration required during this stage will facilitate finding solutions. Even though knowledge of a problem may come from a variety of different stakeholders, as individuals and as a group, they feel responsible for achieving optimal operational reliability. The group is seeking technically and economically correct solutions for concrete problems.

If a function can be seen as an attribute of a component, it implies that a function can fail, although the circumstances or the context can have some influence. This differentiates intrinsically from operational reliability.

To anticipate failures in a man–machine system, we need a model. The model must consider how human operation is determined by the context or the circumstances. Such a model corresponds with the concept of distributed cognition [126]. A concrete expression of these ideas is the contextual models of Hollnagel [123]; these models describe human functions and technology as united systems instead of human interactions with machines. The models emphasize how the man–machine cooperation maintains a balance based on "cognition of the world" instead of "cognition in the mind."

3.3.5 Characteristics of Behavior in Maintenance: Individual and Group

When considering the main human factors related to the management of maintenance, the following definition is useful:

> Human characteristics define the way an individual or a group behaves in an industrial context, including how a maintenance department works.

Note that these characteristics affect both individual and group behavior (whole companies, departments, or work parties).

Individual behavioral characteristics are discussed in the following sections.

3.3.5.1 Ownership of and Responsibility for Equipment

The ownership factor implies the degree to which workers feel a sense of ownership over a machine or an area of the plant.

This factor is extremely important for reliability. When workers feel the equipment belongs to them, it tends to be better operated and well maintained.

One of the main characteristics of TPM is the creation of small independent teams of up to seven equipment operators in charge of a particular process or area of the plant with the responsibility of carrying out simple maintenance on the equipment involved, such as lubrication, adjustments, and smaller maintenance tasks. The team is composed of operators with training in basic maintenance and operators with more professional training. The team is encouraged, with the help of engineers, to design and carry out modifications to improve the operation and reliability of the equipment for which it is responsible (i.e., continuous improvement or Kaizen). Such actions generate a considerable feeling of ownership; the workers worry about the equipment as if it literally belongs to them.

3.3.5.2 Positive Feelings/Goodwill

This factor reflects positive feelings about a person, a cause, or a company. It is closely related to loyalty but is more demanding. In many aspects, it can be considered a key factor. When workers feel a sense of goodwill toward a plant, problems seem to be more effectively and efficiently solved. This type of atmosphere takes a long time to construct, with many years of good relations and confidence in the management and the company. It is a function of how the company treats its workers, and so on, with respect.

3.3.5.3 Motivation

Motivation is by far the most frequently investigated factor. People are only motivated when they are doing something (work, leisure, sport, repairs of the home) they really want to do. Generally, an industrial worker is considered as someone who sees his/her work merely as a means to obtain money and thus to satisfy his/her needs. The majority of the time the worker does not feel motivated at work. Moreover, the nature of the work is such that, normally, it is difficult to establish what changes will create motivation [165].

To apply these ideas to maintenance is not difficult. To a certain extent, maintenance tasks have many of the ingredients necessary to fit Herzberg's [119] theory of the satisfaction and motivation of workers, whereby workers enjoy autonomy, pride in the quality of work carried out, and so on, when companies create TPM policies of autonomy.

Maintenance workers are among the few who still have considerable autonomy in their day-to-day actions. For example, it is difficult to verify if a roving inspection of preventive maintenance has been carried out. It is also difficult to determine if a good repair has been made, and in some cases, if the spare parts used are the best ones from the company's point of view. The maintenance personnel know that the consequences of their actions usually are not immediate; an error committed in a repair will show up later and be difficult to attribute.

In the case of maintenance workers, the indicators of their level of motivation include

1. Knowing what is required of them
2. Knowing the level of effort required to secure the objectives with minimal external control

When trying to influence, include/understand, or audit motivation within a maintenance department, the following aspects must be considered:

- The history of relations in the plant, their present state, and their deficiencies
- The factors that influence the nature of the work and its surroundings
- The social and political surroundings as well as their influence (this ensures that internal change is possible)
- The workers' understanding of maintenance objectives (the most important factor in motivation)

3.3.5.4 Morale

Morale is defined as the mental state of an individual with respect to his/her confidence and happiness. Some [120] maintain that productivity is not a function of morale and, therefore, morale is not a significant concept in maintenance audits. Nevertheless, a lack of morale in individuals or work groups affects the amount and quality of maintenance.

For a person in the maintenance department, morale can be defined as that person's positive or negative perception of his/her work and how it affects the success or failure of the company.

Negative factors that affect morale include the following:

- Bad economic results of the company
- Poorly organized or badly implemented systems that create problems in the quality of product
- Recent labor dismissals and the threat of more

3.5.5.5 Resentment

Resentment can be defined as a strong feeling of bad will. It is common in human relations and in maintenance. Resentment frequently occurs when there are promotions, especially when the promotions do not seem to go to the best candidates. The frustration of those who are not promoted can affect the quality of work carried out. Resentment can even lead to sabotage, causing serious economic losses for the organization.

3.3.5.6 Protectionism

Protectionism can be defined in the context of maintenance as the resistance to share knowledge and information. It can be affected by other human factors like insecurity and low morale. A typical example is a technician (normally older) who has accumulated considerable knowledge over many years about specific equipment but is too obstinate to document or to transmit his/her knowledge to other employees, largely because he/she thinks that his/her job depends on being the unique possessor of that knowledge. This is one of the more serious problems in maintenance management.

3.3.5.7 Parochialism

Parochialism is defined as being narrow in scope. Many intermediate managers impose a form of management dominated by hostility toward the rest of their organization, believing that anything outside their department (or their plant) works badly. This limited vision generates upheavals when new people are appointed or when new departments or plants are created, especially in those with decentralized structures or in geographically dispersed areas where distance handicaps organizational integration. Parochialisms generate other problems related to human factors also, for example, polarization. Organizational design necessarily creates limits between departments. Therefore, managers must work to minimize the injurious effects of parochialism.

3.3.5.8 Jealousy

People become jealous when they lack something that someone else has, including assigned tools, offices, furniture, computers, and so on. In some plants, there is a problem of "jealousy" between the maintenance personnel and production workers. Traditionally, workers operate the equipment and maintenance personnel carry out interventions.

When the production worker tries to learn a little bit about the equipment during an intervention, the mechanic asks him/her to leave or he/she does not want to bother

teaching the production worker since he/she considers that this task is the exclusive prerogative of the maintenance technician.

Imagine this scenario. A worker asks an expert mechanic: "How did you fix it?" The mechanic responds, "It is a professional secret." This type of attitude does not allow the worker to obtain more knowledge about the equipment. In the future, the worker will not try to take part in repairs.

3.3.5.9 Positive Attitude

Creating a positive attitude is fundamental to maintenance performance. The TPM's independent maintenance stresses the use of standards in the workplace. Such work practices create a respectful attitude toward maintenance procedures by both maintenance personnel and production workers; everyone understands the necessity to use them and to improve upon them. This makes independent maintenance a powerful strategy in the continuous transformation of a company. It adapts the organization to meet the new exigencies of the market. Because people understand the processes, a positive predisposition toward work is created, one that is disciplined and respectful of the norms and procedures.

3.3.5.10 Envy

Envy is based on human conflict and is not unique to a particular society or a specific company; rather, it has origins in the human psyche and is a universal and irrational phenomenon. In the workplace, it is often expressed toward someone with whom a worker is in personal or professional competition. He/she will express envy by ignoring the other person, showing contempt, or trying to discredit him/her.

This conduct is displayed by people with low self-esteem and those with narcissistic tendencies. Understandably, those people with low self-esteem who lack the ability to innovate will become frustrated and resentful. Some will try to block the efforts of those with the abilities they lack. In contrast, narcissists cannot distinguish or recognize strengths that are not their own. The world runs on the rules that they themselves are constructing, making other people's efforts irrelevant (or unnoticed); this leads to deep enmities and internal struggles.

Envy is an influential factor in maintenance. Effective maintenance requires both rapid diagnosis and ongoing innovation to achieve improvement, but envy can neutralize the capacity to react to failures, thus affecting RAMS parameters and the costs involved in each failure. This situation worsens when a person is promoted based on his/her innovation over those who think they have more merit.

3.3.5.11 Resistance to Change

Change applies to any situation where certain structures, procedures, and behaviors are substituted for other structures, behaviors, and procedures in an attempt to improve effectiveness [106]. One of the difficulties of introducing change is that some people benefit whereas others suffer (or think they will suffer). Those who resist usually suffer from tension, restlessness, and anxiety during the change [239].

Obstacles include environmental factors that make it difficult to apply change. In addition, feelings of threatened security result in resistance to change. In a certain sense, however, this is positive, in that behavior can be predicted. Resistance to change can be a

source of conflict, but it can also be used in certain crises when it is advantageous to predict individual and group behavior.

A dislike of the introduction of new methods of work, such as the use of computers in equipment or systems, is frequently seen in maintenance. The use of TPM or the acquisition of a CMMS often leads to a strong initial component of resistance, easier to overcome if it is isolated to a small group of people and does not become a general feeling.

Robbins [286] indicates that the sources of resistance to change are both individual and organizational. The individual sources of resistance reside in basic human characteristics including perceptions, personalities, and needs; individuals resist change because of economic factors, habits, safety issues, fear of strangers, or selective processing of information. Meanwhile, organizations, by their very nature, will actively resist change. Since organizations are composed of many individuals, the multiplication effect of individual resistance slows down the organization's ability to change. However, the important thing is that the organization can change since if it does not do so, it will not survive [102].

3.3.5.12 Pride

The maintenance personnel are seldom explicitly recognized by the top management or even by other departments. Even so, they are proud of their work because they see an immediate and positive result. In addition, following the new methodologies introduced by 5S, they express pride in their work surroundings.

Mendoza [211] notes that the aeronautics industry has fostered pride in the workplace and 5S policies, for example, ensuring that tools are not left in the airplane after a repair as this causes accidents. Pride in the location and surroundings and in the possession of certain tools reduces negligence and keeps factories in optimal conditions.

3.3.5.13 Prejudices

A prejudice is an opinion or position on a subject, preconceived or partial, that is often erroneous. Maintenance workers and production workers often have preconceived notions about their respective jobs. Maintenance workers say: "They break it, we fix it." Production's typical response is: "They don't understand our objectives."

Sexto [292] says that it is common to identify maintenance as dirty, heavy work. Yet maintenance is based on scientific and practical criteria. It combines statistics, computer science, experience, diagnostics, accounting, and innovation, applied within the framework of modern engineering. Intervention in machines must be the last decision in a chain of decisions based on the data, the applied techniques of maintenance, and common sense.

Job cuts lead to prejudice. For example, when a company decides to subcontract a service, the sectors and personnel that previously carried it out are seriously affected. This usually translates into prejudice against "outsiders" based on the idea that subcontracting leads to lower wages and poor working conditions and is an attempt by management to eliminate internal workers midterm. Subcontracting is rarely seen as an added value and must be handled carefully.

Characteristics of group behavior are discussed in the following sections.

3.3.5.14 Culture

Kast and Rosenzweig [159] define culture as the collective mental programming of people in their surroundings. It is not a characteristic of individuals but of a number of people

with similar life experiences. Therefore, when a plant is audited, it is important to know and to include/understand the surrounding culture. In the case of maintenance, this includes the technological culture and its influence on quality, costs, competitiveness, and the environment. It is also important to include sociocultural changes and to consider the extent to which traditional cultural values have influenced the transference of innovative technologies to maintenance.

3.3.5.15 Esprit de Corps

This is a sense of belonging in a particular company or group, whereby the group is more important than the individual. The concept has military origins and was picked up by Japanese companies in the 1970s. It is difficult to find an organization with this feeling that is not Japanese. Breaking down large organizations into semi-independent units of manufacture has been suggested in order to generate esprit de corps in each unit, but the result is often parochialism and protectionism, making it difficult to run the units in question.

A company policy with a communitarian and paternalistic vision is often strongly resisted by workers.

Management could attempt to influence personnel at an affective and psychic level, for example, through religion; such initiatives rarely succeed, except in certain cultural or religious microclimates.

3.3.5.16 Horizontal Polarization

Horizontal polarization is defined as the possession of opinions and attitudes that are different from those of other departments at the same level, that is interdepartmental frictions. Figure 3.7 shows this as a pyramid.

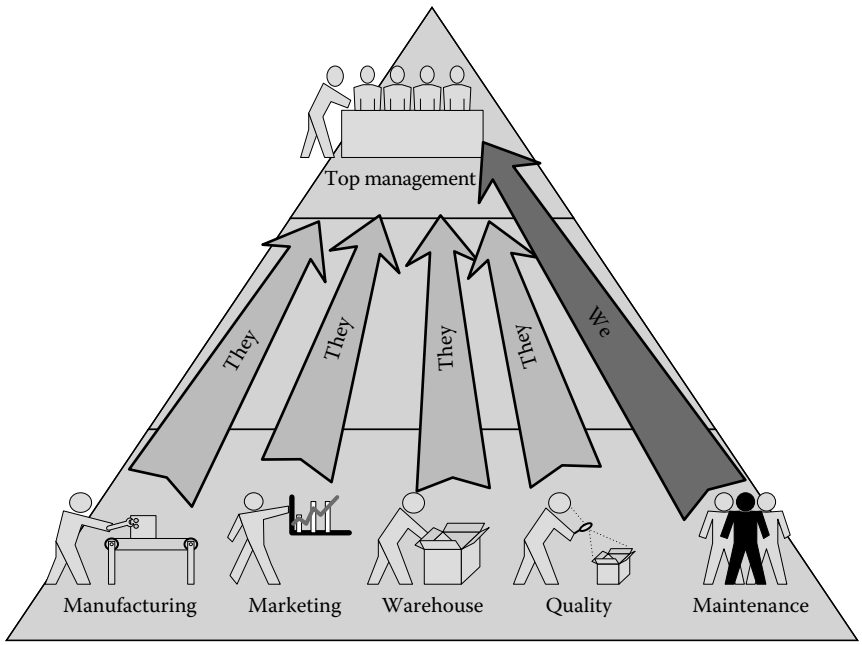

FIGURE 3.7
Horizontal polarization in an administrative structure.

Conflict accumulates in the borders of the main departments, such as production, maintenance, engineering, warehouses, and to a lesser extent in the subdepartments, such as electrical maintenance and mechanical maintenance.

The conflict between production and maintenance is frequently studied. The commonly expressed maintenance complaint is, "They broke it, and now we have to fix it." In other words, "Production operates poorly." For its part, production thinks maintenance does not understand its objectives. Requests for access to equipment for preventive maintenances or modifications that require machines to be shut down are always a source of conflict, especially when a shutdown is not programmed in advance. On such occasions, maintenance should clearly explain the reasons for the shutdown.

Often, there is conflict between maintenance and the warehouse when these functions are the responsibility of different departments. For example, the company wants to reduce the number of spare parts to minimize the cost of operating and stocking the warehouse. Maintenance tries to maintain the inventory of spare parts at a high level; the warehouse management tries to lower it. Not surprisingly, the resulting conflicts polarize the departments, expressed in the figure as feelings of "we" and "they." Communication between the two departments and the understanding of each other's work are completely lost.

3.3.5.17 Vertical Polarization

There can be strong antipathy between the different levels of an organization, especially when there are many hierarchical levels, as shown in Figure 3.8.

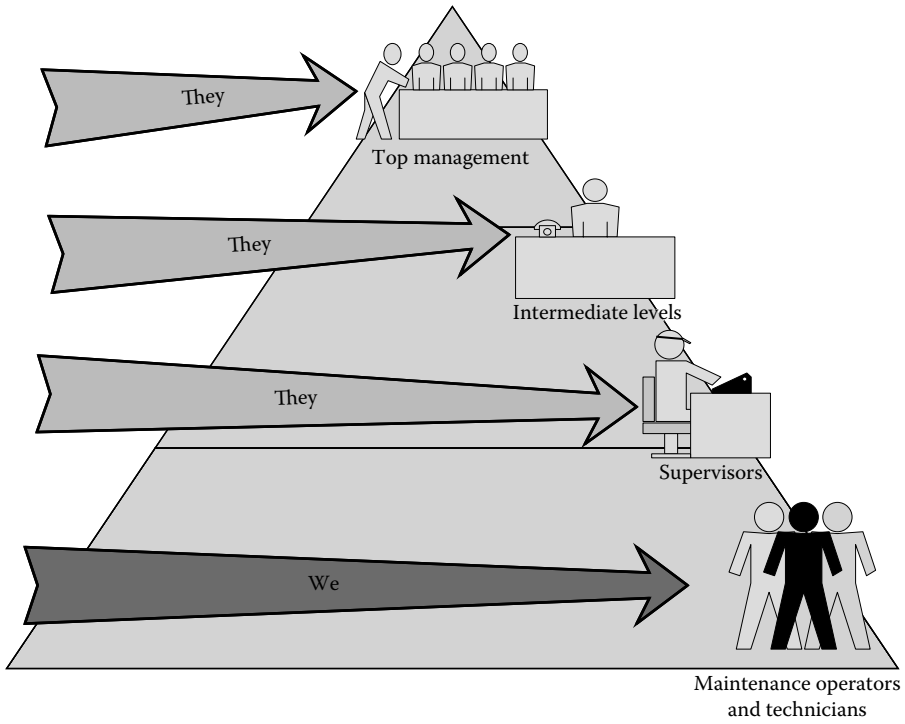

FIGURE 3.8
Vertical polarization in one structure enterprises.

A greater degree of antipathy is often between the plant workers and the directors of the various levels as they may have conflicting objectives and attitudes. This affects communication, along with certain important characteristics of individual behavior, for example, goodwill and motivation. Another vertical friction found in maintenance is in the interface between maintenance supervisors and the directors of engineering services. The supervisors are generally office workers; they do not have engineering degrees and only rarely are they in upper management. For the workers, they represent a lower and more accessible level of management. In addition, they tend to be less movable within the organization, unlike the engineers, who have many avenues open to them.

Recently, the direct management of workers by a control role has been threatened by the introduction of independent equipment. In many industries, the role has evolved into that of a technical adviser, planner, or group leader. The company direction not always assumes those new roles and the lower levels do not just believe that the role they are playing is authentic and whether the new role is a fictitious position to stage the implementation of a new methodology, often imposed.

This has given rise to new conflicts and polarization.

The syndrome of "we" and "they" is more evident in large organizations that are highly hierarchically structured at the top, with long chains of command between managers and operators. The polarization in such organizations can cause total lack of communication, organizational contraction, and possible failures in the system.

3.4 Effect of Subcontracting and Strategic Alliances with Maintenance Companies

To this point, the chapter has discussed human factors within traditional organizations, those in which all maintenance is carried out by personnel inside the organization, except during periods of maximum volume of labor.

In maintenance, contracted services should be correctly applied and controlled. When correctly used, subcontracting can ensure economic savings, fast solutions, alternatives for difficult situations, and a guarantee that large volumes of work can be handled.

Contracted services are generally useful for the following:

- Technology-specific equipment that require specialized personnel and/or tools and/or materials
- Services of noncontinuous nature with defined costs (gardening, painting of buildings and facilities, etc.)
- Services unrelated to the main activity of the company (security, feeding, cleaning, etc.)

Theoretically, subcontracting has the following benefits:

- Liberation of the client to take care of the fundamental activity
- Availability of special technology
- Improvement of the quality of services
- Reduction of operating costs

The reduction of manpower in a company does not necessarily mean increased unemployment, but this is a common fear among workers as they associate externalization with job loss.

Before initiating a contract or extending the services already contracted out, the following measures should be considered:

- Establish a clear definition of the services required, types and programs of maintenance, as well as spare parts, regularity of interventions, guarantee of services, qualifications of the technical personnel, and rapidity of solutions.
- Make the best contract possible so that the contractor strictly fulfills the services for which he/she has been hired.

Fluid communication is essential between the directors and workers so that the latter do not see subcontracting as a direct threat to their job security or a transparent attempt to reduce costs.

- The specifications and the contract, even though important, do not improve the services if the participation and the responsibility of the maintenance director are not considered as he/she must oversee the contracted services.

A recent tendency is the subcontracting of specialized maintenance companies, whereby alliances with organizations generate second and third work contracts.

Often, even the management of the warehouses that are transferred to company object of the alliance generates a mix of personnel, between company personnel transferred and contractor personnel. This practice introduces some quite negative items for the human factors, that is,

- The morale of the present personnel slumps and workers show strong resistance to change since they find their positions less safe. They feel that they have little in common with the contract workers.
- The incoming personnel have little knowledge of the equipment and will not have developed any feelings of goodwill toward the company.
- A sense of the ownership of equipment is difficult to instill in contract workers.

Positive elements of this type of alliance are

- Such alliances offer quantitative indices of key performance, leading to the fast development of the ways to measure maintenance. Contractors know that if the service does not reach expected levels of safety, availability, reliability, and so on demanded, the contract will be terminated. This increases motivation.
- The contractor contributes his/her experience in engineering and work planning with the consequent improvement of efficiency and safety, thus boosting morale.
- Technical knowledge and specialized access to suppliers or services are ensured in the contract.

Nevertheless, the development of a sense of owning the equipment is necessary because this feeling is seldom seen in the personnel who work for contractors.

Tavares [323] says that some companies successfully establish association with their contractors, thus ensuring the continuity of the quality of services without making major changes. There are companies that provide, with the enforcement personnel maintenance services itself, a subcontracting relationship, that is, outsource the service without changing the staff. It ensures that the first generation of employees continue to give the quality of service without the initial fanfare. The association process can provide a company with the suitable logistic, administrative, countable, and legal support for its operation.

A risk of the association process is the loss of interest if the associated subcontractors lose benefits that they previously had. In addition, being outside the organization may lead to insecurity.

These frictions lead companies to negotiate the conditions of subcontracting, guaranteeing the necessary support and reducing the risk due to ignorance.

- They guarantee the homogenization of practices (i.e., standard procedures of the parent organization).
- They orient and stimulate learning (possibility of interchanges of knowledge with the subcontracted companies).
- They stimulate the development of new technologies (in the first company and the subcontracted one).
- They disseminate knowledge of the company's values and organizational culture.
- They maintain the sense of being properly taken care of; the practice of subcontracting is effective only if the service is fast, effective, and efficient.

3.5 Measurement of Human Factors in the Management of Maintenance

Human behavior can have a strong effect on the performance of organizations. Although human factors can be identified, it is difficult to audit them objectively and even more difficult to quantify them.

Some typical questions in maintenance surveys quantifying these factors are the following:

1. Do you have a feeling of owning the equipment that you maintain?
2. Do production workers have a "sense of ownership" toward the equipment they operate?
3. Do you have a positive feeling or a feeling of goodwill toward the company and its direction?
4. Do you consider that you have high morale?
5. Are you motivated to work toward meeting the interests of the company?
6. Is your relationship with production workers and supervisors a good one?
7. Would you define the warehouse service as effective?

These questions constitute a relatively small part of the audit, however, and the questions listed here are for maintenance managers. The auditor must consider different sets of questions for operators, supervisors, and engineers related to maintenance. In addition, the auditor must explain what he/she means by "ownership" and the scale used to measure it. In any case, the answers will reflect human factors, for example,

- We are a multinational group; therefore, we do not have a feeling of owning the equipment.
- Plant rotation goes against the feeling of ownership and the generation of specific and specialized knowledge.
- There is a sense of not owning the production equipment.

A representative sample of the answers should be included in the audit report.

The characteristics of group behavior require a different approach, as indicated in the previous questions for horizontal polarization. Question 6 is conceived to determine opinions, attitudes, cooperation, and communication between production and maintenance. Questions for the production department will ask about their perception of maintenance.

When large organizations are audited, opinion surveys must include questions on human factors. The primary target of the human factors audit consists of identifying the factors that are affecting maintenance performance or of positive or negative way. When positive, it is given advice on how they can be strengthened and sustained. When it is negative, the advice is about how you can eliminate or mitigate their influence. If in a traditional organization is a little sense of property of the teams in officials and workers, breadwinner-operator can improve enough by means of the creation of mixed equipment cars managed, that is to say equipped with autonomy. If such structural modification is neither possible nor desirable, they must look for alternatives within the traditional structure, for example, maintenance managers responsible for the preventative maintenance of specific equipment.

Although structural change can improve the feeling of ownership, it can have negative consequences, for example, parochialism, as described earlier. It is important to emphasize that organizational change requires a complex mixture of decisions about human factors and systems. Before making decisions, however, it is essential to have the clearest possible image of the existing situation.

3.6 Management of Knowledge in Maintenance

A particularly valuable part of maintenance is the management of knowledge. The intellectual capital behind good maintenance must not disappear with the people who have it. Steward [309] defines intellectual capital as "intellectual material, knowledge, information, intellectual property, experience that can be used to create value." In other words, intellectual capital is an intangible asset that includes the implicit and explicit knowledge required to generate economic value.

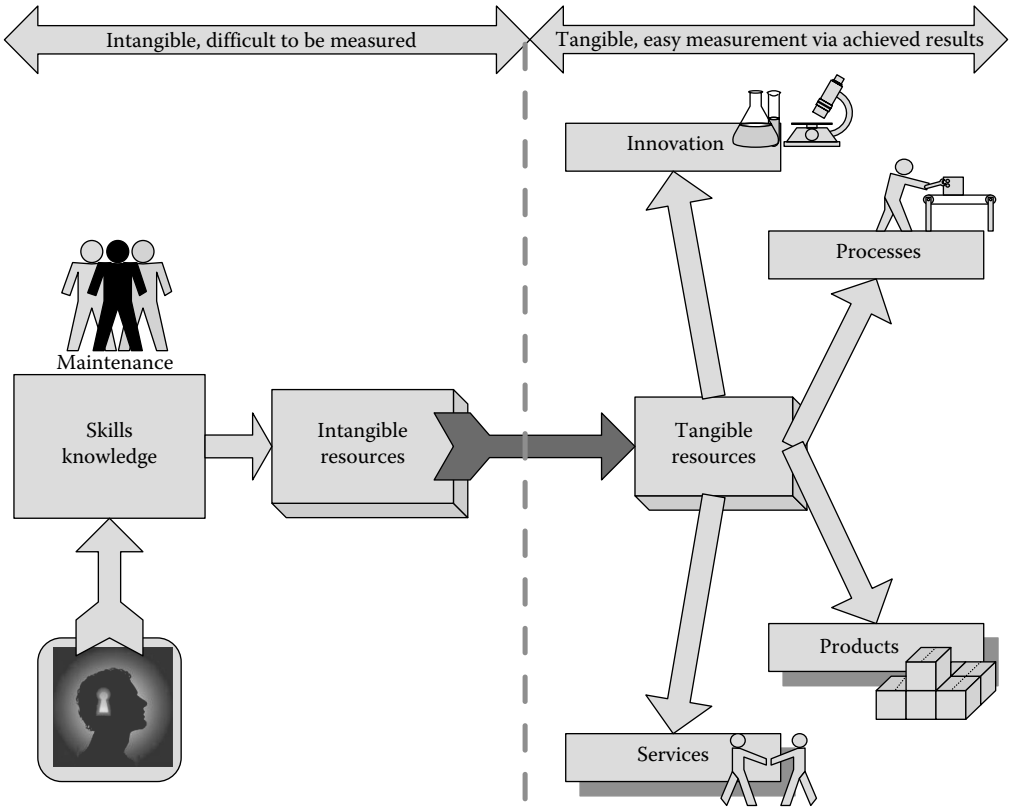

FIGURE 3.9
Intellectual capital.

More specifically, as shown in Figure 3.9, intellectual capital includes the education, experience, "know-how," knowledge, abilities, values, and attitudes of the people who work in a company. Knowledge of the organization resides in intellectual capital, but it is not the property of the company. Rather, it belongs to the workers, and they take it home with them.

Intellectual capital is an aspect of human capital. Human capital includes the capacities, talents, leadership skills, values, and culture that allow the creation of new knowledge and individual learning.

If wisely used, human capital, especially intellectual capital, can lead to innovation, including in the maintenance function. This, in turn, can allow a company to maintain or to secure a competitive advantage. If the intellectual capital concentrates on projects of improvement that are strategic for the maintenance of assets, this will result in the development of an understanding of "the future core business" of the company; from this, the organization can determine which job functions to subcontract out (outsourcing) and establish agreements and strategic alliances with suppliers and other companies.

For Duarte et al. [78], intellectual capital is an intangible resource. Yet intellectual capital generates real value and is a reality that must be incorporated into any system of indicators or measurements.

3.7 Human Factor: An Important Agent for Change in Maintenance

The introduction of any new method of work may be cathartic for many people in an organization. When the new method concerns the measurement of performance, the change affects all the human factors mentioned previously. This is especially the case when it is introduced into a department like maintenance, where performance is traditionally not measured. Most likely, then, the introduction of measurements of maintenance performance will be a major change, where success depends on the personnel carrying it out.

Success will depend on the number of people involved and the extent of their efforts. Workers will cooperate if they see good results, but if they do not, they will lose confidence in the process. The process typically takes a spiral shape, as much upward as downward. People lose confidence, even if they see poor results in other departments. They start to question the process when an action does not give the expected results. Failures take on a life of their own.

The importance of suitable management of the people by using a metric, which is practical was not used before is clear. The handling of those indicators, which would be directed toward the people, is going to be binding for the success of the project or its failure.

3.7.1 Importance of the Human Factor

Kaplan and Norton [155] say that the integral control panel [CMI, also balanced scorecard (BSC)] is a management system or administrative system that goes beyond the financial perspective of managers evaluating a company's progress. Instead, it measures the activities of a company in terms of its vision and strategy. It gives administrators a global perspective of the business. It shows when a company and its employees reach the results defined by the strategic plan. It is also a tool that helps a company meet the objectives and take the initiatives necessary to fulfill its strategy. The control panel can motivate people toward fulfillment of the company's overall mission, channeling the energies, abilities, and specific knowledge of personnel toward strategic goals. It guides present performance to meet future goals.

The CMI or BSC model uses four types of measures in maintenance:

1. *Finances*: To be efficient financially, how can one administer the resources, meeting the assigned budget and diminishing the costs of maintenance?
2. *Internal processes*: To satisfy the clients and meet the company's business vision, in what production process is it necessary to achieve excellence in maintenance?
3. *Clients*: What conception of maintenance will ensure that the maintenance actions are effective and meet production goals?
4. *Learning and innovation*: To reach the company's vision, how can one sustain the capacity to change and improve continuously so that one can respond to the changing conditions of the economic and technological surroundings?

The model emphasizes the value of learning and growth as this allows organizations to improve, learn, and change. Generally, this factor is less developed, however, and

companies have not really advanced in this area. The BSC/CMI control panel classifies the components of learning and improvement as

- Capacity and competence of people
- Information systems
- Culture–climate–motivation for learning and action

The implementation of maintenance measures can strengthen the human component of the workplace. Although learning and growth are less studied, they represent the foundation on which the organization grows (Figure 3.10).

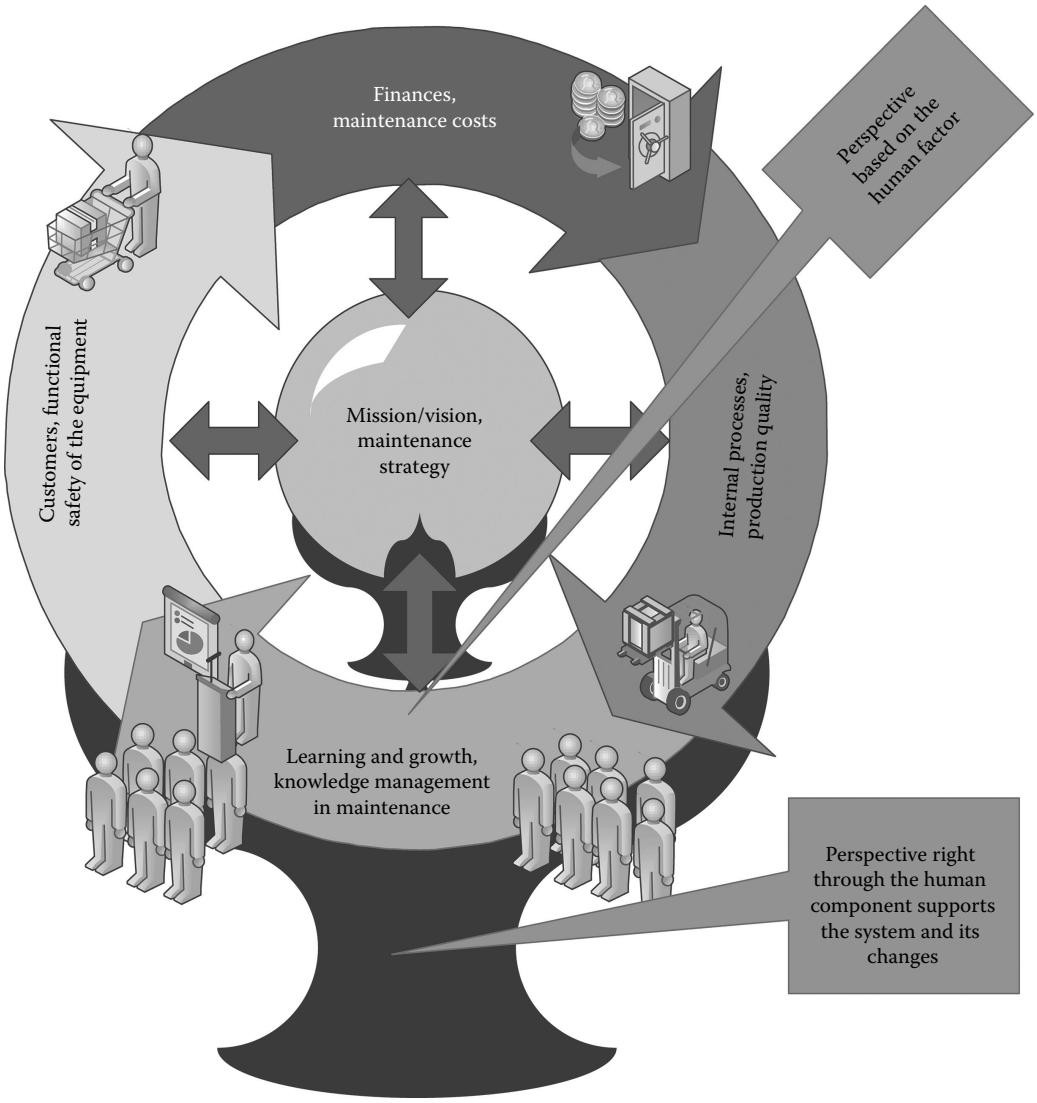

FIGURE 3.10
Components of the integral control panel for the management of maintenance.

That is, the person is the source of and the chief agent for sustaining organizational change. Some might argue that opportunities and changes occur every day, but it is virtually impossible to carry out changes continuously. Some changes are of such magnitude that they create changes throughout the organization. Others are not sufficiently powerful to convince the executive level of the company to initiate them. A certain point must exist where the present situation of the company becomes "saturated," "excessively mature," or "aged," creating the necessity to initiate a new process of change.

In many cases, especially in competitive atmospheres, an evaluation of organizational effectiveness cannot be summarized in the quantitative measures of performance (financial or nonfinancial) but must include intangible factors.

The human element is therefore doubled. First, before the introduction of a system of measurement, it is necessary to avoid the stumbling blocks caused by the human condition of the participants. These people must collaborate in the change, and in many cases, they must start the change so that the organization does not become lethargic. Second, it is necessary to measure the human impact, that is, gathering information on the psyche, the formative states, and so on to know how the personnel are reacting to and affecting the change.

Emphasis should be placed on creating a certain work atmosphere, and so on, not just meeting the financial or operating goals. Several authors emphasize the importance of understanding the barriers to change; they all agree on the importance of considering how changes affect the work culture.

The following constitute a set of necessary conditions for the transformation process to succeed:

- The leaders must be involved in the process.
- There must be a convincing reason for the change, properly communicated.
- Employees must participate in diagnosing the problem, deriving a solution, and implementing it.
- There must be good internal communication with all employees affected by the change.
- The functional and hierarchic barriers must be reduced.
- The desired culture must be clearly envisioned and related to expected behaviors and results.
- The critical mass of the leaders of change must be carefully considered.
- The structures and systems that reinforce the desired behavior must be appropriately adjusted.
- Feedback on initial successes must be communicated.
- Leaders at all levels must display tenacity, persistence, and commitment.
- Leaders and participants in the process must have increased autonomy.
- The action, measures, and results must follow a specific direction.
- The procedures to solve problems must be laid out.
- The needs of both external and internal clients must be considered.
- The leaders of change must be aware of people who are internal and external to the company.

The essential component in a transformation process, whether born of innovation or from a process of continuous improvement, is the balance between the actors, both the leaders and the operators. If there is no synergy between them, the project will not succeed. Certain factors are very important during the process of changing the system of maintenance management in order to neutralize or at least to diminish the possibility of errors while allowing continuous improvement. Of these factors, the following are worth mentioning:

- Ensuring that all organizational levels participate in the process of change, actively participating in identifying the problems and removing obstacles to improvement
- Reaching a consensus on possible problems and the areas to concentrate on
- Creating conditions that allow participants in the improvement project to feel they are the owners of the process
- Effectively communicating all aspects of the process of change, including the new vision of the company, identifying obstacles and problems, defining short-term objectives, and noting improvements
- Defining short-term landmarks and benefits

The development of a consensus on and effective communication of the necessity for change are fundamental principles in the effective implementation of any improvement. Participatory change will only be effective and efficient if the reason for change is made clear and is accepted by the participants.

3.7.2 Questions and Suggestions

Defining and implementing new ideas of maintenance management inevitably lead to a series of changes. Organizational changes or transformations help some companies adapt to changing conditions, increase their competitiveness, and better position themselves for the future. In other cases, the results are disappointing, with a waste of resources, a loss of confidence in the agents of change, and a great deal of frustration with those involved. In such cases, the managers have had great difficulty identifying, prioritizing, and aligning their resources to produce solid organizational transformations.

Certain questions come to mind during any process of organizational or functional change. These must be handled carefully when an innovative project is proposed:

- Is there an obvious reason for the change? This is the first and most important question, and as such, the answer must be convincing. This requires careful study of the present conditions of the organization of the maintenance and its deficiencies and strengths, as well as an evaluation of its position relative to the maintenance done in competing companies and an understanding of how maintenance supports the company and contributes to its success.
- Is the reason sufficiently understood by those working in the production and support systems? People must agree on the reason for change if it is to be well implemented. It is not sufficient that the manager is aware of the necessity for change; the reasons must be demonstrated to others and backed up by numbers and facts so that all the personnel support the new ideas.
- Is it accepted as a good reason for change by the key people in the company? If the maintenance director does not secure the support of the leaders of the company,

the project will not be successful since it will not have resources or help from the other heads of the various levels of the organization.

- If the reason is understood and accepted, is it clear what production area or maintenance procedure will be the object of the change? It is best to select a single critical area with a potential for greater growth and more impact. It is not a good idea to apply changes throughout the system; it is better to prioritize one area. In addition, it is important to show successes quickly, even if these may be small, to maintain cohesion and morale.
- Is a clear vision of the situation of the company shared by everyone concerned so that a consensus can be reached on what must be changed. The problem must be understood and correctly interpreted by the people who make decisions. Here, it is important to have a common language to explain the facts so that managers from all levels can understand.
- Who is going to be the agent (or agents) leading the process of implementing change? The person who assumes the leadership of the process of innovation in maintenance should be the present director of maintenance, providing he/she has up-to-date technical knowledge and experience of managing both financial resources and human resources.
- What levels will be involved in the consideration of alternatives before measuring maintenance performance? The implementation of changes in maintenance must be done by a work party representing all areas related to maintenance. But it is very important that the director of the company be involved in the implementation and the evaluation of the project. In the phase of implementation, high-level management is required to facilitate the cooperation of departments involved or affected by the project. When the results of new maintenance practices are evaluated, upper-level management needs to know the benefits deriving from it and also contribute to any conflict resolution required.
- Should workers be involved? This is a key question. If a project is to be successful during its elaboration and later application, all those affected by it must feel that the project is something they own, that "my participation is important, and without my help, this cannot go forward." A project in the maintenance area requires information on many aspects; for example, technicians have information on the use and capacity of the equipment, and each worker has his/her own special "know-how." If operators cooperate in a project they know and understand, it is more likely to remain operative and be constantly updated.

Other equally important questions are related to the knowledge of techniques and tools, availability of resources, capacity to work on equipment, facility to manage the conflicts that derive from it, evaluation of the effectiveness of the changes, and good relationships with superior levels of management. Each represents a risk for the success of a project and must be considered in the planning and execution.

It is not enough for a company to have a good reason to apply change; personnel in the affected areas of action must be totally motivated, predisposed to take the initiative, and desirous of success. This is vital. For that reason, it is necessary to carefully plan the process of transformation, anticipating problems and questions that can arise.

3.7.3 Maturity of the Organization

A factor that causes problems when a new concept is proposed, for example, when new forms of maintenance are designed, is ignorance or only a vague perception of the technological and human capital available in the organization. If such capital is ignored or forgotten, an effective plan cannot be designed and the company will not meet its projected goals.

It is important to understand that all units in an organization (including maintenance) go through their own processes of maturity as they work toward excellence. To measure the maturity of an organization, its current state is analyzed in relation to the ideal attainment of its objectives. A mature maintenance department will be meeting its objectives.

Performance measurement of a mature maintenance department will reveal a combination of action (ability to act and decide), attitude (desire to be involved and pride of ownership), and knowledge (understanding the need to measure performance). To evaluate the maturity of the maintenance function, it is necessary to measure five aspects: commitment, social and cultural aspects, communication, tools and methodologies, and interactions (Figure 3.11). In maintenance, these aspects mean the following:

- *Commitment*: This is the ability to accept change as an integral part of the maintenance strategy, in agreement with the objectives of the organization. It includes the level of acceptance of the global objectives of the organization as these affect the formation of interdepartmental work parties. Commitment includes the provision of suitable resources to ensure the project is effective and that all personnel at all levels who have a connection with maintenance participate in all stages of the project.
- *Social and cultural aspects*: It mainly concerns to the people as a change element, aspect involving the behavior of people, perceptions and attitudes toward change. It includes the level of participation and support of a project, not only by maintenance personnel but also by those in production, human and financial resources, logistical support, and computer science systems.
- *Communication*: All aspects of internal and external communication are important. What is occurring in new projects, the benefits, and how the maintenance function will change as a result must all be communicated effectively.
- *Tools and methodologies*: Although the main interest is the methodology of the management of maintenance projects, process and performance are important as comparison measures. This also covers the underlying (implicit) knowledge required for change and facilitates the use of knowledge entry and external training.
- *Interactions*: Any new method should not interact negatively with other methods that are already in place. It is necessary to balance normal operations with changes that occur so that no new function or routine develops to the detriment of an existing one. It is also necessary to maintain a balance between the different factors that lead to the success of each of the various departments in a company.

An organization can be mature in the management of maintenance and still not be excellent. Excellence requires, but is not limited to, maturity.

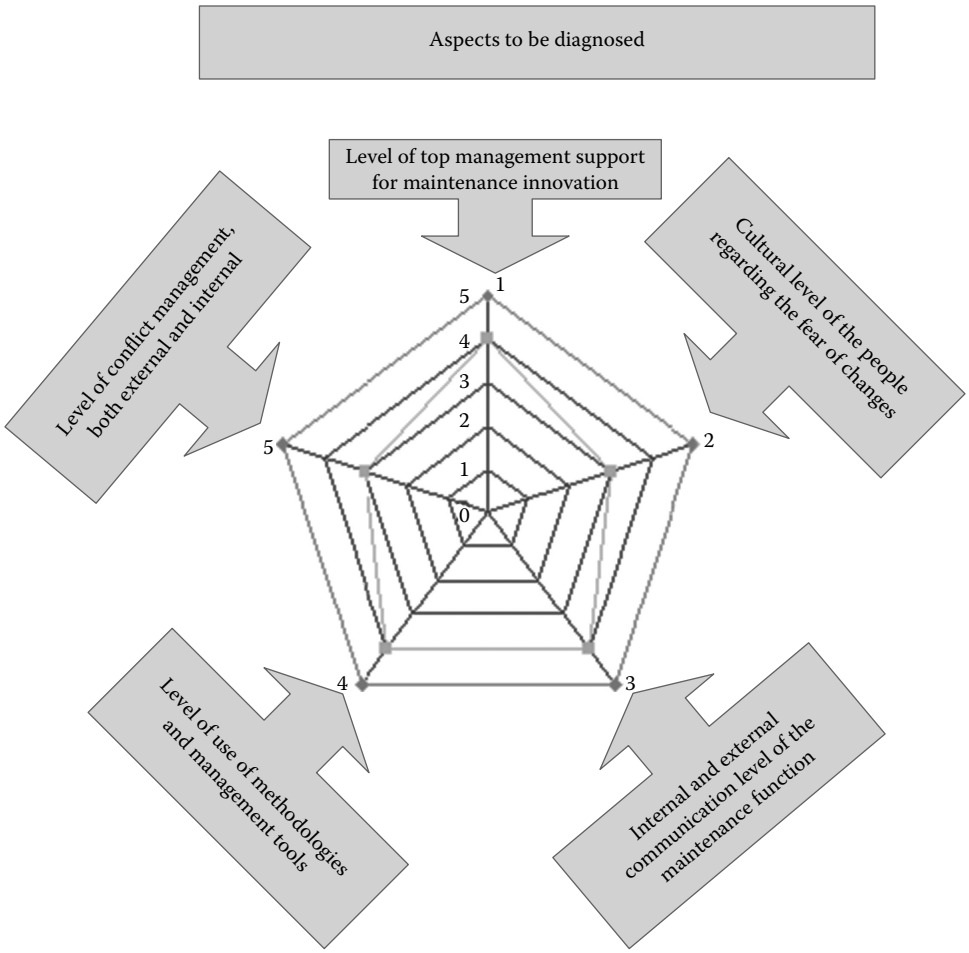

FIGURE 3.11
Model of analysis of the maturity of a maintenance organization.

When an organization develops mature systems and processes, two additional benefits arise:

1. Work is done with a minimum of scenery changes.
2. Processes cause the minimum number of problems by being aligned with the company's mission and vision.

Excellence represents the perfect balance of effectiveness and efficiency. In the case of maintenance, it can be described as the following:

- *Capacities and abilities of the work force*: Maintenance personnel have an average training compared to the rest of the employees, and their knowledge is transferred to the people who use the equipment, with the purpose of decreasing unplanned maintenance. Workers recognize the need to improve themselves and to contribute knowledge that will lead to the improvement of the assets. The rotation of personnel is low, and information flows easily among them.

- *Management training*: The training of maintenance managers usually is specific to this particular function. Managers rotate through several maintenance functions to extend their experience.
- *Quality*: Maintenance workers must always align the maintenance department's services and procedures with the needs of its clients, the equipment used in production, with a long-term commitment to the quality of service, and applying concepts of availability, maintainability, reliability, and safety to the products that the company manufactures.
- *Participation of the work force*: There is a culture of confidence between the personnel of several departments and workers and managers. The resulting continuous flow of information strengthens maintenance actions. People work together to analyze maintenance and to decide when and how it should be performed. They complement each other, together creating a total knowledge of the function of maintenance.
- *Continuous improvement*: The contribution of maintenance to the improvement of the equipment focuses on increasing the rate of production, installing automated equipment, participating in the selection of new equipment, and deciding when to replace equipment.
- *Incremental approaches to improvement*: Maintenance must advance in the use of information technology so that it can use accurate data to evaluate its performance and propose and implement remedial actions when its performance is not optimal. Quick responses, flexibility, and economic savings are the resulting benefits.

Each stage of maturity imposes different conditions on management. The most adverse phase (where disorder predominates) is characterized by deficiencies that must be rectified if the company is to meet its objectives. But it is very difficult to carry out change in this state or to convince personnel to reach a better level of performance. In this stage, the company directors must be committed to the development of the maintenance function; in addition, the support system must participate actively and effectively to measure and improve maintenance.

When implementing a system of measurement, it is possible to develop a methodology using tools of selection and evaluation that can be extended to the whole organization. Obtaining commitment to the process is most simple, defining a way to implement measurements and at the same time, communicating the need for the department.

In the mature phase of a maintenance department, a system has been developed to manage maintenance costs and plan tasks; programs have been established to improve the performance of the equipment, and the negative aspects of the human factor have been mitigated.

4

Maintenance Costs Model: Base of Financial Indicators

4.1 Introduction

This chapter describes the second pillar of the maintenance scorecard, a model of costs; see Galar et al. [100]. The chapter's objective is not to propose a strategy to optimize maintenance costs, nor does it provide a detailed study of the model's application using various maintenance methodologies. Instead, it describes a simple model, based on a realistic collection of data and discusses the processing of those data to create maintenance indicators, especially financial ones.

Creating the model of costs is not the ultimate goal. Rather, the data that result from its application can be used to extract financial indicators, allowing an organization to quantitatively assess the economic efficiency of the maintenance function.

Previously, hard and soft costs have been differentiated. When defining a model of costs, it is necessary to select those that are easily measurable, from which soft indicators, representing an intangible aspect of a much more complex measurement, can be extracted; see Arbulu and Vosberg [12]. However, soft indicators, such as the cost of not having carried out training or the nonavailability of condition monitoring equipment that could have detected an anomalous vibration, are not measurable using a traditional collection of data. Therefore, it is necessary to look for more easily seen hard costs that contribute the required information.

To analyze the efficiency of maintenance finances, three requirements must be satisfied if the systems are complex:

1. The equipment, groups of machines, or whole plants that are being evaluated and compared must have the same functional objectives.
2. Assessment criteria of technical and nontechnical interest factors must be determined. That is, the model of costs will not be sufficient for the preparation of financial indicators; it will be necessary to contribute operational information.
3. The majority of the details of the systems being evaluated must be available, or they must be able to be estimated in such a way that the components of maintenance costs of each system can be predicted.

In the first step, the objectives of the system must be properly defined. The costs of a system's maintenance cannot be modeled when the inherent objectives of its design

or the operational objectives for which it has been acquired are not known. Thus, for example, in the case of a spare or redundant centrifugal pump, the objective of the system is its condition of redundancy; its maintenance costs will be entirely different from an identical pump used in an area of high criticality due to the vastly different operating conditions.

Once the objectives have been identified, the next step is to select the equipment, if this has not been already done and to identify the alternate systems in which it is used. Finally, the optimal configuration for each system is determined using a method of economic evaluation. These parameters that make up the life cycle cost (LCC) at the stage of equipment selection are the seed of the cost model and its derivation of performance indicators.

The criteria of evaluation at the time of selecting equipment must balance aspects of both LCC and operational effectiveness. These criteria are shown in Figure 4.1.

A priori, it is less difficult to establish the cost criteria than the criteria of effectiveness using the manufacturer's data or drawing on similar experiences with similar equipment. This does not mean that the estimation of the cost is simple; it only means that normally the various classifications are better understood.

Maintenance costs are an inherent part of LCC and cannot be dissociated from the LCC concept. The cost of the maintainability of a system cannot be assessed if it is not considered from its conceptual design stage until its disposal. Therefore, a model of costs must cover the system's entire life cycle; it must include costs associated with research and development, engineering, design, production, operation, maintenance, and disposal, as shown on the left side of Figure 4.1.

RAMS parameters are used to measure the effectiveness of systems, including criteria like availability, maintainability, reliability, and so on. Although not all are purely quantitative measures and their estimation accuracy is low, they are useful to describe a system's effectiveness.

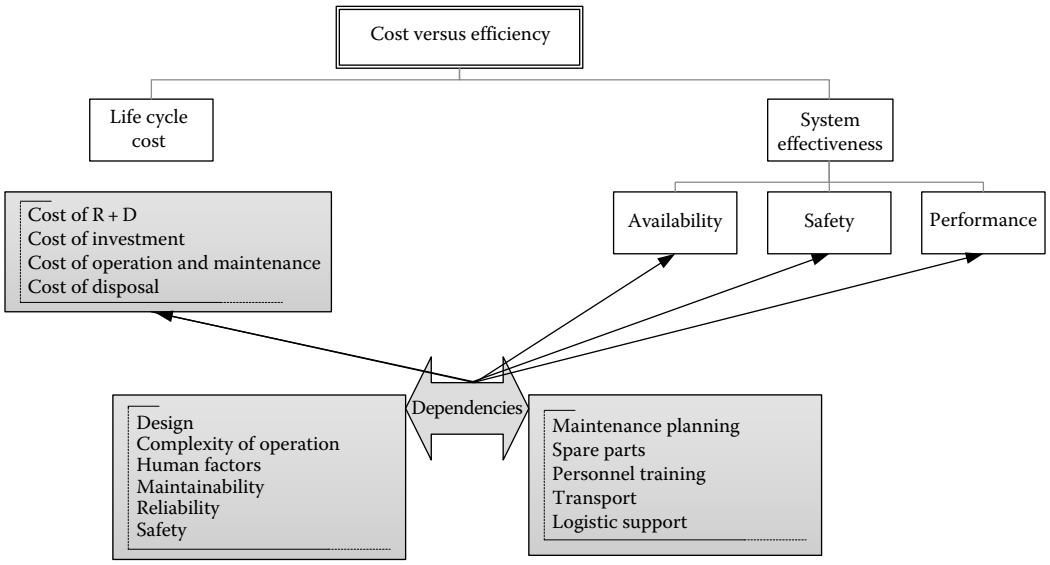

FIGURE 4.1
Effectiveness–cost relationships.

In a study of the cost–effectiveness of equipment, the various systems must be analyzed according to their qualities, ranking the systems according to their capacity to satisfy the most important criteria. If both cost and effectiveness of a particular alternative are superior to others, the selection is obvious. If two alternatives are identical, or almost identical, in their ability to satisfy the main criteria and there is no significant difference in the cost, either can be selected. Finally, if the cost and effectiveness of systems differ significantly, the selection must be made by prioritizing the objectives of upper management and adapted to the maintenance department. The balance between effectiveness and efficiency depends on upper management decisions on what balance will achieve company goals. Effectiveness is not always more important; sometimes, a combination of low cost and effectiveness will meet the company's requirements.

The final step of a financial efficiency–effectiveness study includes documenting its purpose, hypothesis, methodology, and conclusions. In this step, information is communicated to stakeholders; this must be carefully executed because it will have an impact on the future use of the methodology.

4.1.1 Considerations of LCC

Many actions, both technical and nontechnical, are taken during the service life of machinery. The majority, particularly those in the first stage, have implications on the service life of the equipment and thus influence the cost. The calculation of the LCC is based on the concept of the service life as this applies to a specific system.

4.1.1.1 Problems of Traditional Design

Traditional engineering has mainly focused on the acquisition phase of the life cycle, but a product or system is properly coordinated and operated to be competitive, through actions implemented long before being conceived.

Therefore, engineers must consider operational viability during the first stages of the development of a product as well as its impact on the entire LCC. This implies the use of a sequential method using relevant milestones in the LCC if the outcome desired is a cost–effective design.

A good design that fulfills the main function of the asset or global system often has indirect and undesired effects in the form of operational problems. This results from the exclusive consideration of the main function instead of approaching the most challenging task of the design phase, namely, that the design should satisfy the RAMS parameters. There is plenty of specialized knowledge on this topic and the problem can be solved. Fabrycky and Blanchard [97] say the difficulty lies in the systematization of the integrated usage of known methodologies.

Economic considerations can be applied to engineering, as shown by Thuesen and Fabrycky [328]. Economic considerations are important in the integration of the product's service life, production, and support or maintenance.

Figure 4.2 shows different stages of the life cycle and the most important functions associated with each phase, as described by Fabrycky and Blanchard [97]. Traditional design means a later involvement in maintenance; once needs are identified and solution adopted, the chosen maintainability or support strategies are null. It implies in many cases that a more optimized cost policy is not applied. If not those that respond to the urgency to quickly commission of new equipment that is being developed or even put into operation.

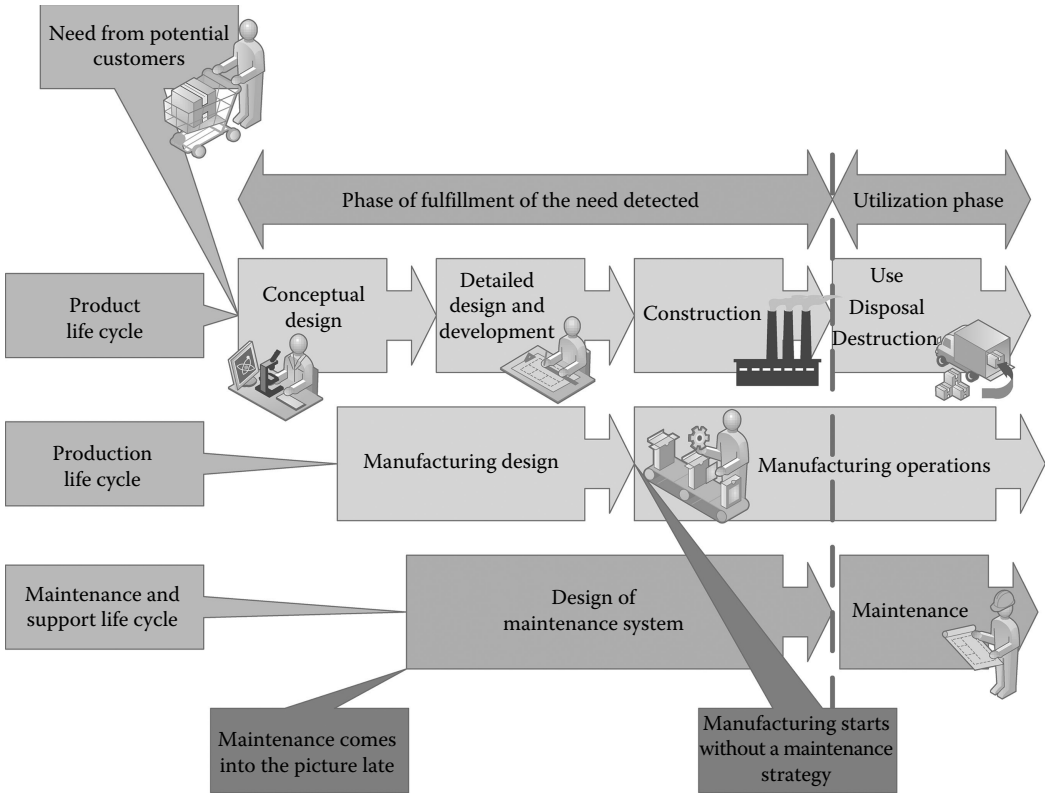

FIGURE 4.2
Life cycles of product manufacturing and maintenance.

4.1.1.2 Problems of Cost Visibility

The combination of reduced spending power, budget limitations, and increased competition has generated interest in the total cost of the machinery. With the current economic situation, it has become more complicated with the addition of problems related to determining the real cost of the system. These include the following:

1. The total cost of the system is not visible, particularly costs associated with its operation and maintenance. The problem of cost visibility is a consequence of the "iceberg effect," as shown in Figure 4.3 and explained by Blanchard and Fabrycky [27]. To avoid the iceberg effect, cost analysis must tackle all aspects of the LCC.
2. Often cost factors are applied incorrectly. Individual costs are wrongly identified or placed in the incorrect category so that variable costs are treated as fixed (and vice versa); indirect costs are treated like direct costs, and so on.
3. Accounting procedures do not always allow realistic and opportune evaluations of the total cost. In addition, it is often difficult (if not impossible) to determine the costs on a functional basis.
4. Budgetary practices are often inflexible with respect to switching funds from one category to another or from 1 year to the next to facilitate improvements in acquisition costs or to exploit the system.

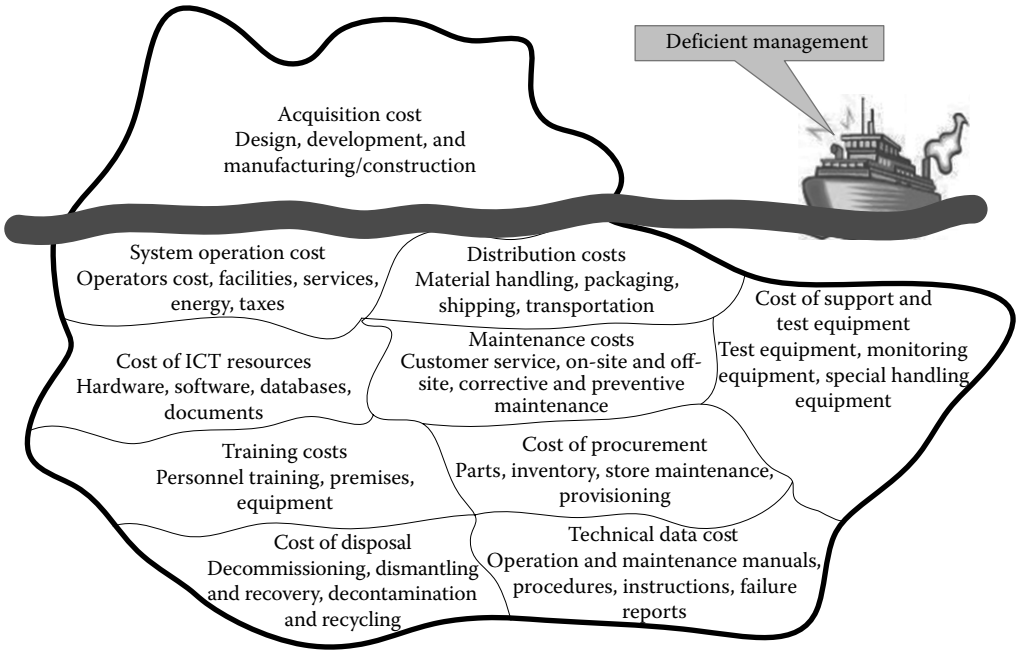

FIGURE 4.3
Iceberg effect in costs associated with service life.

4.1.1.3 Structure of Cost Breakdown

Generally, costs during the life cycle are divided into categories based on organizational activity. These constituent categories and their elements comprise of a cost breakdown or decomposition (cost breakdown structure [CBS]). According to Thuesen and Fabrycky [328], the main cost categories are

1. *Research and development* (*R&D*) *cost*: Initial planning, market analysis, product investigation, requirements analysis, engineering design, data and documentation of design, software design, tests and evaluation of the engineering models, and other related functions
2. *Production and construction cost*: Industrial engineering and operation analysis, production (manufacture, assembly, and testing), construction of facilities, process development, production operations, quality control, and initial requirements of logistics support (e.g., initial support to the client, production of spare parts, production of test equipment, and support)
3. *Cost of operation and support*: Operation of the system or product by the customer or end user, distribution of the product (marketing and sales, transport and shipping), maintenance and logistical support during the life cycle of the product (e.g., service to the client, activities of maintenance, support related to test equipment, transport and handling, engineering data, facilities, and modifications of the system)
4. *Cost of decommissioning and elimination*: Elimination of nonrepairable elements during the service life, disposal of the system or product, recycling of material, and all applicable requirements of the logistical support for disposal, with special emphasis on environmental and health and safety issues

Cost breakdown relates the organization's objectives and activities to its resources. It constitutes a logical subdivision of the cost for each area of functional activity, important system elements, and one or more of the discreet classes of common or similar elements. The CBS provides a means for the initial allocation of resources, monitoring of the cost, and the control of the cost.

4.1.1.4 Cost Analysis during the Life Cycle

Once the cost breakdown of the system is defined and the methods of estimating the cost are established, it is time to apply the results to the system life cycle. The resulting cost profiles must consider inflation, the effects of learning curves, the future value of money, and other aspects.

A variety of procedures can be used to develop cost profiles, but in all procedures, the following steps are essential, according to Langdon [183]:

1. Identify all the activities that will generate costs of any type during the service life. This includes functions associated with planning, research and development, test and evaluation, production or construction, distribution of the product, operative use of the system or product, maintenance and logistical support, and so on.
2. Relate each activity to a specific category of cost. All activities must be in one or more categories of the CBS.
3. For each activity of the CBS, establish appropriate factors of the cost in constant currency, where the constant value reflects the general spending power of the currency at the time of the decision. The related costs, expressed in terms of constant currencies, will allow a direct comparison of the levels of activity year to year, before the introduction of inflationary factors, changes in the levels of prices, economic effects in contractual agreements with the suppliers, and so on, which can cause confusion during the evaluation of alternatives.
4. Transfer the individual elements of the cost within each category of the CBS to the future, year to year throughout the system's service life to have all the activities represented in a comparable value. The result must be a flow of costs in constant currencies for the relevant activities.
5. Introduce appropriate inflationary factors, the economic effects of learning curves, changes in price levels, and so on, for each category of the CBS costs and for every applicable year of the service life. The modified values constitute a new flow of costs; they reflect the realistic costs and can be seen as an anticipated version of the real expenses for every year of the service life. These costs can be used to prepare future budgetary needs since they reflect real monetary needs, anticipated for every year of the service life.
6. Summarize the individual flow of costs in the main categories of the CBS and develop an overall cost profile.

It is possible, and often beneficial, to evaluate the flow of cost of individual activities throughout the service life, such as research and development, production, maintenance, operation and support, and so on. These individual cost flows can be accumulated to develop the profile of the total cost per activity. Consequently, the profile of the total cost can be observed from the point of view of the logical flow of activities and the monetary cost considering financial issues like inflation, currency stability, and so on.

4.1.1.5 Estimation of Cost Elements

Operative and support costs that are costs in the exploitation phase are based on activities planned for the life cycle phase of operative use and logistical support and are normally difficult to determine.

Operative costs are a function of the requirements of the system or product and its utilization.

Support costs are basically a function of the inherent characteristics of reliability and maintainability of the system's design, and the logistic requirements necessary to support all the actions of maintenance programmed and not programmed throughout the projected service life. Logistical support includes maintenance personnel and their training, supply management (spare parts and inventories), support and test equipment, transport and invoicing, facilities, ICT resources, and certain technical and engineering data. The individualized estimation of the cost of support to the system is based on the anticipated frequency of maintenance actions or the average value of maintenance and on the resources required during maintenance activities. These costs are deduced from reliability and maintainability predictions, from the analysis of logistical support, and from any other information on support obtained from the design data of the system or product.

The proposals, catalogs, data, reports on the design, and studies by suppliers (or potential suppliers) can be a source of data for cost estimation. The main elements of a system are often categorized by a company or developed through a subcontracting agreement of some type. Potential suppliers will present/display proposals that include the cost of acquisition and also the service life cost forecasts. If the data of the supplier are used, the analyst must be aware of what is included and not included to avoid omissions and repetition of costs.

During the final phases of the development and production of the system, when the system or product is tested or put into operation, the obtained experience represents the best data source for analysis and definitive evaluation. These data are collected and used to analyze the cost of the service life. The operation data are also used as much as possible to evaluate the impact on the cost of the service life of any proposed modification to the equipment or its logistical support elements.

The data must be coherent and comparable to be useful in the estimation process. The inability to decipher is frequently a characteristic of the data of costs resulting from the lack of comprehension or different interpretation of the definitions, errors in the production volumes, absence of certain necessary elements of cost, inflation, and so on.

The different practices require adjustment to the initial data of costs. Organizations register their costs in various ways; often, accountancy data are submitted to public authorities in categories different from those used internally for LCC estimations. Categories also change from time to time. Due to these differences in definitions, the first stage of the cost estimation must fit all the data to the definition used. Consistency in the definition of the physical characteristics and the performance of assets is needed as well. When the cost data are obtained from several sources, it is important to arrive at suitable definitions of the physical characteristics and performance of assets and cost elements. Integration of disparate data sources leads to more accurate estimations.

The estimations of the production cost often consider both recurring and nonrecurring costs. This area demands a clear definition. Recurring costs are a function of the number of produced units but nonrecurring costs are not. If the research and development of a new product is considered a cost of the current production, it will not have an impact on

the new product. In this case, the cost to bring in a new product would be underestimated and the cost of existing products overestimated. Recurring and nonrecurring costs must be separated, lowering the costs of the current production, adjusting the costs of existing products, and transferring the impact of the current research and development to the production of the new product, not penalizing the current one.

Besides the initial cost necessary to construct or to produce a new structure or system, there are many large recurring costs associated with the operation: maintenance and removal. Energy, fuel, lubricants, spare parts, supplying in general, training, maintenance manpower, and logistical support during the service life are some of these costs. When the life of many complex systems is estimated and recurring costs of this type are considered, the total figure can be high, much higher than the initial cost. Often, operation and maintenance costs are given little attention, and the initial investment cost takes precedence. This is a mistake; the cost of the life cycle of a system, considering O&M, is the real system value. In fact, Operation and Maintenance requires proper LCC estimation for its various optimizations. For Langdon [183], predicting the LCC of systems is the only way to establish a suitable strategy of maintenance.

4.2 Economic Management of Maintenance

4.2.1 Economic Importance of Maintenance

Industrial plants increasingly use available front-end technologies, working toward becoming totally automated. These facilities can expect more qualitative and quantitative production possibilities and better services but must invest significantly higher in equipment.

As a result of the high cost of these investments, company managers try to optimize production capacities to maximize the return of investment. The shutdown of production due to a failure of important equipment compromises production, generating a loss of performance and increasing expenses.

Two types of costs can be distinguished in any company:

Variable costs depend on the volume of production or sales. These costs include

- Proportional costs of sales
  - Packing
  - Personnel
  - Shipping
  - Financiers (loans)
  - Unpaid debts
- Proportional costs of manufacturing
  - Direct manpower
  - Materials
  - Energy
  - *Corrective maintenance*

Fixed costs are independent of the volume of sales. These costs include

- Fixed costs of manufacturing
  - Indirect manpower
  - Amortization of productive machinery and buildings
  - *Preventive maintenance*
  - Rental of equipment
  - Insurance
- Fixed costs of administration
  - Materials
  - Personnel
  - Taxes
  - Amortization of office materials

From this initial cost breakdown into two maintenance costs, we can arrive at two conclusions:

1. Fixed expenses can adversely affect otherwise brilliant results. As many authors argue, for example, Dohi et al. [75], preventive maintenance must be considered as a fixed manufacturing cost; an economic analysis can be counterproductive if preventive maintenance is not determined.
2. Corrective maintenance, as a variable cost, influences the estimation and analysis of these costs and the gross margin of profit.

Consequently, the maintenance function influences performance and revenues through

- Cost of preventive maintenance (fixed)
- Cost of corrective maintenance (variable)
- Availability of the machines (failure cost)

These three parameters have an enormous influence on economic analysis; the simple cost model proposed here combines the three parameters, creating an easily understood way to perform such analysis.

4.2.2 Economic Objectives of Maintenance

The purpose of maintenance is to maintain a company's equipment in a functioning state of operation at the most reasonable cost, thus combining efficiency with effectiveness. That being said, there are often two points of view on economic objectives:

1. *Upper management*: Persons in upper management must make decisions on the installation of new equipment. Decisions are based on the relation of the total cost of the equipment, including its acquisition and maintenance, to the amount generated during its entire service life.
2. *Maintenance personnel*: These persons are responsible for the management of the asset. In this case, the equipment already exists in the company; acquisition costs

and production are fixed, so these variables cannot be modified. Therefore, the decision criterion will be the total cost of maintenance, comprising of

- Loss of benefit to the company as a result of reduced production caused by the nonfunctioning of equipment (failure cost)
- Cost of maintenance operations:
  - Cost of operating the units responsible for repairs (tools, equipment, and personnel)
  - Cost of the pieces and spare parts used and additional expenses of acquisition and storage (spare parts in addition to financial costs)
  - Cost of maintenance operations outsourced to contractors, especially to those with specialized technical expertise that are very costly and seldom used for in-house maintenance

These costs depend on

- The importance and nature of the maintenance operations undertaken
- The more or less random behavior of their appearance
- Organization and management of the company's maintenance units

The shutdown of a production machine causes two classes of costs to the company:

- A loss of benefit from lost and nonrecoverable production if a machine's failure leads to a bottle neck. This happens for assets that are highly critical to the production process.
- Additional costs of production, such as waste, loss of materials, maintenance manpower, and so on. This loss depends mainly on
  - Duration of shutdowns, their frequency, and technical severity and criticality
  - Rapidity and effectiveness of units responsible for recovering the damaged equipment to a state of operation
  - The more or less random appearance of failures

The relationship between benefits/produced units and the cost of maintenance can be represented in the following way (Figure 4.4):

- *Point 1*: Low benefit due to absence of maintenance and low production caused by equipment failure
- *Point 2*: Maximum benefit with optimal maintenance
- *Point 3*: Excessive maintenance

In short, an initial breakdown of the costs of maintenance can be done if these points are considered.

4.2.3 Classification of Maintenance Costs

Maintenance costs can be divided into four different areas that will appear on the scorecard of indicators proposed later in this chapter.

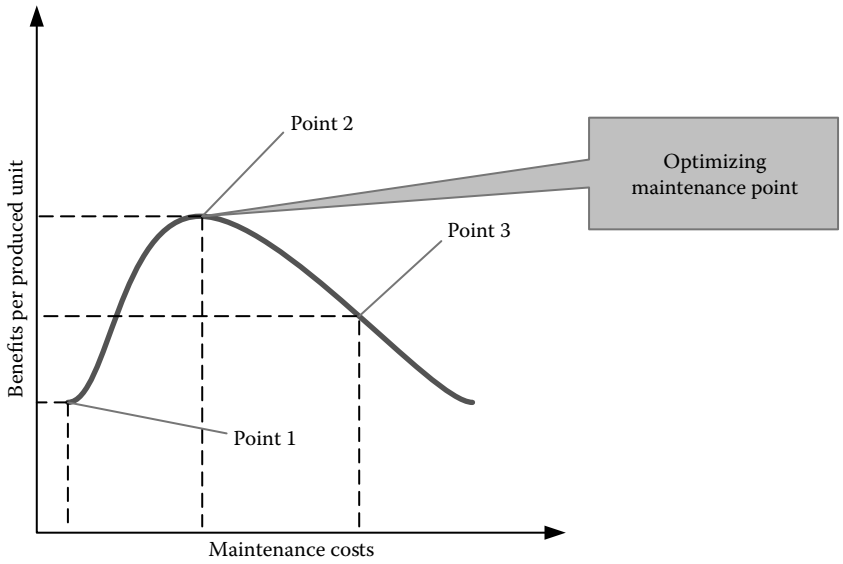

FIGURE 4.4
Benefits versus maintenance cost.

The first division of maintenance costs comprises of the actions of personnel in both production and maintenance. Note that not all people performing maintenance actions belong to the maintenance department, especially when total productive maintenance (TPM) is implemented and the border between production and maintenance is blurred. Four subdivisions can be differentiated here: costs related to actions, purpose, accounting concepts, and trade unions/professions.

The first division contains the costs related to maintenance actions. These include

- Cost of the daily maintenance: lubrications, painting, and so on
- Cost of the control and measurement of the degradation of the machinery through visual inspection, predictive maintenance, and nondestructive testing
- Cost of the repair of the facilities

A second set of costs is related to the purpose of maintenance. These costs include

- Cost of corrective maintenance
- Cost of preventive maintenance
- Cost of modifying maintenance

It is necessary to differentiate the costs of corrective and preventive maintenance as these are relevant to the company's fixed and variable costs. Another cost applies to modifications made to the machinery, such as a complete overhaul, and redesign, and so on. These should be considered separately because their total cost usually upsets the economic balance. Note that predictive maintenance should be included within preventive maintenance.

Following accountancy concepts, a third set of costs includes the following:

- Cost of materials
- Cost of manpower
- Cost of subcontractors
- Cost of failure
- Financial costs

In preparing performance indicators, the maintenance budget must consider the costs of manpower, spare parts, and subcontracting as easily measurable ones, and the cost of failure as a controversial and conflicting cost; it is also one of the more difficult costs to evaluate and impute.

Trade unions incur a fourth set of costs, which can be divided into the following professions:

- Mechanical
- Electrical
- Electronics and instrumentation
- Masonry and plumbing

For trade union costs, the intervention of specific trades must be properly separated as each commands a different price; the profiles of installed machinery related to each trade differ as well, and the criticality of electrical, mechanical failures, and so on will differ. The separation of these costs will favor the subcontracting of certain professional trades seldom used in maintenance and high-wage costs per hour.

These four sets of costs depend on the scale of the plant and the size of the facilities; the administrative complexity of data collection and the associated costs centers can be divided into three types:

1. Machine level
2. Section or line level
3. Plant level

4.2.4 Global Cost of Maintenance

The global cost of maintenance is the total value of a company's management of all maintenance. Machines, installation, sections, and a plant or factory with a high global cost most likely have poor maintenance management. But if the global cost is low, the management of maintenance is good, that is, the effectiveness demanded by the plant is being provided.

The global cost must be considered in an integrated approach to maintenance; it must include benefits and losses for the company.

4.2.4.1 Definitions

Traditional cost of maintenance: The traditional cost of maintenance includes the production cost of a plant; costs are both in variable and fixed forms.

Special cost of maintenance: This refers to maintenance required as a result of major or minor loss of production and the financial expenses incurred by immobilizing spare parts, amortizing maintenance systems, and inadequately handling equipment redundancies.

Variable cost of maintenance: These costs are traditional ones and depend on the major or minor production of the plant or machine. They include the costs of the following:

- Direct manpower or corrective maintenance
- Manpower for preventive maintenance
- Spare parts
- External repairs

Fixed cost of maintenance: This corresponds to the fixed costs of manufacturing and consist of

- Manpower for preventive maintenance
- Indirect manpower (supervisors, office staff, and technicians)
- Lubricants, tools, and so on
- Insurance for maintenance

Cost of failure: Strictly speaking, the cost of failure is composed of losses of benefit in addition to fixed expenses. In fact, the loss of production could be considered as a cost of manufacturing or preventive maintenance shutdowns. Energetic losses caused by failures and sanctions due to environmental failures imputable to maintenance must be added to the losses as well. It is important to emphasize that redundant equipment must be considered having no effect on halting production, and the cost of failure is therefore nil.

Figure 4.5 represents a complete scheme of the global cost with the concepts previously defined. Lambán et al. [182] propose a model of costs based on the ABC model, with a division into two large blocks referring to direct costs and indirect costs. The earlier figure is simplified; the special costs, according to this model, are direct costs imputable directly to the equipment.

The variability and total dependency of the assets are shown in Figure 4.6. This approach calls for the following two considerations:

1. The raw material of the maintenance process is the man-hours used in the process and the spare parts consumed, as well as smaller quantities of other accessories. This is particularly relevant in maintenance; in other processes, manpower is considered as an operational cost. In this case, it is clearly a resource.
2. The operational costs derived from the execution of the tasks of maintenance (preventive, corrective, systematic, etc.) are associated with the cost of failure, that is, the repercussions on the product or service of the maintenance actions and the consequences of these actions.

For example, an analysis of vibrations with a technician and a portable collector consumes direct resources of raw material (man- and equipment-hours) but does not stop the machine; thus, the imputable operational costs would be zero. A relatively frequent

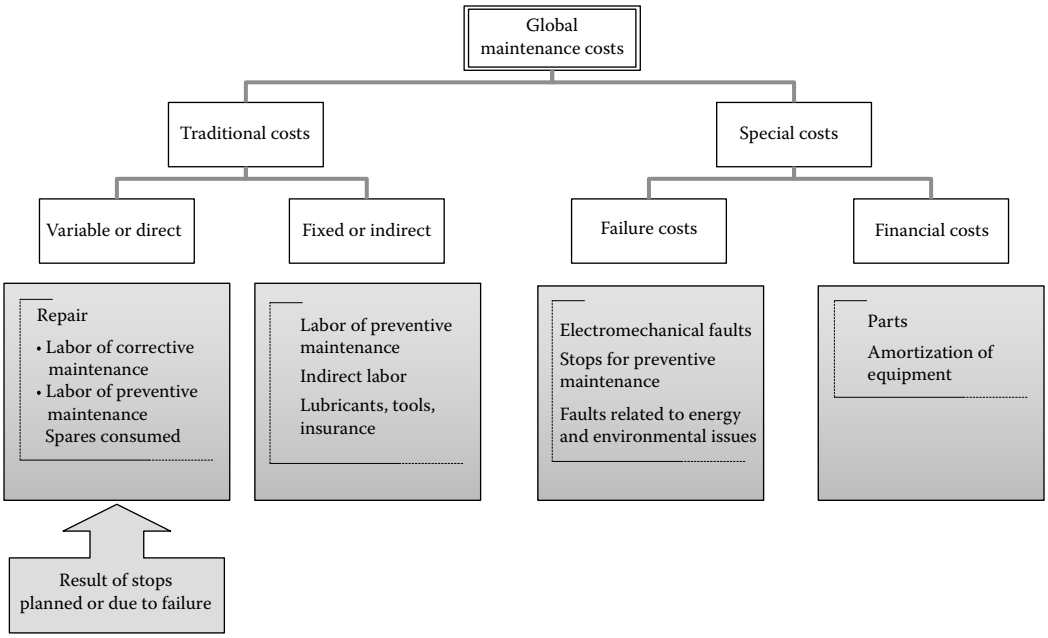

FIGURE 4.5
Breakdown of global costs into concepts.

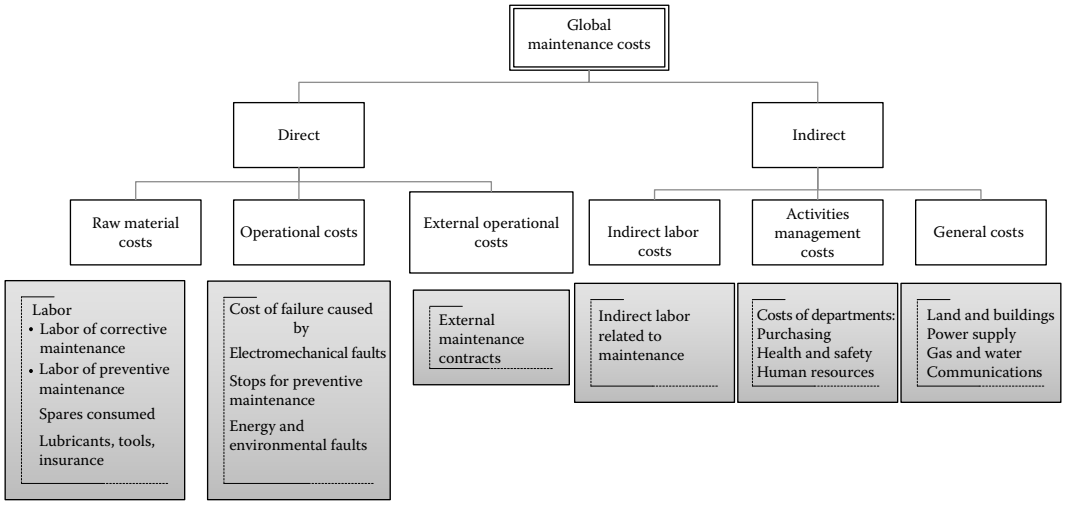

FIGURE 4.6
Costs of maintenance according to Lambán ET model. (Adapted from Lambán, M.P. et al., Modelo de gestión económica de la Cadena de Suministro, *Primer Congreso de Logística y Gestión de la Cadena de Suministro*, Zaragoza, Spain, 2009.)

example is halting production to take a machine to the manufacturer's workshop during its warranty period for an external overhaul. In this case, external operational costs would occur due to subcontracting the overhaul, as well as an operational cost caused by the absence of productive assets, but the cost of internal maintenance would be zero for the raw material used, that is, spare parts or manpower, since actions are performed by contractors.

4.2.4.2 Imputation of Global Cost of Maintenance

The global cost can be imputed, as previously noted, at the following levels:

- Machine level
- Set of equal machines/group level
- Section level
- Plant level

Costs are commonly imputed to the machine or group level (e.g., a room containing centrifugal pumps). These grouped machines are installed in sections, in a way analogous to a plant's setup; thus, the costs can be obtained by summation. The collection of data will also depend on the level to which the financial indicators are required, bearing in mind bureaucratic complexity and administrative and document management in case users want to obtain detailed machine indicators in plants with hundreds of assets, numerous subsets, factories with multiple locations, and so on.

4.2.4.3 Optimization of Global Cost

In terms of mathematics, and at first glance, when some fixed and variable costs are increased, even financial ones, the global cost should also increase, but this does not happen because the failure cost is the inverse of the other costs; that is, it tends to decrease when these grow (Figure 4.7).

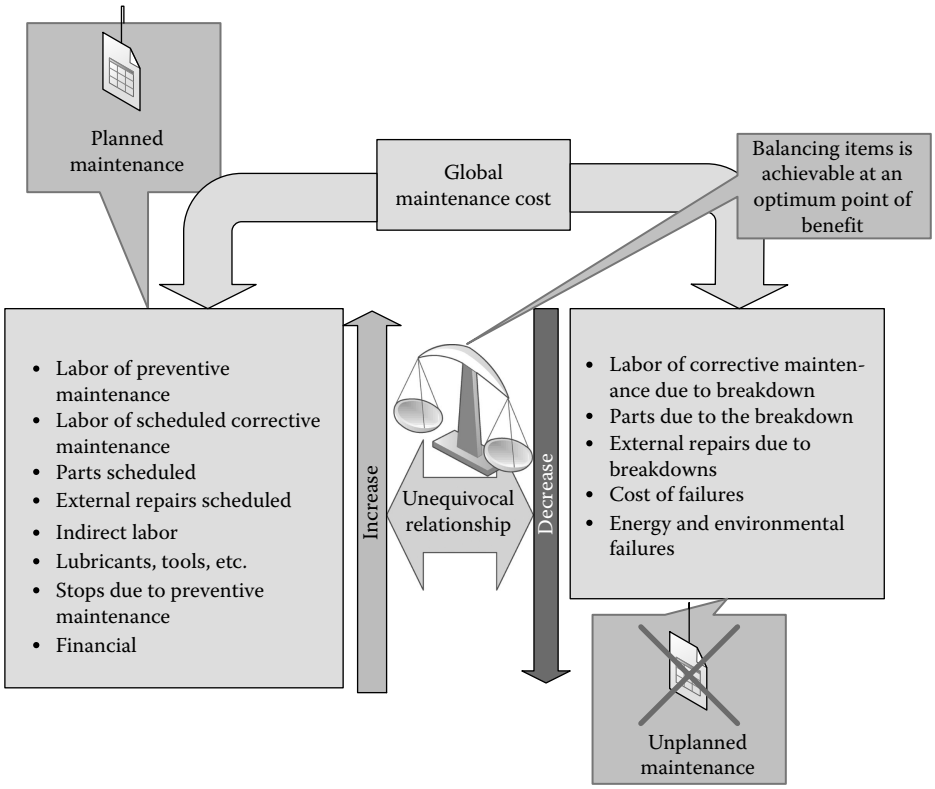

FIGURE 4.7
Relationship between the amount of preventive maintenance and medium repair.

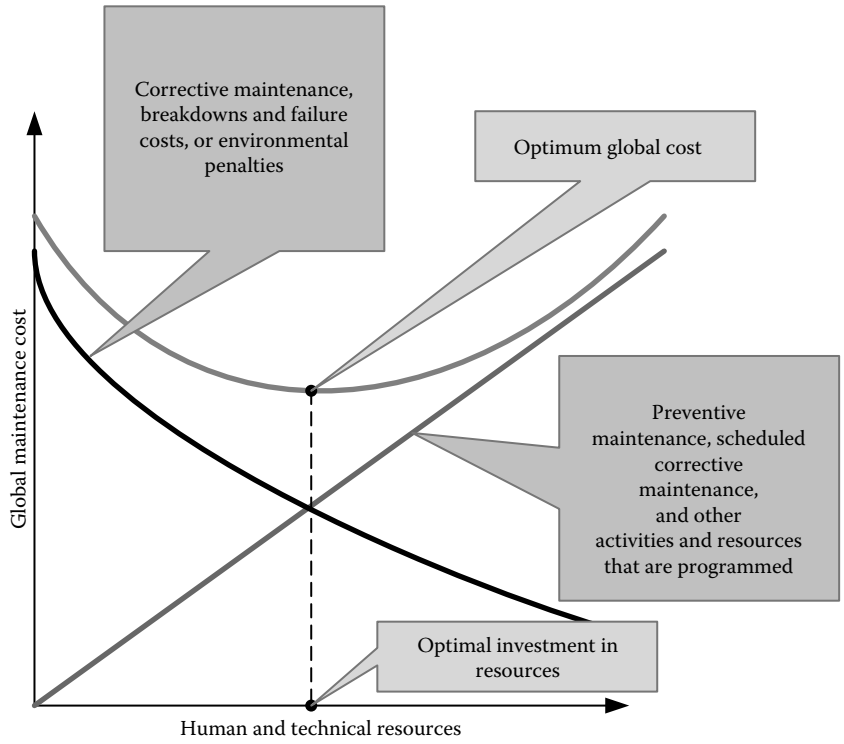

FIGURE 4.8
Optimal global cost versus inverted resources.

If the cost of preventive maintenance is increased (indirect manpower, programmed shutdowns, the consumption of lubricants, tools, etc.), the cost of corrective maintenance will drop (direct manpower, consumption of spare parts, and repairs by external companies).

The increases and reductions in maintenance can be based on the budgets of various maintenance facets to find the proper balance between planned and unplanned maintenance.

Corrective maintenance can be programmed (as a result of preventive maintenance) or reactive/unprogrammed (as a result of a shutdown due to failure). Figure 4.8 graphically represents both types of maintenance. The figure shows that increasing planned maintenance causes the cost to rise, while the costs of failures and breakdowns fall. When the balance is optimal, the global cost is a minimum value.

Note that the block of planned maintenance costs is responsible for the optimal global cost. By acting on this block of costs, failures and their effects can be controlled, a direct consequence of the excess or absence of planned maintenance.

4.2.4.4 Other Factors

Several factors influence the weight or value of the costs explained before. These factors are

- Markets for manufactured products
- Production rate
- Seasonality of certain products

These factors determine whether a shutdown due to failure will cause an economic loss.

In the food industry, production is often concentrated during 2 or 3 months of the year, with the rest of the time available to perform all types of maintenance and overhauls, or to acquire and install new machinery. This usually applies to the perishable food industry, like fruits, vegetables, or fish, as they are materials that are available at certain times of the year and must be processed quickly.

This type of production depends on the amount of raw material that is available. Due to meteorological, environmental, or competitive factors, in some years, there may be more raw materials and/or more demand. Thus, production can vary from year to year.

The market affects these industries as well. For example, stringent parameters of quality can limit production and/or increase costs. The export of products to countries without specific regulations will circumvent this.

4.2.4.5 Determination of Cost of Failure

The costs of failure caused by the intervention of maintenance stem from the following:

- Lost production costs
- Costs of accidents
- Costs of loss of image, sales, and reputation
- Costs of quality rejections

At the beginning of every year, the rate of lost monetary units to machine/hours of nonavailability must be fixed.

The work order (WO) must show that a failure has resulted in nonavailability, an increase in energy consumption, or environmental problems. As a result of nonavailability, one or all of the following may occur:

- Energy savings because of the preventive maintenance program: annual savings/12 = monthly rate or monthly discount
- Increased power consumption, for example, an energy failure during the entire WO, from the initial request to closure
- Environmental deterioration: costs determined by fines or sanctions imposed

4.2.4.6 Cost Breakdown on the Shop Floor

Most companies differentiate between maintenance performed in the field and in the workshop; the corresponding costs are also separated. For that reason, the direct manpower of corrective maintenance, the consumed spare parts, and so on can be broken down to study what areas (workshop or field) occasion the greater cost.

4.2.5 Calculation of Global Cost

According to Komonen [174], the costs derived from maintenance can be divided into two groups:

1. Costs that appear in the operation of maintenance (administrative costs, cost of manpower, cost of material, cost of subcontracting, cost of storage, and cost of capital)
2. Loss of production due to shutdowns of production assets or reductions in the production rate, and loss of quality in the product due to equipment malfunctions

This classification emphasizes the two main objectives of the maintenance function, both corresponding to the desired balance of effectiveness and efficiency:

1. High availability of production assets
2. Low maintenance costs

4.2.5.1 Global Cost

According to NOR [2], the global cost of maintenance C_g is the sum of four components:

- Cost of interventions (C_i)
- Cost of failures (C_f)
- Cost of storage (C_s)
- Cost of overinvestment (C_{oi})

$$C_g = C_i + C_f + C_s + C_{oi}$$

The objectives of all the facets of the maintenance organization must be aligned so that an attempt to reduce one factor of the global cost will not result in an increase in another factor.

The global cost can be calculated for a specific machine, group of machines, or whole plants, but policies like RCM that rationalize the observance and application of maintenance only request the calculation of the costs of that equipment whose criticality or economic relevance affects the overall performance of the entire system under consideration. For this reason, the equipment that most affects global cost will receive more attention and be the subject of more detailed cost analysis.

Recall the problem noted in previous chapters of the mismatch between overwhelming amounts of data and information that is too little. For this reason, the data contributed by a cost model to the set of financial indicators will only come from critical equipment or equipment consuming a high percentage of the allocated money (i.e., relevant in the maintenance budget).

4.2.5.2 Cost of Intervention

Intervention cost (C_i) includes expenses related to preventive and corrective maintenance. It does not include costs of investment nor those costs related directly to production: adjustment of production parameters, cleaning, and so on.

Intervention cost can be divided into the following:

- Internal or external manpower
- Stock spare parts or parts bought specifically for an intervention
- Required expendable material for an intervention

The cost of internal manpower is calculated by the time spent in the intervention multiplied by the cost per hour of implied manpower. External manpower is determined by the cost of the contract or the hours required if this is the subcontracting format.

The expendable material, the amortization of equipment, and tools in general are also considered in the hourly cost of intervention; the time taken for intervention is multiplied by all aspects already included in this cost.

Two main costs are, therefore, configured within intervention cost: manpower costs and spare parts and other costs. Expendable equipment, amortized equipment, and tools required for specific uses are considered as spare parts and separated from labor costs.

4.2.5.2.1 Costs by Time Unit

It is important to assign a realistic value to the costs of intervention by units of time and man-hours because they directly influence the global cost of maintenance, which needs to be minimized.

The cost of internal manpower is commonly compared to the cost of external manpower, but internal costs are affected even if external manpower is contracted. It is necessary to define the two costs:

1. Cost of intervention by time unit: only includes direct costs of interventions
2. Cost of maintenance by time unit: considers direct and indirect costs of maintenance

The cost of intervention by time unit is determined by

$$C_i = \frac{\text{Direct costs}}{\text{Total intervention hours}}$$

The direct costs only include

- Wages
- Hiring services
- Expendable equipment and spares
- Costs of energy related to the intervention

The cost of maintenance by time unit $c_{i,t}$ can be determined as

$$c_{i,t} = \frac{\text{Direct costs} + \text{Indirect costs}}{\text{Total intervention hours}}$$

Indirect costs include

- Wages of specialists required for the management, planning, and technical analyses of interventions
- Prorated services, such as accounting, ICT services, health and safety, human resources, and so on

4.2.5.2.2 Cost of Spare Parts

To undertake a technical–economic analysis, it is necessary to distinguish the technical cost of the countable cost:

- Technical cost corresponds to the value of the piece on the day of its use. This cost must be included in the intervention cost.
- Accountancy cost corresponds to the value used to valorize the book inventory. For financial reasons, this can be reduced by depreciation.

These data are fundamental to calculate the real value of the inventory of spare parts in the warehouse and to extract indicators related to these values, replacement costs of the equipment, or the return of the investment.

4.2.5.3 Cost of Failures

These costs correspond to the loss of profit due to a maintenance problem that has reduced the production rate. They are the result of the following:

- Preventive maintenance poorly defined
- Preventive maintenance poorly executed
- Corrective maintenance performed over an overly long period, badly executed, using bad or low-quality spare parts

It is important to highlight that the asset failure cost corresponds to the loss at the operation level, the cause behind which is an error that presumes production losses of acceptable quality.

The dilemma is whether the cost is attributable to the reasons cited before or to the following:

- Errors of use (misuse) that imply degradation of the asset
- Environmental conditions outside normal working conditions specified by the asset manufacturer

Such costs must be charged to the production, purchases, or even engineering functions but not to maintenance.

By slotting the costs of failure into various functional areas, not just into maintenance, those responsible in each area can take corrective measures and, in some cases, assume full responsibility for the expenses. A single policy that puts all shutdowns and costs of failures under maintenance whatever the reason and no matter who is responsible should not be adopted.

For example, a maintenance failure should not be mistaken for a machine failure resulting from buying unreliable equipment. Decisions to purchase or reengineer equipment almost never depend on the maintenance department but are driven by productivity criteria, making it absurd to transfer that cost to maintenance.

Consider an organization with an engineering department that deploys projects or productive improvements using assets of low reliability, maintainability, safety, and so on, without consulting or considering maintenance in any phases of any of the projects. The maintenance department is not at all involved in the decisions and therefore is not responsible for any of the resulting problems. However, as the general perception is that these costs should be attributed to maintenance, there is friction between departments about the imputation of the failure costs, which actually result from making poor decisions at the outset.

4.2.5.3.1 Evaluation of the Failure Cost

Failure cost can be calculated using the following formula:

$$C_f = \text{Unperceived income} + \text{Extra production expenses} - \text{Raw material not used}$$

The components of this cost are

- *Unperceived income*: This factor will depend on the possibility of recovering lost production by rescheduling, working weekends, and so on. In cases of continuous production, however, there is no chance to recover; therefore, the production of that time slot and all incomes that could have been generated during the shutdown must necessarily be imputed to this first part of the equation.
- *Extra production expenses*: If it is possible to recover part of the production in other temporary slots, the following additional costs will be incurred:
  - Energy required for production
  - Raw materials
  - Expendable materials
  - Services related to quality, purchases, maintenance, and so on
- *Unused raw material*: When it is not possible to recover production, the cost of unused raw material will be subtracted from failure cost. While the raw material has not been used (unless it is a perishable product that must be thrown away), it will be consumed if the productive plan is recovered, possibly with some extra storage costs, transport cost, or costs related to the degradation of the materials.

The most popular model used to calculate the cost of failure when there are productive assets that totally or partially assume the tasks of the assets under maintenance is the Vortex method, described later in the chapter. It is used to calculate maintenance costs and other financial indicators.

4.2.5.4 Cost of Storage

The inventories represent about a third of the assets of a typical company, according to Diaz and Fu [70]. This is typical of all types of companies and business activities, whether industries or services. In fact, in maintenance costs, 70% of the budget typically goes to manpower and 30% to spare parts.

Nahmias [233] says that in 1980, the value of the inventory of the U.S. Army was 100,000,000,000 U.S. dollars. Inventories like this one do not have a progressive obsolescence, but obsolescence can suddenly occur with the discovery of a device that technologically surpasses the existing ones. The obsolete devices and their spare parts have practically a null accountancy value and become scrap iron.

Storage cost comprises of costs incurred for financing and manipulating the necessary inventory of spare parts and other materials consumed by the maintenance function. It includes

- Financial worth of the immobilized inventory
- Manpower required to manage and handle the inventory
- Costs of operating warehouses: energy, maintenance
- Amortization of auxiliary systems: fork-lift trucks, computers, software
- Cost of insurance
- Depreciation of spare parts

Storage cost is measured as a cost by a unit of time based on the level of spare parts available at every moment $c_s(t)$. The cost of personnel of the warehouse is included in this cost by time unit. It is important not to consider the wages of the warehouse personnel in the intervention cost; this cost comes under storage.

If the storage cost is evaluated during a given interval T, then

$$C_s(t) = \int_0^T c_s(t)dt$$

4.2.5.5 Cost of Overinvestment

When designing a plant, it is wise to make select production equipment that minimize the global cost of maintenance during its service life. This equipment will require a higher initial investment to fulfill the same productivity requirements as cheaper equipment, but the costs of maintenance intervention and spare parts storage will be lower.

To include overinvestment in a global cost analysis, the initial price difference is amortized during the life of the equipment, making it possible to determine the extra investments required to minimize other components of the cost.

4.2.5.6 Referential Values

In designing the maintenance department (also in reengineering), it is important to know the reference values for the components of global cost. These will depend on the size of the plant and the type of industry, among other criteria.

To establish reference values for intervention costs, it is necessary to compare the company with others to benchmark the indicators. A number of variables can be used for comparison, including the following:

- Value of assets in the plant
- Volume of production
- Added value

4.2.5.6.1 Cost of Intervention versus Value of Equipment

A reference value that can be directly moved into the financial indicators is the cost of intervention compared with the value of the equipment. More specifically, this will be the value of maintenance with respect to the value of replacement. The goal is to study the optimum replacement time of productive assets in terms of required maintenance and to know the real situation during their service life to optimize the LCC.

The value of the equipment (V_e) corresponds to the expenses that would be required to buy equipment that perform the same functions. It does not consider transport, installation, maintenance, or other expenses like decommissioning or disposal. C_i/V_e is one of the most interesting indicators for benchmarking since it is relevant for renewing or overhauling existing assets.

4.2.5.6.2 Cost of Intervention versus Volume of Production

The volume of production (V_p) is a measurement of the level of the use of the equipment. This indicator allows us to

- Compare similar equipment or plants, taking into account the equipment's hours of use
- Highlight that the redundancy of equipment or oversized equipment elevates intervention costs

A C_i/V_p that is very high on the reference value indicates aging of the equipment or difficult conditions of operation (harsh environment or low-skilled operators who misuse or mistreat the equipment, thus speeding up degradation).

4.2.5.6.3 Cost of Intervention versus Added Value

Added value (V_a) is a frequently used indicator, but it does not consider the conditions of operation. The automation level may not influence C_i/V_a because of the greater amount of equipment and major productivity (added value) that the end user can obtain; however, the intervention cost is increased.

For failure cost, we can use the following as comparison variables:

- Hours of shutdown/running hours
- Acceptable production/nominal capacity

Avoiding failure costs is a paradox of the function maintenance because such effort implies increasing intervention cost. The control of the global cost of maintenance is then an iterative process (for stable levels of equipment use, i.e., constant asset demand).

For storage cost, we can use the following indicator:

$$\text{Cost warehouse management} = \frac{\text{Warehouse cost}}{\text{Inventory cost}}$$

Storage cost has an approximate referential value of 30% in industries. It is necessary to consider that the level of spare parts and the infrastructure to take care of them are closely related to failure cost and to the risk of failures taking place.

The average value of the inventory of spare parts can be determined as

$$\text{Average value of inventory} = \frac{\text{Inventory value}}{\text{Asset replacement value}}$$

The inventory value varies between 1.5% and 2.5% of the value (new) of the equipment.

Storage cost represents between 4% and 6% of C_i. For that reason, it does not constitute a major concern in the management of the global cost of maintenance.

4.2.5.7 Full Costing of Global Cost Components

Now that the model has been proposed, separating direct and indirect costs and applying the concept of global cost to the components listed earlier, we should analyze how full costing affects global concept, as expressed in the following equation:

$$C_g = C_i + C_f + C_s + C_{oi}$$

Among the global cost components, the last three correspond to direct costs, with the cost of failure having greater relevance and being more difficult to quantify.

Warehouse cost is a direct cost of the maintenance function; the decision to keep large volumes of expensive spare parts implies a greater repair cost; in effect, maintenance is punished because of uncontrolled and possibly unwise purchases. Finally, over-investment cost is directly related to the equipment, especially if the investment in a more expensive piece of equipment is intended to reduce failure costs.

Intervention cost is the unique element of global cost that conflates direct and indirect costs; it absorbs both visible interventions and indirect maintenance expenses and is expressed as the following:

$$C_g = C_{direct} + C_{indirect} = C_i + C_f + C_s + C_{oi} = C_{i_direct} + C_{i_indirect} + C_f + C_s + C_{oi}$$

The indirect costs of intervention correspond to

$$C_{i_indirect} = c_{i_indirect} T$$

where

T represents the number of required man-hours for the intervention

$c_{i_indirect}$ is the coefficient of monetary units per hour of indirect costs imputed to maintenance

Therefore,

$$c_{i,t} = \frac{\text{Indirect costs charged to maintenance}}{\text{Total intervention hours}}$$

This value must be determined at the beginning of the accountancy period so that it does not cause an excessive financial burden; in normal production plants, the most relevant factor to consider is that very high indirect costs will increase the system's inefficiency, driving up the maintenance costs.

Therefore, following the model of Lambán ET [182],

$$C_g = C_{direct} + C_{indirect} = C_{Mat} + C_{Op_proc} + C_{Op_ext} + C_{labor_indirect} + C_{Gest_proc} + C_{Gen}$$

where

$$C_{direct} = C_{Mat} + C_{Op_proc} + C_{Op_ext}$$

$$C_{indirect} = C_{labor_indirect} + C_{Gest_proc} + C_{Gen}$$

For global cost, the following definitions apply:

$C_{indirect}$: This represents a part of the cost of intervention in man-hours.

$C_{Op_proc} = C_{failure}$: This indicates that the operating costs of the maintenance process originate in the absence of production capacity, and these failure costs will be considered operating costs. In fact, these failure costs are habitually the most relevant; thus, they merit a special section in this chapter, along with a discussion of the Vorster method (mentioned previously).

C_{Op_ext}: This includes the costs of outsourced overhauls, predictive inspection, or nondestructive testing.

$C_{Mat} = C_{oi} + C_s + C_{intervention_direct}$: Along with failure cost, this is the most relevant parameter; it includes the resources (materials) required for the intervention, manpower (around 70% of the cost) and spare parts (around 30%); both overinvestment in the equipment and the storage cost derived from warehousing spare parts are imputed to raw material in this section since all are physical resources acquired for the unique and direct purpose of reducing the impact of failure in a specific piece of equipment.

4.2.6 Use Unit

Use unit (UU) is an accountancy and maintenance term. It allows maintenance costs to be controlled and permits a reduction in the stock of spare parts, leading to financial profit and positive statistics.

The UU can be defined as a machine model, equipment, installation, or set that can appear in diverse sections of a company; it constitutes a countable unit but can comprise of one or several items.

If a company has 50 equal centrifugal pumps, working in the same or similar conditions, for the maintainer, it is simpler to take care of the incidents, costs, and types of failures, and generally of all types of information that this family of machines produces, rather than do it for each pump separately. It is easy to have several dozen exactly equal pumps; Figure 4.9 shows two rooms of cooling pumps in a corrugated steel plant.

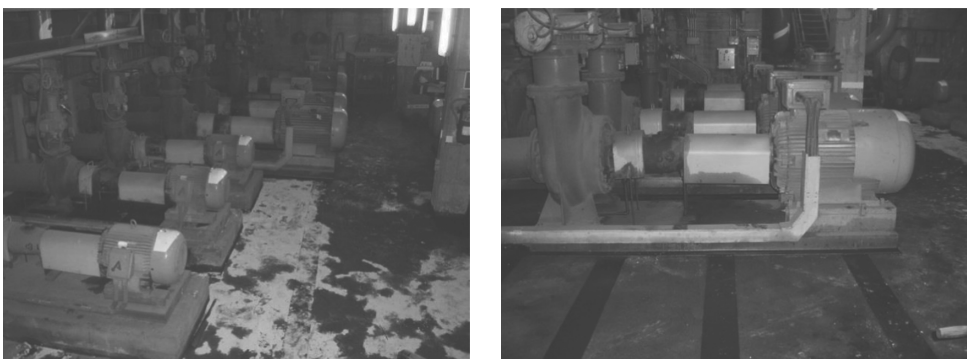

FIGURE 4.9
Rooms of cooling pumps in a corrugated steel plant.

UUs can be determined either by model or by room to enable the global management of populations of identical machinery.

The statistical data that the maintenance manager commonly uses and analyzes have more value if the whole population is considered, not just an isolated case.
Certain elements that compose machines can be also considered UUs, for example:

- Gearboxes
- Electrical motors
- Couplings
- Steam turbines
- Fans
- Valves

That is, a certain machine can be broken down into several UUs. UUs are helpful for companies with many machines and a high repetition of brands and models.

4.2.7 Basic Documentation to Determine Costs

Costs must be imputed to each machine or each UU. The documents required include

- Current value of equipment
- Work order
- WO request and all generated reports as a consequence of the WO
- Warehouse bond
- Current value of spare parts and amortized maintenance systems

Figure 4.10 shows a typical flow of maintenance documentation. The WO corresponding to a specific machine originates in the computerized maintenance management system (CMMS); for this to happen, however, a warning from production or from a visual inspection by the maintenance team must have been introduced into the system. The WO initiates a reaction, that is, a visual inspection by a preventive maintenance worker (operator 1), who tries to restart or repair the machine. If he/she does not succeed, operator 2 must perform corrective maintenance; operator 3 will repair the equipment in the workshop, if necessary. Both spend time on maintenance, and their costs must be evaluated according to the price per hour related to their professional category.

4.2.8 Cost of Maintenance versus Investment

Modifications and improvements introduced by the engineering department or new projects expanding the current facilities in which the maintenance workers take part, including assembly or disassembly, adjustments, and construction, are often wrongly charged to the maintenance budget. This concept of cost is confusing. To prevent confusion, the following should be considered:

- When the modification or improvement of a machine is based on its design, introducing material of another quality, reinforcing pieces, changing shapes, and so on, that is, when modifying maintenance is performed, the cost must be charged to

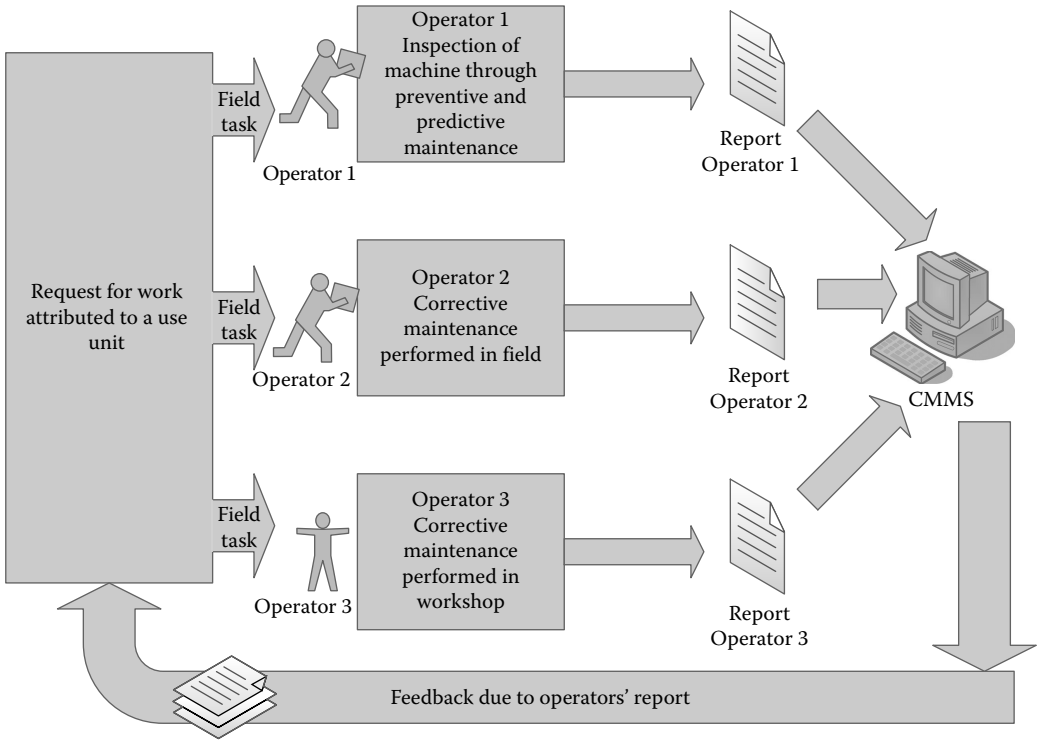

FIGURE 4.10
Example of process of document generation.

the UU since it does not directly cause an increase in production or an increase in immobilized finances.

- If modifications are made that require engineering, for example, expanding the installation, modifying structures, or changing the conditions of the process, the cost is not charged to the UU but to a center of cost related to investments since both production and immobilized finances are increased.

4.2.9 External Repairs: Subcontracting

When maintenance requires carrying out repairs in external facilities or in the official workshops of the machine manufacturer, the documentary system must show a proper request that indicates the work to be executed and the UU to which the cost will be charged.

Three different cases may happen:

1. *The machine or a part of it is repaired in an external workshop*: In this case, a formal order is made to this external company and the global cost of the invoice (manpower, material, and general expenses) is charged to the UU, following the accountancy concept of outer or external repairs.
2. *Manpower is needed*: If maintenance personnel from other companies are required, and these persons are paid hourly with an undetermined completion date, the

resulting manpower costs are charged to the UU affected. Note that these costs are usually higher than those for in-house maintenance personnel.

3. *External maintenance labor is contracted for certain specific maintenance work*: In this case, a contract may include manpower with materials or without tools but will have a detailed description of the specific work to be performed. The resulting invoices must be charged to the corresponding UU, following the rules for external or outer repairs.

In many cases, the repairs conducted in external workshops are cheaper than those done in-house because of the specialized nature of the operation (some companies specialize in certain types of interventions), the equipment (costly tools that only certain companies have), and so on. The economic factor causes an increase in maintenance subcontracting; as noted in previous chapters, there is often friction between the in-house personnel and the subcontractor.

4.2.10 Static Relative Global Cost

Talking about the global cost in terms of the absolute value of a machine makes no sense from the point of view of maintenance management. However, the present value of the machine may be an indicator:

$$\text{Static relative asset global cost} = \frac{\text{Asset global cost}}{\text{Replacement value}}$$

This primitive indicator shows the annual maintenance cost of a machine or the accumulated inter-annual cost with respect to the present replacement cost; this allows decision-making on the replacement of the equipment. The concept may be extended to other levels, that is, sections, plants, and even companies.

4.2.11 Dynamic Relative Global Cost

The previous indicator says nothing about the operation of the machine, that is, if it has produced a lot or a little. For that reason, another indicator is proposed:

$$\text{Dynamic relative asset global cost} = \frac{\text{Asset global cost}}{\text{Annual turnover produced by the asset}}$$

This dynamic parameter is more difficult to evaluate if it is confined to a single machine, but its application is very interesting if applied in a global way to an entire plant or the company. Realistically speaking, this indicator is easy to measure for a whole plant, where the invoicing data are easily extractable from the ERP system; it is much more complex to segregate the turnover generated by a set of pumps, fans, or compressors.

This indicator combines data from both productivity and maintenance.

The indicator has evolved toward the OEE by adding a quality parameter and has become an interdepartmental indicator accepted worldwide and an icon of world class manufacturing (WCM).

4.2.12 Measurement and Control of Global Cost

So that the maintenance director can control the evolution of the cost and its components, two reports are generated, both originating in the CMMS. These reports show the monthly costs of the UU and the cumulative value from the beginning of the year (Figure 4.11).

Thus, the maintenance manager will be able to verify information that will help him/her make proper decisions. Important economic data in maintenance costs must not be forgotten: the value of each machine. This parameter must appear in the reports. The present value of the machinery does not have to be a preoccupation because use depreciates the value and elevates maintenance costs, and this may justify a replacement. But if it is replaced, the initial value (accountancy) of the new machine is significant; the investment eventually incurs proportional maintenance costs, usually preventive maintenance provided by the machine manufacturer, thus saving money in corrective maintenance. Therefore, the displayed value of the acquisition or purchase must be corrected according to inflation and cost life, independently of the actual age of the machine.

The necessary values for the evaluation of the cost are extracted from the following sources:

- WOs and the work requests by operators and technicians
- OEM information and technical documentation describing the number of units composing the use unit as well as the price of new machinery with similar characteristics

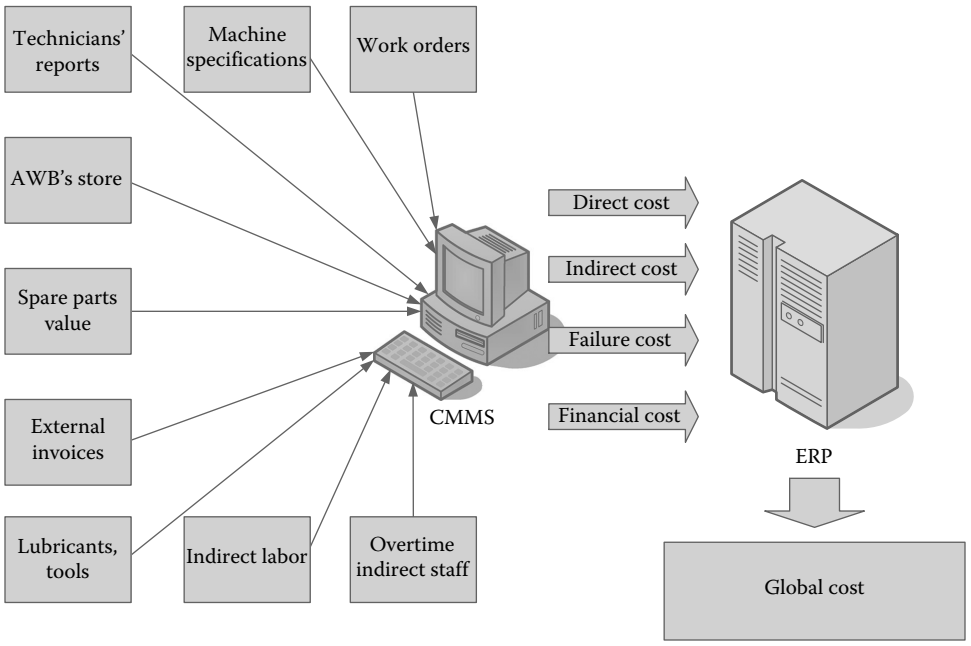

FIGURE 4.11
CMMS reporting for obtaining maintenance global cost.

- Accounting and investment data, price of purchase, cost of installation, and cost of startup
- Average index of industrial prices in the present year (from public sources, usually governmental)
- Labor cost and fixed expenses that compose the overall nature of the parameter (from ERP)

4.2.13 Productivity of Maintenance

Maintenance managers denominate the quotient between the plant production and the global cost of maintenance in the following way:

$$\text{Maintenance productivity} = \frac{\text{Achieved production}}{\text{Global maintenance cost}}$$

The productivity value must always be relative, that is, comparative between years of similar activity. Managers must also be aware of certain periods when production was interrupted or decreased for some reason, internal or external.

Using this equation, it is possible to observe the relationship between the production obtained in a plant and its dependence on maintenance policies, shutdowns, and all other consequences of maintenance.

Figure 4.12 emphasizes the shutdowns caused by exclusively logistic problems (in dark gray). They are normally due to problems in supplying raw materials or energy. They are totally detached from maintenance and should never be imputed to the maintenance cost center.

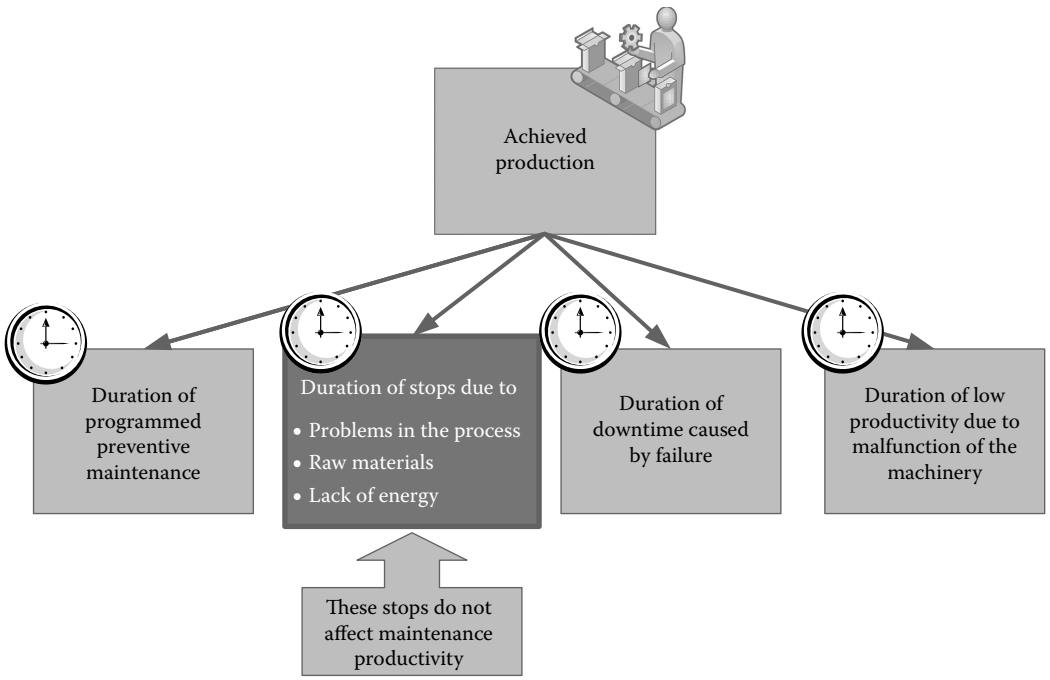

FIGURE 4.12
Classification of shutdowns that stop production.

Therefore, during these shutdowns, to calculate the productivity of the maintenance, the plant must be considered as working normally.

In many companies, the concept of "obtained production" makes no sense. In such cases, it is better to use "service provided" or sales in monetary units. Today, the importance of the latter wording is increasing due to the impact of maintenance in buildings, hospitals, and other types of infrastructures not related to manufacturing, where the product is a service that is provided. The productivity of the maintenance of these facilities is a recent technological challenge. It has inspired an enormous amount of research and development as it marks a complete shift in the role of maintainers and the goals to be achieved.

4.2.14 Maintenance Budget and Its Deviations

The increasing use of analytical accounting for costs has raised the question of rigorous control of the evolution of costs and their deviations. The basic idea is to budget the expenses to be incurred during an economic exercise and then verify the real expenses afterward. The difference will be equivalent to a loss or a gain, or bad or good management of the maintenance department or function.

During the economic term/exercise, the following two economic parameters can vary:

1. Amount of manpower and spare parts
2. Unitary prices (of manpower and spare parts)

The former is a responsibility of the maintenance function, whereas the latter belongs to the purchasing department. It is necessary to work with prices that are fixed at the beginning of the year to minimize undesired deviations and frictions between departments clarifying who is responsible in any given situation.

4.2.14.1 Budget

At the end of the year, maintenance headquarters will indicate the following in the maintenance budget:

- Indirect number of personnel with their categories
- Direct number of personnel with their categories
- Annual useful hours in each category
- Predicted extra hours in each category
- Unrecovered holidays
- Participation of indirect personnel (department director, administrative personnel, etc.) in each service area (mechanical, electrical, instrumentation)
- Anticipated annual consumption of lubricants (based on consumption in previous exercise)
- Anticipated expenses of tools, clothing, and protective equipment
- Hours of shutdown due to failure and preventive maintenance, based on past results
- Predicted number of spare parts for each use unit in the warehouse

To measure the productivity of each corrective maintenance service (mechanical, electrical, instrumentation), each service must budget the hours of personnel to be used during a year, thus determining the total labor cost to invoice in the repairs.

4.2.14.2 Budget Errors

A simple budgetary error can cause major deviations that disfigure maintenance actions. Therefore, the maintenance director should prepare the annual budgets in close collaboration with all maintenance hierarchical levels, that is, supervisors and technicians.

It is also important to consider the statistical data of previous years as these can indicate the tendency of each cost area.

Failures, external repairs, or excessive spare parts can increase the maintenance budget. In addition, the evolution of indirect maintenance costs must be monitored by the maintenance head as they can be a relevant part of the global cost.

The budget must be prepared in detail, a task that takes some time and requires knowing the responsibilities of the maintenance function. Sometimes during the course of a year, the prices of spare parts dramatically increase or manpower wages reach higher levels than those predicted by the personnel department, but these deviations do not have to alarm the maintenance director. The maintenance director is not responsible for the management aspects of price negotiations, wage bargaining, or the legal aspects of wages. His/her concern is simply the consumed spare parts and manpower, not the evolution of the units' prices, as this variation may stem from external factors (social or economic). Other departments are in charge of such negotiations and must keep the units' prices close to those predicted at the beginning of the economic term.

4.2.15 Doubtful Costs of Production and Maintenance

The manufacturing or operating cost contains the maintenance cost. But the personnel and assets of production have their own costs (manpower, raw materials, energy, etc.) and these are differentiated from maintenance costs.

Nevertheless, in some cases, these costs are confusing and wrongly charged to maintenance. In what follows, the chapter analyzes such cases, establishing the criteria that allow their correct application. These costs are caused by the wearing of certain elements; the proposed criteria are the following:

Costs imputed to maintenance

1. The change or substitution of the worn element is performed by maintenance workers.
2. The life of the elements is long and undetermined.

Costs imputed to production

1. The change or substitution is performed by production workers or by maintenance workers.
2. The life of the elements tends to be short and well-determined.
3. The manufactured items are directly modified through the influence of the worn element (i.e., negatively modified—poor-quality results).

4.2.16 Costs of Maintenance: The Tip of the Iceberg

On the one hand, maintenance generates visible costs, including manpower, subcontractors, spare parts, materials, formation, and some administration expenses. All these appear in the maintenance budget. However, they are not the only costs that maintenance can incur in the absence of proper management.

For example, hidden costs are generated by poorly performed maintenance. These include hidden costs due to loss of production, poor quality of products or services, delays in deliveries, capital costs for excessive stock (both spare parts and products in process), energy loss, safety problems, environmental problems, and finally, the additional (and usually unexpected) investments (costly maintenance interventions or early replacements) due to an abnormally short life of the equipment and facilities.

Sueiro [310] indicates the magnitude of the various hidden costs using the classic iceberg example. For Sueiro, the visible part (the tip) is direct costs, and the unseen part (submerged) comprises of indirect costs. Like an iceberg that is much larger underwater, the hidden or indirect costs are 5–10 times greater than direct or visible costs. Success is achieved when the investment in direct costs helps to decrease or even eliminate indirect costs.

The tip of the iceberg shows

- Direct maintenance costs
- Indirect maintenance costs
- Financial costs

The submerged part of the iceberg hides

- Failure cost

The center of the iceberg is the global cost. The sunken part is much bigger (as shown in Figure 4.13) than the tip in the case of companies with weak or insufficient maintenance. Companies with a good level of maintenance constitute an anomalous iceberg that is much smaller with an extremely small sunken part.

Sueiro's analogy is well used. However, the proposed cost model fixes the cost of failure as a direct cost, albeit hidden, thus relegating indirect costs to traditional costs.

4.2.17 Annual Maintenance Budget for an Installation Based on Real Costs of the Past Year

Many heads of maintenance have questions when they must calculate *a priori* the cost of annual maintenance of a machine or concrete installation. It is difficult to predict this cost, especially if the available information is the real cost of maintenance of the current year.

The use of simplistic formulas, such as increasing the cost of maintenance to parallel increases in the cost of living, causes errors that lead to enormous discrepancies at the end of the year. If there are irregularities in the maintenance cost, the credibility of the forecast is destroyed. For example, the costs can be low for years, but an unexpected breakdown can suddenly necessitate a complete (and expensive) overhaul.

The global plant maintenance budget does not have special difficulties. The only difficulty is its allocation per machine under consideration if it is to subsequently obtain partial financial indicators of an equipment or group of equipment (units of use).

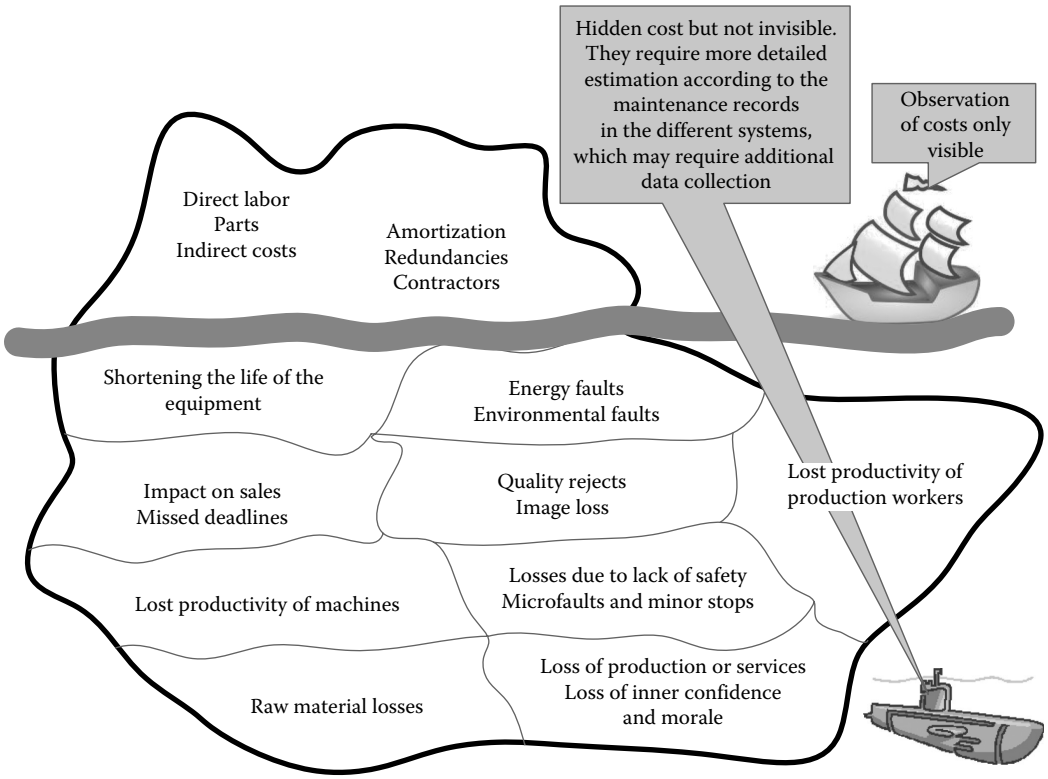

FIGURE 4.13
Iceberg of maintenance costs: the tip versus below the surface.

The starting point for budget estimation is the cost of maintenance of a machine during the current year. Even so, in the cost budgeted for the next year, several factors may be modified, such as

- Life cost (inflation)
- Use of the machine
- Condition of the asset due to premature aging, catastrophes, repair, and reconstruction or modification during the year

Because these changes are provable and knowable, they allow a company to establish weighting coefficients for the cost of the current year and use them to accurately and realistically estimate maintenance costs for the following year.

4.2.18 Standby and Redundant Equipment and Cost of Maintenance

The decision to duplicate equipment to increase a facility's safety must include a consideration of maintenance. In other words, the cost of maintenance of the asset (including duplications) must be properly estimated during its entire lifespan.

When companies invest in duplicate (redundant) assets, the cost of acquisition, corresponding amortization, and maintenance cost must appear in the relevant accounting. Therefore, the maintenance director must answer two questions:

1. When should we acquire redundant equipment?
2. If we have already decided to get this equipment, which is better?
   a. Having it in reserve and starting up when the "holder" breaks down
   b. Selecting an alternative operation, whereby one of the duplicate pieces of equipment works during certain timeslots and the other works during the remaining timeslots, working together to achieve the demanded capacity

Redundant equipment causes problems for maintenance: specifically, the value of annual amortization of the new equipment is imputed to maintenance because the equipment is bought to reduce the cost of failure. The redundant equipment, even though it is not working, is progressively degraded due to the influence of the surrounding environment, and this incurs maintenance costs. It is commonly accepted, although it does not always happen, that the use of equipment is proportional to the cost of traditional maintenance, repairs, consumed spare parts, and wear.

The key question is what to do with equipment that, because it is redundant, does not operate as much as it could but requires maintenance attention, especially preventive maintenance. Other indirect costs are also generated simply by the existence of "idle" assets. Monga and Zuo [225] analyzed redundancy and preventive maintenance, a consideration that is normally ignored.

Having duplicate equipment allows a company to reduce its stock of spare parts for that use unit; it eventually can be reduced to zero stock in the warehouse. Nevertheless, prudence dictates reducing it, not eliminating it.

From all these data, a global cost of maintenance including redundancy can be inferred. A company can verify if the increase in the required availability justifies the increase in the resulting global cost due to the increased equipment that must be maintained.

In the Middle Ages, a philosopher named Ockan said, "Non sunt multiplicanda entia sine necesitate" or "Things do not have to be multiplied if there is no need," a now-famous comment simply referred to as "the knife of Ockan."

Ockan's quip is equivalent to saying that theory is one thing and practice or reality is another. Similarly, many directors of maintenance argue

- In a redundancy, there is almost always a machine that works better than another. Therefore, it is convenient to keep it continuously working (standby redundancy) because using the reserve creates electromechanical problems. In fact, the reserve is frequently unable to start and operate when required. No one notices the problem as the redundant machine is simply sitting there; the condition only becomes visible when operators try to start it up.
- In certain facilities (e.g., pumps or boilers), if redundant equipment must be operated alternatively, it can cause chaos in availability; starting and stopping a pump or boiler frequently will lead to thermal fatigue and disastrous failures.

Therefore, having a redundant alternate piece of equipment is advisable when both pieces of equipment work in the same operating conditions, and the frequent starts

and stops (i.e., micro idle times during switches between assets) do not damage the equipment or the production schedule.

4.2.19 Method MAPI: Practical Application

Method MAPI [197] (Machinery and Allied Products Institute) appeared in 1956 and made a brilliant contribution to discussions of machines, equipment, and facilities in the field of economic engineering. Its philosophy and methodology are based on the following concepts: "defender" is the equipment or machine available or in operation; "challenger" is the equipment or machine proposed to replace the defender.

Operating inferiority represents the differing amount in monetary units between what a machine produces and its better variant. Operating inferiority accumulates through time because of equipment wear and failures (the machine cannot produce the same amount or quality of work as a new machine). Operating inferiority also accumulates with the development of new machines that do the work faster and better. In summary, operating inferiority is due to aging and obsolescence.

The cost of capital is the annual average of the value of the capital recovered with interest; the adverse minimum is the minimum sum of the average of the cost of the capital and the operating inferiority of a machine. The word adverse indicates that operating inferiority and cost of capital are undesirable concepts (costs). The adverse minimum is not inherent to a machine but is only applied under specific conditions of production in certain work.

Finally, the gradient of annual inferiority is the annual amount of operating inferiority that accumulates in the challenger.

The mathematical development of MAPI [197] is complex and not very practical, even though it is based on the following concept (Figure 4.14).

When a machine or installation is working normally (the defender) within its predetermined costs of maintenance and operation, obviously the asset is generating income for

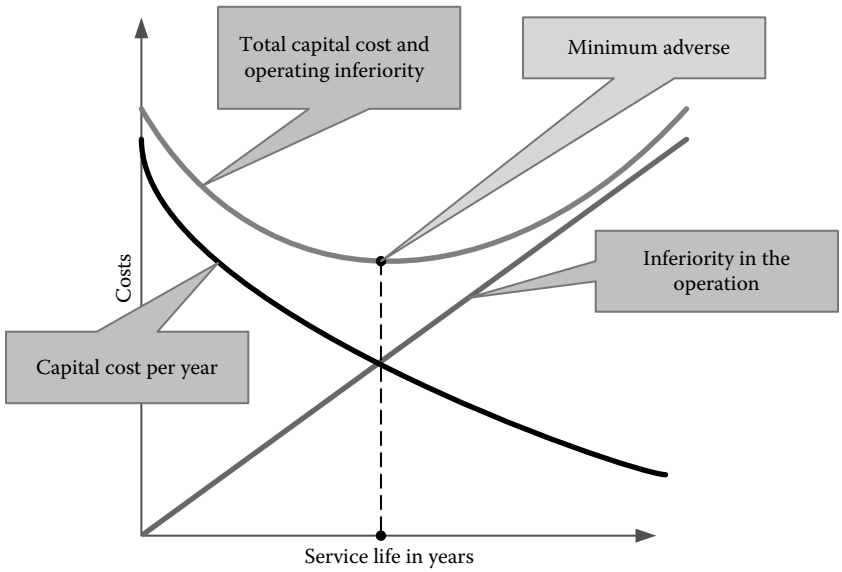

FIGURE 4.14
Obtaining adverse minimum using MAPI.

the company. A new machine on the market (the challenger) is proposed; it too comes with certain costs balanced by potential income. As changing technology will make the challenger obsolete over time, the disadvantages of installing it now or a year from now must be calculated. In short, MAPI attempts to answer the thorny issue of replacement based on obsolescence in a quickly changing world. This method, along with price reductions in computer hardware, estimates the adverse minimum in terms of 2 and 3 years; even though equipment may be in perfect condition, obsolescence is unstoppable and delaying the acquisition by a year is not a good idea.

De Garmo and Canada [62] say MAPI is too rigid, and the diagrams required to integrate it into decision-making are too complex to calculate and too difficult for people without a solid economic education to understand. Nevertheless, most authors agree that MAPI is an appropriate method for decision-making when deterioration and degradation variables are considered.

4.2.20 Reconstruction of Machinery

When a machine has been used for many years, despite excellent maintenance, it inevitably wears down, making it necessary to get rid of it or reconstruct it so that it can continue operating normally. The reconstruction or overhaul must meet the following conditions:

- Future maintenance must be similar to previous maintenance.
- Production capacity must at least remain constant, with no decrease.
- Technical improvements can be introduced to make the machine more effective.
- Reliability and maintainability must be improved.
- Machine must already be amortized.

The overhaul of an installation, machine, or equipment must be considered as an alternative to buying a new one. The decision must be based on correct technical–economic analysis; therefore, the overhaul cost must be calculated carefully and compared with the replacement cost. Normally, if the estimated cost for a complete overhaul surpasses 50% of the cost of a new machine, buying a new one should be rejected unless the advantages of the reconstructed machine surpass those of a new one.

MAPI has been described in the previous chapter as an effective way to estimate costs and compare available alternatives to determine the optimal choice for the company.

The problem is correctly estimating the overhaul cost; to achieve this goal, the maintenance department must use data from reliable sources. The total cost of overhaul comprises of

- Cost of manpower
- Cost of spare parts and materials
- Extra cost due to loss of production during reconstruction
- General and extraordinary expenses

4.2.20.1 Cost of Manpower

Manpower can be measured based on the amount of necessary work and the degree of complexity of the machine. This field has not been investigated in depth due to the variety of equipment and facilities, with the exception of some well-known and universally standardized assets such as machine tools.

TABLE 4.1

Average Degree of Complexity across Industrial Sectors

Industry	Average Degree of Complexity
Machine tool industry	7.00
Heavy machine tool industry	8.00
Instrument/tool industry	5.00
Precision machinery industry	7.5
Cars/automotive industry	8.00
Paper industry	8.00
Agricultural machines and tractor industry	7.00
Construction machinery industry	9.6
Transportation assets industry	9.8
Electric home appliances industry	6.00
Chemical industry and refineries	6.00

Grothus [110] classifies the categories of maintenance and assigns 60 working hours for each unit of "degree of complexity" necessary to reconstruct a machine or to carry out a complete overhaul. For example, a machine with a degree of complexity of 8 needs 480 working hours. Obviously, before calculations are made, each type of machine must be classified according to its degree of complexity.

Some researchers maintain that there is a relationship between the working hours required for a complete overhaul and for other main types of maintenance, inspection, verification, and simple repair. Thus, the degree of complexity determines the number of necessary hours for reconstruction or complete overhaul and the necessary hours for ordinary maintenance.

As a general guideline, some average values for the degree of complexity of productive machinery are shown in Table 4.1.

4.2.20.2 Spare Part Cost and Materials

Information collected from the historical records of a machine will indicate which pieces experience more failures and require reconstruction, thus helping to reduce the probability of failure. In addition, a general inspection is obviously helpful to ascertain which spare parts are necessary. If parts cannot be produced in-house or are too expensive, spare parts must be ordered from the manufacturer of the machine. The cost of spare parts is easy to calculate as long as the maintenance costs control for ordinary repairs, corrective and preventive maintenance are properly performed and cost records are available.

4.2.20.3 Costs Incurred by Loss of Production during Overhaul

A product normally manufactured by one machine must be produced by another during reconstruction, giving rise to higher costs. Also, the production has been previously accumulated to mitigate the effect of the undesired overhaul, which implies a stock with its corresponding interest. This forecast can be expensive. Arditi et al. [13] consider that environmental conditions and the complexity of design causes greater risk. Both factors affect the cost of overhaul due to lost production.

4.2.20.4 General Expenses

Indirect costs, such as office and staffing expenses, energy, and water, must be added.

When deciding whether to overhaul a machine or buy a new one, companies have a number of techniques of evaluation from which to select, but all are based on the operation and maintenance expenses predicted for the following year. The maintenance service must contribute to the calculation of this cost. Experience shows that the cost of maintenance during the first year after reconstruction is lower than that for a new machine of the same brand and model if the overhaul is done correctly. This is mostly due to actions taken during reconstruction (modifying maintenance) directed at reducing the expenses of operation, for example, by installing a system of centralized lubrication, using longer-lasting spare parts, standardizing machine elements, constructing better devices for repairs, or troubleshooting (predictive maintenance).

It has been verified that a reconstructed machine should have lower tolerance levels. During reconstruction, it is usually easy to introduce improvements that reduce the time of operation, increase the quality of product, increase the capacity of the process, and so on. In other words, all possible improvements must be considered before deciding on reconstruction. The savings or income resulting from the increased production must be considered as well.

An old machine that is correctly overhauled and improved will definitely increase in value, with its exact valuation based on MAPI estimations and current value.

The decision to reconstruct a machine is based on two points:

1. Lack of quality in the manufactured product because of problems in the machine
2. High costs of operation and maintenance

Pathmanathan [264] links both of them to worker negligence and poor service conditions, that is, poor quality operation and maintenance link the human factor to the need for an overhaul.

Many industries and companies recommend an overhaul whenever it is technically feasible, instead of the replacement alternative (for an identical new or similar one), since it often implies an improvement in the machine design. To ensure reduced costs in the overhaul and a reconstructed machine of excellent quality, the overhaul process must be carefully planned, scheduled, and followed up.

I am not saying that it is always preferable to inspect and overhaul a worn machine rather than replace it with a new one. The pros and cons of the alternatives must be studied and analyzed. In addition, the maintenance and production functions must be able to arrive at joint decisions. A unilateral decision by production to replace or reconstruct equipment is not necessarily the best decision because it may lack crucial information from the maintenance function.

4.2.21 Definition of Some Concepts of Life, Deterioration, and Obsolescence of Machines and Facilities

A machine or installation can have several types of lives: useful life or service life, economic life, ownership life, accountable or financial life, and physical life; see Bravo [31]. While useful or service life may seem the most important at first glance, equipment have other lives based on the accountancy perspective or according to obsolescence. That is,

assets without value in one country or one productive sector can have real value in a different geographical location or another sector.

1. *Useful or service life*: It is the period during which the equipment is useful, performing the functions that motivated its acquisition.

   EN 13306 [354] defines useful life as the time interval that under given conditions begins at a certain time and finishes when the failure rate becomes unacceptable or when the element is considered irreparable as a result of a failure or other relevant factors.
2. *Economic life*: Two definitions fit in this case:
   a. This is the period during which the equipment's minimizes the equivalent uniform annual cost (EUAC) and resembles to its net present value. EUAC is usually made up of two factors: the initial cost of the asset spread over its life (the "capital recovery" annuity) and the annual cost of repairs and maintenance. The capital recovery should include a deduction for the salvage value of the asset, if any. The annual cost of repairs should, if appropriate, include a contribution representing the cost of correcting any defects in the product resulting from the use of an outmoded machine. The first factor will go down as we consider longer lifetimes, while the second will usually go up. The sum of the two will, therefore (usually), have a minimum value. This minimum value is the minimum EUAC, and in most cases, this will correspond to the economic life of the asset.
   b. Alternatively, it is the period of time before the equipment is replaced by another piece of equipment after economic and technological analysis.
3. *Ownership life*: This is the period until the equipment or machine is sold or disposed of.
   a. Ownership life begins when the decision to acquire the asset incurs costs. This may include costs that occur before the actual arrival or asset use begins, such as loans, planning costs, transportation costs, or setup costs.
   b. Ownership life ends when the asset stops causing costs and has no continuing financial impact of any kind. This means, for example, that all costs of disposal or decommission have been paid and no longer appear in an asset's account on the company's balance sheet.
4. *Accountable or financial life*: This is the period selected by the financial department to calculate depreciation, following the company's accountancy procedures. An equivalent term is depreciable life, formally defined as the time period over which an asset can lawfully depreciate. In each year of depreciable life, a depreciation expense is calculated and declared for the asset using standard accounting methods. This expense lowers the book value (balance sheet value) of the asset, lowers the company's reported income, and creates tax savings.

   When depreciable life is over, the asset is said to be fully depreciated or fully expensed. If the asset is kept beyond that point, its book value is called either its residual value or its salvage value. Asset residual (or salvage) value is typically a small percentage of the asset's original purchase price; it may even be zero.

   For some assets, management can simply choose a number of years for depreciable life based on the asset's expected useful life. For other kinds of assets, however, depreciable life is prescribed by the country's tax authorities.

5. *Physical life*: This comprises of the time until the machine is incapable of performing any work. This life is longer than any of the previously mentioned types. A machine can have several owners and several useful lives but only one physical life from the very beginning until the end or destruction.

   Physical life can be seen as the potential service life of an asset before it physically becomes unable to produce a good or service for anyone. An asset is often physically able to continue operating at a cost that renders it economically obsolete for certain users but usable for others. The economic life, as opposed to the physical life, is most important in evaluating the asset.

Among the lives described previously, the one that can be established beforehand, taking into consideration the industrial sector where the asset is going to be used, is the accountable or financial life. In the past, decisions for replacements were generally based on financial criteria rather than operation or maintenance aspects.

4.2.22 Vorster Model for Failure Cost Estimation

4.2.22.1 Introduction

The model proposed to develop financial indicators is oriented to tasks carried out by groups of similar equipment, that is, the concept of UU previously described, for example, a set of similar/identical centrifugal pumps.

4.2.22.2 Analysis of Failure Cost

In order to properly estimate the cost of failure of equipment, it is necessary to relate it to other assets that perform similar functions in the groups (pumps, fans, gearboxes, etc.). Such classification allows the consideration of a failure scenario. When failure occurs and the equipment is shut down, other equipment will partially or totally assume the tasks that the failed equipment was performing. Vorster and De la Garza [364] proposed that when failure of a UU occurs, there should not be any pause in production. Similar equipment will replace the failed one or will stop certain functions of less importance and take care of the tasks that were going be stopped, that is, if they are more important than the function they are currently performing. However, lost production is not the only hidden cost. There is a hidden cost in the associated resources that are directly or indirectly linked to the equipment; this could lead to idle times for workers, raw material costs, or contractors being forced to stop work.

Equipment can perform diverse production tasks according to a series of variables: level of production, seasonality, requirements of other productive areas, and so on. Therefore, it is a good idea to define diverse scenarios of operation where equipment failures can occur, each with different consequences on associated failure costs.

Creating diverse categories of failure costs can help prioritize and facilitate the analysis of costs. For a given set of equipment, the following categories can be applied: group, scenario, or corresponding categories.

The failure modes of equipment could be included as well, but this can overextend the analysis. It is better to select fewer but relevant data. The ability to consider failure costs depends on the availability of information to describe what happens when an asset fails. Therefore, it is necessary to create scenarios to define the task of the equipment as well as what happens when it fails. In this way, the analysis can focus on the desired costs, defining reference frameworks to describe the economic effects of failure.

Many assets perform more than one unique task and fail under different circumstances. The time (and resources) necessary to address failure is generally different for each scenario. That is why, when considering the failure costs, the various possible scenes must be weighed and added.

4.2.22.3 Categories of Failure Costs

To simplify the analysis, the following four categories are used (Figure 4.15):

- Impact on associated resources
- Financial cost of the equipment
- Impact on the group of equipment
- Impact of alternative methods

4.2.22.3.1 Impact on Associated Resources

This type of cost appears in the effect of the failure of an asset on associated resources, such as manpower or other assets. Normally, they appear instantaneously after the failure. They are directly related to the occurrence of the failure and are proportional to the number of failures. The clearest cost of this category is the cost associated with a worker's lost productive time when the machine stops and there are no alternative tasks to perform. In the case of maintenance, it is the cost associated with the lost

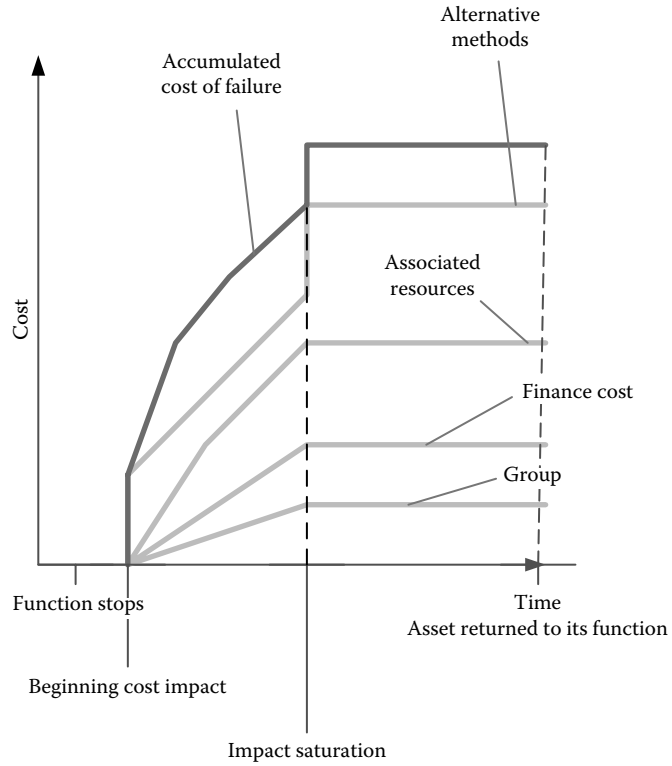

FIGURE 4.15
Components of the accumulated failure cost.

productive time of the technician who must take care of the shutdown and not do his/her regular work. This type of failure cost also includes costs that occur when the failure of one asset affects the productivity of another (even though the latter may be in a different group).

This type of cost, according to Monchy [224], is difficult to determine. For Monchy [224], the hidden costs of production shutdown or slowdown have a subjective nature because it is impossible to quantify some impacts, such as customer satisfaction or brand image. Other elements, like the operator's idle time mentioned previously, are much more easily determined if an agile information system (SCADA, ERP, or CMMS) is in place and triggers an immediate warning about idle resources (assets or labor) during shutdowns or slowdowns. In this case, the idle time of those resources may be properly and accurately quantified.

4.2.22.3.2 Financial Cost of Equipment

The financial costs of the equipment are defined as those costs that can and/or must be imputed since the company purchasing those assets hopes that the resources, represented as investments of capital in productive goods, will be available to operate as much as possible. The concept is based on the idea of a punishment mechanism that motivates managers to have the equipment available for production whenever it is needed.

These costs are analogous in many ways to the storage costs. Some authors think that it is arbitrary to impute them only when the machine has failed, when the storage cost is charged 100% of the time. So, the key question is whether these costs that are paid on a continuous basis should be considered just when failures happen.

4.2.22.3.3 Impact on Group

This type of failure cost is related to the group of equipment. The cost is incurred when one or more assets of the group fail, forcing other assets to work more intensely, in worse conditions, and normally less efficiently, to meet the desired and expected level of demand. Accelerating production lines or increasing the speed of rotating machinery to recover lost production force the machinery to work in degrading conditions and with elevated risk of new shutdowns.

4.2.22.3.4 Impact of Alternative Methods

This type of failure cost happens when the failure of a machine forces a change from an optimum method to one with higher operation costs. It normally happens only after a prolonged period of failure and frequently implies additional costs to mobilize the resources that are necessary for the alternative method. Examples include the improvised installation of redundancies or provisional electrical or mechanical configurations (electrical wirings, batteries, generators, etc.).

4.2.22.4 Estimation of the Cost of Failures

To evaluate each category of cost, detailed procedures must be followed.

4.2.22.4.1 Impact on Associated Resources

Figure 4.16 shows the period of time when this type of cost occurs and demonstrates its temporary evolution.

These costs are located somewhere between the ending of normal operations and the moment when normal operation resumes. Generally, each resource associated with the

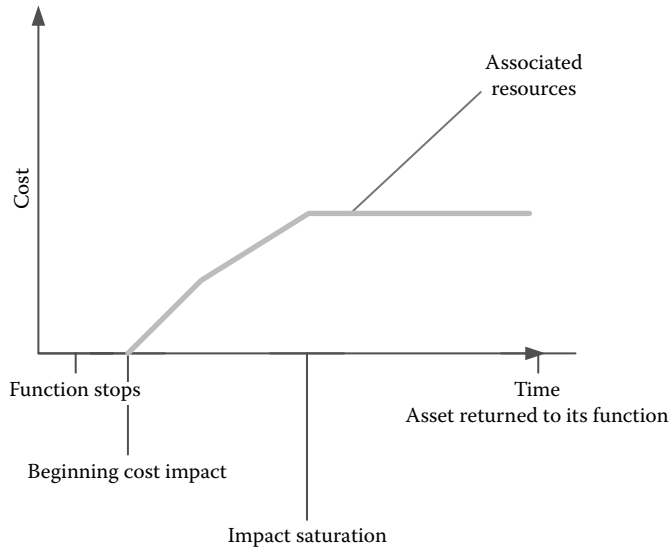

FIGURE 4.16
Impact on associated resources.

failed equipment is affected in a different way and takes a while to appear. During this interval, the impact of the failure is not observable.

Each of the associated resources generates costs during the shutdown. The duration of the impact can be equal to the total duration until the startup of the stopped asset if relocation of the productive (and idle due to the shutdown) resource is not possible. It can be substantially shorter if the resource affected during the period can be relocated to another task, thus avoiding the negative influence on cost due to the resource's inactivity.

As the duration and delay are different for each affected associated resource, the accumulated curve of failure cost has an irregular profile.

4.2.22.4.2 Financial Cost of Equipment

This is calculated much like the previous case, taking into account the delay and its duration. In order to estimate the financial cost of the equipment, the financial cost by time unit is required; this is obtained from the initial investment in the asset (Figure 4.17).

4.2.22.4.3 Impact on Level of Service

Such costs occur when one or more pieces of equipment in a group fail, causing the rest of the equipment to absorb its workload, incurring more expenses to maintain the required service level.

Quantifying these costs depends on the following factors:

- Level of demand of the service versus the available pieces of equipment to fulfill the demand.
- The group's ability to work is defined by the condition of a given number of pieces of equipment and is based on the availability of each member of the group.

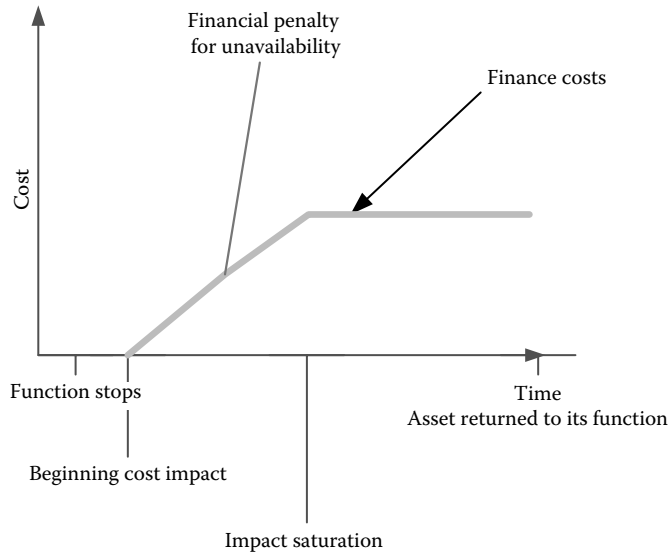

FIGURE 4.17
Financial cost.

This cost is generally extremely complex to calculate, and Monte Carlo simulations are a well-known resource to solve such workgroup problems, given the mixed demands and availabilities.

4.2.22.4.4 Impact of Alternative Methods

These costs appear when the failure of a piece of equipment in the group forces a change in the method (operation or manufacturing) and the organization undergoes an additional failure cost, proportional to the differential cost between the applied methodologies (optimized and alternative). The evolution of this type of cost once the failure starts can be seen in Figure 4.18. In this case

1. Use of the new method implies a vertical cost jump right at the beginning of using the alternative; this represents the cost to configure the new method.
2. Cost by unit of time during the use of the new method is the difference between the costs by unit of time between the original method and the alternative method.
3. A second vertical jump at the end of the use of the alternative method reflects the cost to return to the original method.

The graph in Figure 4.18 shows the three sections of costs implied in the use of alternative methods while the repair of the original equipment takes place. The first stage indicates the configuration of the new method shortly after the activity of the original equipment ends and a decision is made to the use the alternative method.

After it is configured and deployed, the alternative method usually performs more poorly than the original method, thus generating a cost. Once the original equipment is repaired and the original method restored, there is an additional and final cost related to the restitution of the original and the disassembly of the alternative method.

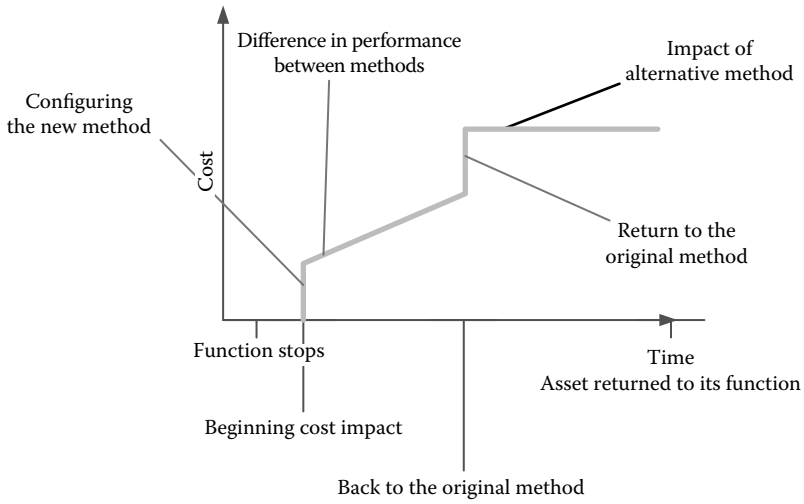

FIGURE 4.18
Cost of use of alternative methods.

4.3 Estimation of Maintenance Costs

Once the basic costs on which the model can be constructed are defined, all economic maintenance management must be sustained in a cycle of continuous improvement, from the measurement to the control and finally to the reformulation of the model, completing the cycle again and again. To deploy any model of costs, particularly the proposed one, the following elements are necessary: a database, records and measurement of cost, and systems for cost analysis.

4.3.1 Maintenance of a Database

A system of costs generates a great amount of data and information useful for

- Segregating the different types of costs in the maintenance process
- Providing relevant information to help managers make better decisions
- Providing information to plan, control, and measure efficiency

The database must be maintained with costs appropriately codified and classified so that the relevant data can be retrieved according to the previous requirements. A proper system of codification allows the costs to be accumulated according to the desired targeted costs (such as preventive maintenance, corrective maintenance, contractors, productive areas, and different cost centers) and to be classified in appropriate categories. The typical classification of costs within a database is by categories of expenses (direct material, direct manpower, indirect expenses) and by type of costs (fixed or variable). Future costs (estimations and predictions) as well as past costs are necessary for decision-making. In short, the costs in the database must be retrieved and analyzed in a changing environment of prices and strategies.

The classification is important to evaluate other aspects such as the financial impacts of decisions to resize plants, both up and down, but in the database they are not classified this way since this relevance is relative. In fact, once cost data are retrieved, they will acquire a meaning for the user (maintenance, production, etc.) according to the scenario the organization is facing.

In any case, proper documentary management of the maintenance costs in a database, normally the financial aspect of a CMMS, is fundamental for later processing and use as "raw material" to prepare the maintenance scorecard.

Note that the collection of data must be simple, objective, that is, not open to interpretations, hard to manipulate, and aseptic. In this way, later processing will not be vitiated due to a collection of data that produces poor quality analysis, for example, when the use of the deployed methodologies depends on the goodwill of the workers. In conclusion, the human factor must be removed from data collection as much as possible.

The objectives for establishing a model of costs include knowing accurately what the maintenance function costs and establishing a scorecard of indicators that can be supervised at various organizational levels. The objectives of a cost program must include deliberate reduction of the global cost of maintenance to a minimum level (or maintain it at a certain desired level) compatible with a healthy production level, high quality, and well-maintained facilities. The objectives must be realistic; otherwise, they will be seen as impossible.

Objectives of costs for specific pieces of machinery, groups of machines, auxiliary equipment, supportive functions, or facilities can be elaborated. The objectives of machinery costs are quantified in monetary values of manpower or material for the maintenance imputable to the machine, or quantified in man-hours. Note that objectives of cost for certain areas (departments) or specific activities can settle down. The cost objective can be the lowest monthly maintenance cost, achieved in an area over 5 years or the average of the best cost in 3, 4, 10 months, and so on. These costs are also expressed in monetary values of manpower or material used in the maintenance work by unit of measurement.

Elaborating the objectives of costs requires the analysis of past costs. These records must be accurate; otherwise, the objectives will be become distorted and untrustworthy. Not only must the accountancy records be accurate but the internal records (often improperly recorded) corresponding to manpower and the maintenance equipment must also be trustworthy. As the cost units usually are expressed in monetary units, it is necessary to modify the previous numbers by manpower and material so that their level is constant. This update usually takes the current year as reference, and the figures of past years are adjusted so that they reflect the differences in base rate level and the changes during the period as indicated in the historical records. In a similar way, the prices of material will have to be adjusted to consider their changes and the inflation rate during the period of study.

Tavares [324] specifies the necessary actions of a CMMS for proper measurement and further processing of maintenance costs:

- To allow linking the different cost centers according to the internal organization of the company and other types of relations that the end user may require
- To register the cost of acquisition of the equipment
- To automatically record the programmed and unprogrammed work orders in the different cost centers

- To be related and connected to the accounting system, creating harmony between accounts (formal accountancy with books) and cost centers
- To obtain costs of manpower for different assets selected by the user in a specific period
- To obtain costs of manpower contracted for the different assets selected by the user in a specific period
- To obtain costs of material for assets selected by the user in a specific period
- To estimate costs of maintenance by each activity and applicant
- To calculate the index of cost of maintenance by invoicing for a user-defined period
- To calculate the index of accumulated cost of maintenance by cost of acquisition of equipment for a user-defined period
- To calculate the index of cost of manpower of third parties in relation to the total cost of manpower (in-house labor in addition to third parties or contractors)
- To allow maintenance to directly obtain the costs of pieces and commonly used material in the associated work orders from the spare parts management system within CMMS

4.3.2 Records and Measurement of Costs

Most CMMSs merely consider the direct costs of the maintenance, that is, the hard costs. The soft costs are much more difficult to consider and can only be calculated by complex programs of data mining, where the difficulty is more in the necessary feeding of data than in the software or embedded algorithms.

Therefore, the CMMS will control the direct cost of the maintenance through the correct and efficient use of time, materials, labor, and additional services. To this end, it can prepare a budget annually, with suitable justification of the cost of maintenance. This direct cost is closely related to the cost of intervention (in its more visible version). Contributing data include the following direct costs:

- Cost of personnel (in-house labor)
- Costs of external or outsourced personnel
- Spare parts and other consumable materials from the maintenance warehouse
- Cleaning
- Trip expenses
- Audits
- External maintenance (outsourcing)
- Renovations of maintenance workshops and warehouses
- Rent
- Patents, taxes, and insurance
- Amortization

Indirect costs are less visible and often forgotten in calculations of the intervention cost. Their estimation demands the feeding of a series of data into the CMMS that requires a communicative transparency, whereby maintenance managers try to involve maintenance workers in the contribution of data that are known by very few people outside the

maintenance headquarters. Eventually, they may try to affect these costs in order to have a positive impact on maintenance. Even so, the real impact in the improvement of the efficiency of maintenance comes from the direct costs and failure costs.

Internal indirect costs distributed between all cost centers are

- Land and buildings
- Electrical provision
- Gas, water, and communications

External indirect costs are

- Technical purchases
- Health and safety
- Medical service
- Personnel department
- Top management

For the selected cost model to function properly, cost centers must be created. A cost center is an organizational structure that allows grouping all the costs of a productive process, auxiliary service, or simply a group of assets based on a common geographical location, brand, or function. The maintenance personnel of a production plant must be divided/allocated into internal and external maintenance (Figure 4.19). The internal maintenance is carried out by the in-house personnel of the center and by personnel from subcontracted companies. Working under annual contracts, these subcontracted companies usually issue a monthly invoice according to the performed maintenance hours; the price is previously negotiated with the company (contracting party).

External maintenance is carried out by external companies that perform specific and concrete maintenance tasks. For this type of maintenance, the work is performed under a previously negotiated budget; invoicing does not depend on hours worked but on tasks carried out (including manpower, materials, trip expenses, accommodation costs, or even additional partners as third parties required by the contractor who can freely contact them as long as the invoice does not increase and the task is properly carried out, etc.).

Internal maintenance can be divided into electrical maintenance, mechanical maintenance, and general maintenance. Tasks can be performed by the company's personnel (in-house maintenance) or outside personnel (contractors). A different set of maintenance tasks will be assigned to each of these maintenance groups (differentiated by function/specialization) to determine the hours performed by each specialty.

Mechanical maintenance tasks: The personnel required for mechanical maintenance are generally trained mechanics with diverse specialties. The tasks performed include

- Maintenance tasks involving any type of mechanism: gears, conveyer belts, pistons, lubrication, changes of format, combustion engines, boilers, and so on
- Operation of machine tools: turning machines, drilling machines, material removal machinery, and so on
- Installation of pipes, tubes, plates, and so on
- Welding

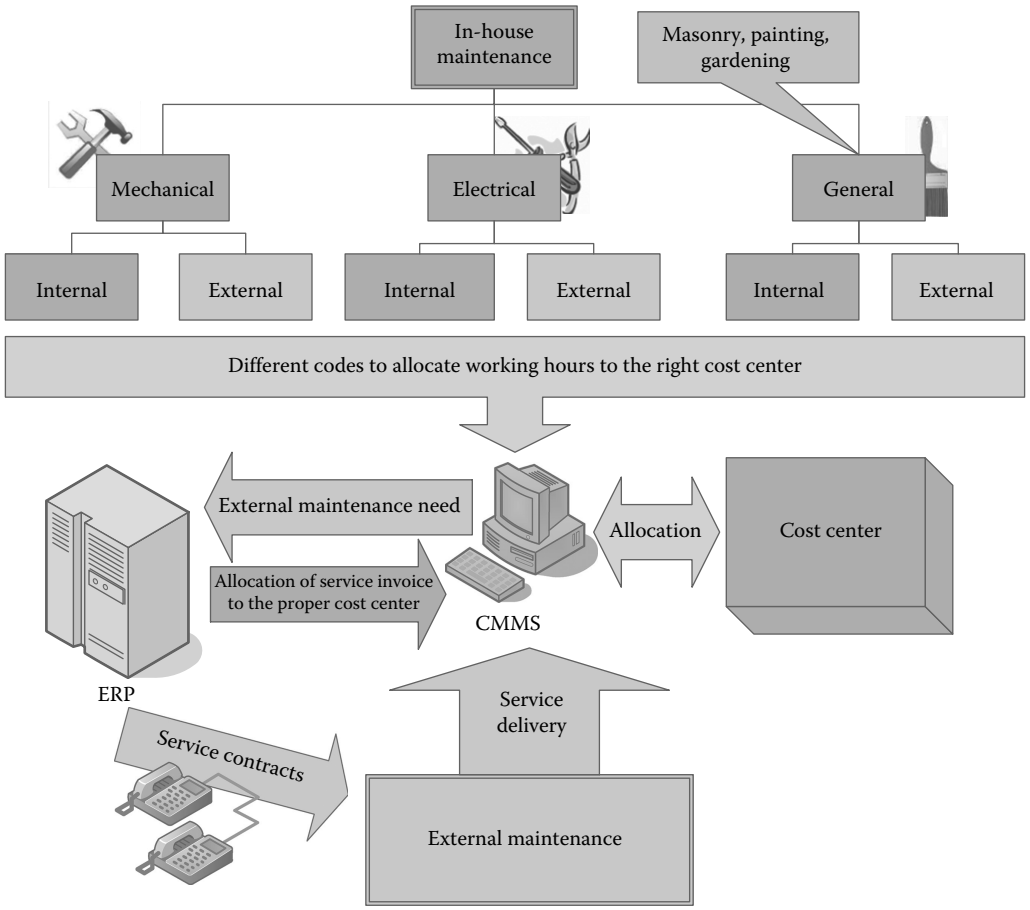

FIGURE 4.19
Structure of internal and external maintenance.

Electrical maintenance tasks: The personnel required are trained in electricity and/or electronics. The tasks performed include

- *Tasks involving any electrical/electronic system*: Electrical wiring, transformers, illumination, electrical connectors, switches, cables for data PLCs, electric motors, all artifacts belonging to the power supply and automation systems, and so on
- *Manipulation of electronic measurement systems*: Oscilloscopes, ampmeters, voltmeters, network analyzers, spectrum analyzers, and so on
- *Programming robots and other automation devices*: PLCs, industrial networks, and so on
- Manipulation of power electronics devices

General maintenance tasks: Personnel required for these tasks have career office training

- Painting
- Masonry
- Gardening
- Other tasks of general nature that do not require specific training

The personnel working in each separate area cannot perform all the different types of maintenance. Repairs or interventions must be performed by people with specific training and/or technology. When a company carries out maintenance work, the relevant cost center must provide a maintenance order specifying the work to be done; the cost center to which the cost will be imputed must also be clearly specified and detailed. Once the work is completed, the external maintenance company issues a delivery note on what has been done. The supply department then transforms the order into an invoice so that the company doing the maintenance can be paid.

Any invoice for external maintenance is imputed directly to the cost center where the maintenance is done. External maintenance does not have a particular impact on any specific asset associated with the cost center where maintenance actions are performed, but it directly affects the cost section. This complicates the budgetary classification based on UUs, turning budgetary processing into the black hole of maintenance.

For external maintenance, the cost of the work is imputed directly to the cost center where the work is done. By way of contrast, the maintenance department has an annual budget that covers all internal expenses. Therefore, an hourly rate for maintenance labor must be established so that the number of hours performed by an in-house maintenance crew will be imputed to the budget according to the agreed-upon hourly rate. However, when workers in the previously defined specific areas perform maintenance, the hours must be entered into the system as hours of internal maintenance charged to the cost center where the maintenance is done. The costs of the different cost centers are divided according to the UU. A cost center for maintenance where all maintenance costs are charged must then calculate one of the thorniest issues in the maintenance function: the real price per hour. Dividing the total of costs charged to this center by the total number of realized hours will determine the real price per hour; this, in turn, becomes a key indicator of the cost of in-house maintenance, facilitating subsequent decisions about outsourcing, overhauls, or replacements.

The cost center that usually only includes maintenance must aim for statistical quantification—it is not a real and active cost center. Rather, it must distribute the costs to other centers based on the hours of maintenance spent in each of them. The total sum of costs in hours of maintenance imputed to the different centers must agree with the sum of costs of the center that represents the overall maintenance function. This is especially relevant in companies with TPM implementation where the borders between production and maintenance are blurred; it also emphasizes the idea of maintenance as a function rather than a mono-block department, with a cost center absorbing all the company's maintenance (Figure 4.20).

Structuring a factory by means of cost centers allows the company to impute hours spent on maintenance in each center using the reports and work orders issued by maintenance crews. As might be expected (and verified), hours of maintenance oscillate throughout the year since maintenance depends on the availability of resources, scheduled and unscheduled production shutdowns, and in-house maintenance planning and execution.

For external maintenance to be performed, it must be ordered. The cost reflected in the order, like the cost of the material and/or necessary spare parts, is imputed directly to the cost center where the maintenance contractor is working. If external maintenance has been selected for a machine for any reason (i.e., it is a technology unknown to the company or there are economic factors), if this machine is defective and it is necessary to carry out an excessive number of interventions, or if the interventions cost much more than is

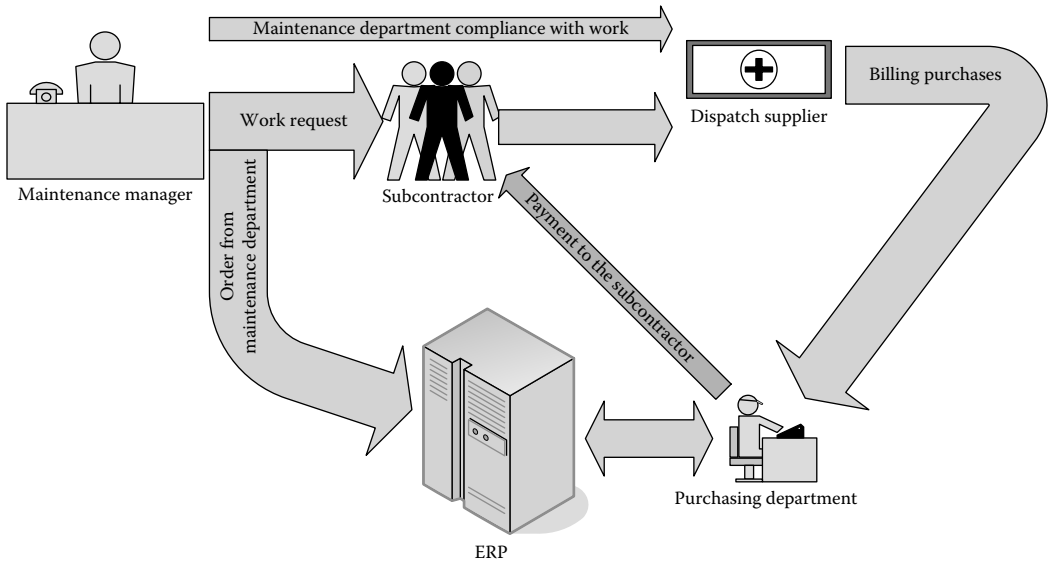

FIGURE 4.20
Controlling external work with systems of integral management.

usual, these are not generally reflected in the costs of the machine's maintenance. On the one hand, as the cost of the maintenance is being imputed to the cost section, it increases the cost of external maintenance in that cost center and, consequently, boosts the price of the product/service produced in that section. On the other hand, this abnormal cost will also indirectly impact each and every piece of equipment in the section without specifying which one is generating it. In a common and dangerous practice, the abnormal costs produced by a faulty machine are absorbed and masked by other surrounding equipment. As previously noted, this shows the difficulty of calculating the LCC of each of the UUs associated with that cost center.

Instead of imputing the cost of maintenance orders to a cost center, the orders for external maintenance can deliberately be left open. In this way, even though the cost is imputed to the cost center after closing the work order, the document remains in the CMMS with all detailed incurred costs for further processing and calculation of the LCC of the different UUs.

To all previously mentioned costs, it is necessary to add the cost of material for the maintenance activity, such as a general spare part, a consumable, a specific spare part, safety material, and so on. During the first stages of a maintenance action, these costs are not usually considered directly or associated with a specific repair. However, they are finally entered and charged to a cost center as a cost of additional maintenance in the global cost and associated with each intervention, thus avoiding the temptation of creating a kind of maintenance cost warehouse that absorbs all spare parts, materials, and so on. This is a common practice where spare parts are linked to work orders, and this option is definitely better than a common cost center absorbing everything with no chance of further processing. It is not an optimum practice, however, as a work order can comprise of several subtasks and proper analysis would be relevant (Figure 4.21).

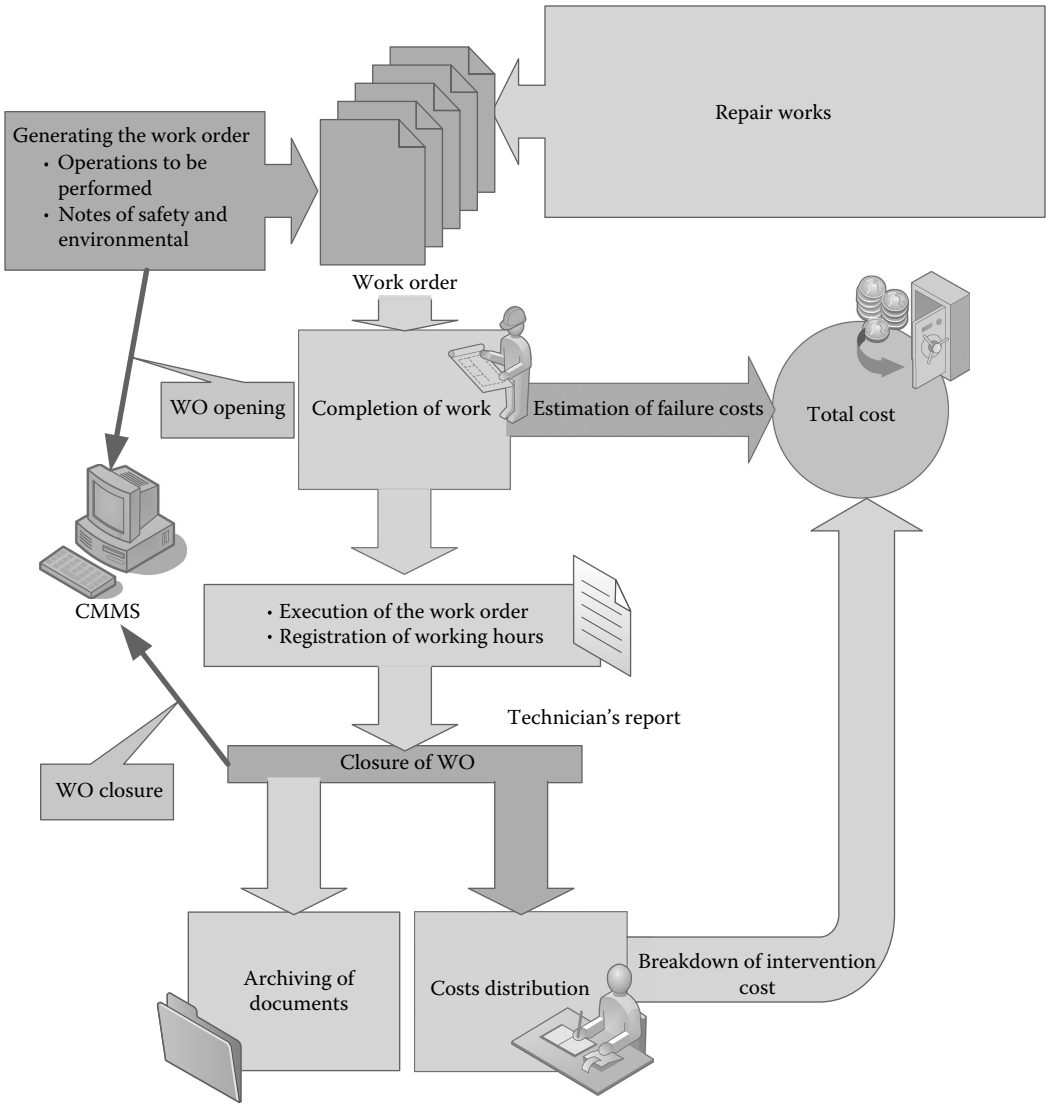

FIGURE 4.21
Process of allocating costs before a work order.

Supervisors and managers must be notified of workers' operations during a work day, along with the time dedicated to each activity, for the following reasons:

1. The person in-charge must know the failures that have occurred to be able to properly plan the required tasks.
2. Workers must record their activities during a working day, including extra hours worked, visits to the doctor, training, and union meetings, to justify wages.
3. The hours of maintenance performed by each special area (electrical, mechanical, electronic, etc.) must be recorded to accurately calculate their cost per hour.

4. Both the maintenance manager and production manager or factory director must know what activities consume more maintenance time and to what extent (percentage of failures, percentage of planned work, etc.).
5. The number of active workers is determined by sick leaves, special activities, participation in union meetings, and so on. The real number of annual maintenance workers must be calculated by the total hours spent in maintenance, not by the number of working hours of those formally employed as maintenance crew.
6. It must be known which cost centers require more maintenance than others.

All this information is given back to the company via the reports of work done by technicians (mostly the WO with all generated documents). This allows the retrieval of the necessary data. In fact, it takes a long time to process all the information provided by the technicians as the amount of data is overwhelming and the quality of data can be low. This increases the possibility of errors.

Two types of documents must be processed for cost analysis: work orders and reports from the technicians (if these are not formally a part of the work order like a work request or a technical analysis). Within these documents, for the proper imputation of costs, at least two types of maintenance (corrective and preventive) must be differentiated in three types of activities:

1. *Failures*: Failure leads to undesired shutdown or slowdown in the productive process; it may be necessary to stop the productive process to carry out the maintenance tasks.
2. *Repairs*: Repairs do not interrupt the productive process. The productive process should not stop to solve the problem. Neither necessary materials nor other resources have been planned in advance to solve the problem.
3. *Planned activities*: These include activities designated in prevention plans or repairs for which the necessary materials and resources have been planned, along with the time to do them.

4.3.3 Systems for Cost Analysis

With suitable measurement of costs (proper data collection), further processing will be able to construct the desired financial indicators to display the efficiency of the maintenance function. Clearly, as mentioned before, when estimating soft costs, the complexity will be seriously affected by the difficulty, indicating the urgent need to take control of costs when analyzing the LCC maintenance perspective.

There are three main reasons why a system of accumulated costs is required to generate relevant information in the maintenance decision-making process:

1. Many indirect costs are relevant for the decision-making process.
2. An information system with properly triggered warnings is required to identify those areas whose costs are rising beyond the planned budget.
3. Decisions on changes in certain areas of maintenance activities are not independent; there are always repercussions and impacts (both positive and negative).

There is a danger that only incremental costs that are solely attributable to specific activities will be classified as relevant in decision-making due to their easy collection and

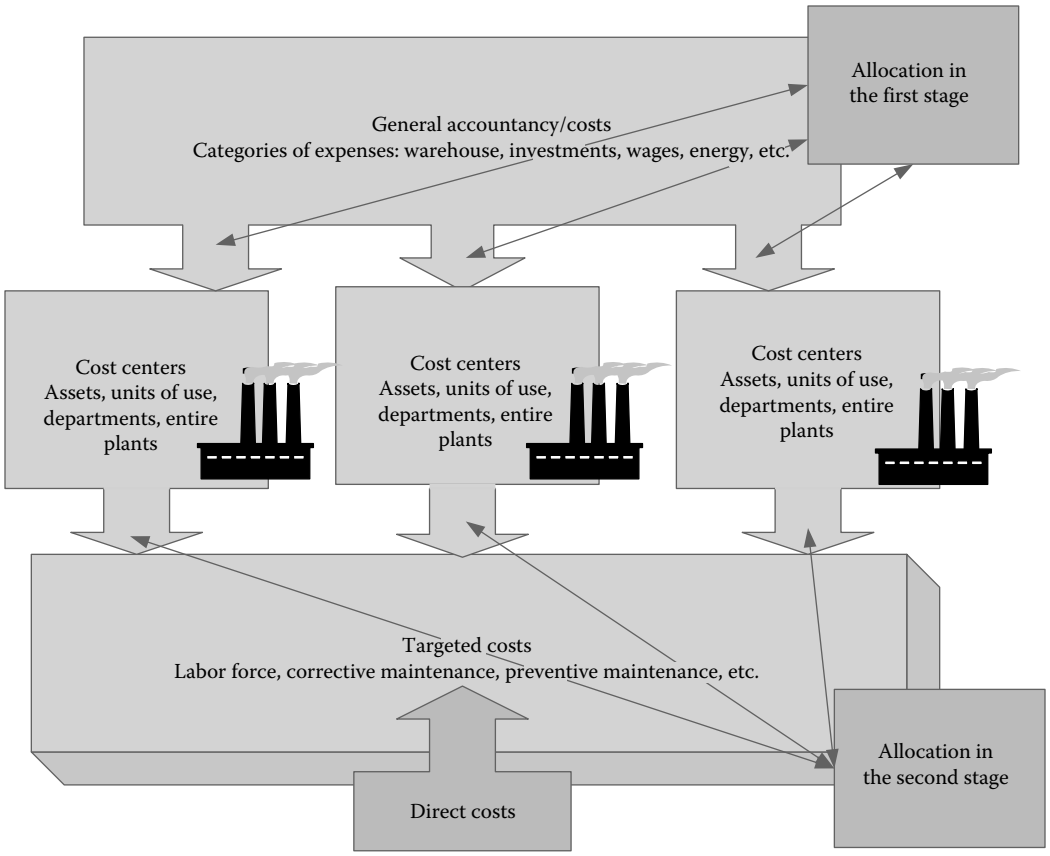

FIGURE 4.22
Traditional model of maintenance costs.

processing. Direct costs are transparent; therefore, they will be considered and obviously affected by decisions, and variations will be clearly observable. Indirect costs are also affected by decisions but in a less transparent way and with a certain delay in appearance, making them less likely to be noticed at a glance.

Cost models can vary depending on what costs are assigned to the cost object and its level of sophistication. Typically, models are classified as one of the following:

- Direct cost models
- Traditional model of cost by absorption
- Models of cost based on activities (ABC systems)

As the name indicates, direct cost models only assign direct costs to the cost object, in this case, maintenance. Here, these costs contribute to indirect costs and are incorporated directly into the results as expenses during the economic term in question. This method can support decision-making when the cost of lateral resources (services and other indirect costs) that fluctuate according to demand is insignificant. The items with negative or low cost contributions must be looked at more closely. At any rate, an estimation of the indirect costs relevant for decision-making must be incorporated into the analysis at

some point. The disadvantage of systems of direct cost is that they cannot measure and assign these indirect costs to the cost object (maintenance). That is why the system of direct cost can only be recommended when the indirect costs are of a very low proportion of the total costs of the organization; its application when these costs are not negligible will paint a false picture of the economic health of the maintenance function.

On the other hand, in traditional and ABC systems, indirect costs are assigned to the cost object. Figure 4.22 shows the fundamental process of these models of cost. In the first phase, the general costs, all expenses (including the indirect ones) are assigned to cost centers. In the second phase, the accumulated costs in the cost centers are transferred to the cost object using a well-defined basis of allocation. The traditional system of costs, the one most commonly found in maintenance, uses a small number of the allocation's bases in the second stage, typically direct working hours or machine hours.

In other words, a traditional system assumes that hours of work or machine hours have a significant influence on long-term general expenses. The ABC system differs because it has many cost centers in the first stage or phase and a great number and variety of allocation bases in the second phase.

5

RAMS Parameters: Indicators of the Effectiveness of Maintenance

5.1 Introduction

This chapter considers RAMS parameters, that is, the conjunction of reliability, maintainability, availability, and safety, to create the third pillar of the indicators of maintenance and the control scoreboard; Galar et al. [100]. This important pillar makes solid and consistent contributions to the indices for information on the system's effectiveness (Figure 5.1).

Together, these parameters indicate the state of a system's dependability; put otherwise, a system may be considered dependable if it has these four characteristics. This recently coined term is also used in maintenance engineering and management to indicate functional safety; in this case, determining dependability follows strictly technical criteria of system effectiveness without considering efficiency.

In Norm IEC 60300-1 [130], dependability is defined as "the collective term used to describe an operation based on the availability and the influential factors: reliability, capacity and support to the maintenance." A primary assumption of this definition is that availability is the real goal; the system must operate correctly when its use is required. For this purpose, the system must be both trustworthy and able to be maintained and repaired with the allocation of proper resources. The specific mention of the maintenance function is important as it constitutes the basis for dependability. This definition explicitly does not include safety, even though, as already has been indicated, this point is the origin of the development and application of the dependability theory.

An informal definition of the *effectiveness of a system* is the following. The effectiveness of a system is its capacity to carry out the work for which it has been bought. Adding further clarifications leads to the following two additional definitions:

1. The effectiveness of a system is the probability that the system can satisfy the demand of operation within a given time interval and under certain conditions.
2. The effectiveness of a system is the probability that the system satisfactorily operates when demanded to do so under certain conditions.

The effectiveness of a system obviously depends on how the system or equipment is designed and constructed, but how it is used and maintained is equally critical. Thus, the following people or elements of the organization are involved and may affect this parameter:

- Design engineer
- Manufacturing engineer

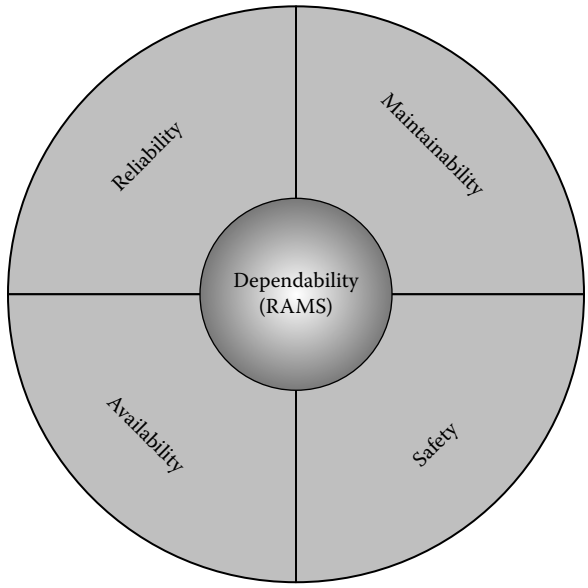

FIGURE 5.1
RAMS parameters.

- Operator or user
- Maintenance personnel

Finally, effectiveness is influenced by the logistic systems that support operation, the administrative policy for personnel, criteria governing use of the equipment, and other decisions of an administrative nature.

5.2 Effectiveness of Systems

Modern industrial systems are very complex and represent huge economic investments, both of which affect their management. Safety and quality are further concerns for the system, the people working on it, and the environment.

This requires an *integrated exposition* of the specifications for the design and operation of the system (the technical effectiveness) considering both logistic conditions and security.

It is necessary to choose those methodologies and procedures that lead to the best design, optimized use/operation, and logistical support, not to mention the optimal monitoring and control of their application.

To achieve this goal, *integrated logistical support* (ILS) is used throughout a system's service life. The concept is not new; systems engineering has always incorporated all aspects of ILS.

ILS is now a necessity if the objective is efficiency and effectiveness in both human activities and in the systems created and run by humans.

ILS establishes the frame for activities by defining the activities, identifying the various interrelations, and monitoring and controlling them.

For practical purposes, the *analysis of logistic support* (ALS) unites ALI with the engineering of systems.

ALS comprises of a series of planned and iterative activities to determine the requirements of logistical support of a system and to influence in its design so that the system and its logistical support can be provided according to the specifications and at an optimal cost in both acquisition and operation.

ALS is a tool of design analysis used in the first stage of development of the system. It usually includes the analysis of the maintenance and the analysis of the cost of the service life. It results in identifying and justifying the resources required for logistical support, including the types and amounts of spare parts, test equipment and support, number and qualifications of personnel, among others. UNE-EN 60300-1 [357] specifies that machinery suppliers must contribute data on reliability and maintainability for further analysis of dependability as well as data on their logistic requirements so that life cycle costs can be calculated. Having available information simplifies RAMS analysis, along with the valuation of maintenance indicators and the resulting audit.

MLS or logistical support of maintenance is also part of ILS. MLS includes all iterative maintenance tasks (ALM). The selection of these tasks and their reach and intensity in a specific application will vary according to the needs and restrictions of that program. According to UNE 20654-4 [345], these tasks can be divided into the following general groups:

- Use (mission) and definition of the logistic system of maintenance
- Preparation and evaluation of alternative logistics of maintenance

Within ILS, certain parameters comprise of the nexus of the union of design and logistic considerations. These parameters become measures of the effectiveness of the system and its support; therefore, they are stated as objectives in engineering specifications.

5.3 Effectiveness Measures

Effectiveness measures, also called the logistic parameters of a system, are the quantitative representation of concepts associated with quality. Sols and Múñoz [305] take a historical perspective by equating effectiveness with availability, but this term can be extended to include the dependency of availability on reliability and maintainability. When we add the necessity for safety in all industrial surroundings, the proposed metrics can be stated as follows:

- Reliability
- Maintainability
- Availability
- Safety

These parameters are interrelated, but different systems emphasize them differently. The effectiveness of any metric requires the achievement of a certain value or a specific relationship among values.

A single system can have different objectives for the different parameters, depending on the functions. They can also change in the various phases specified in the system's

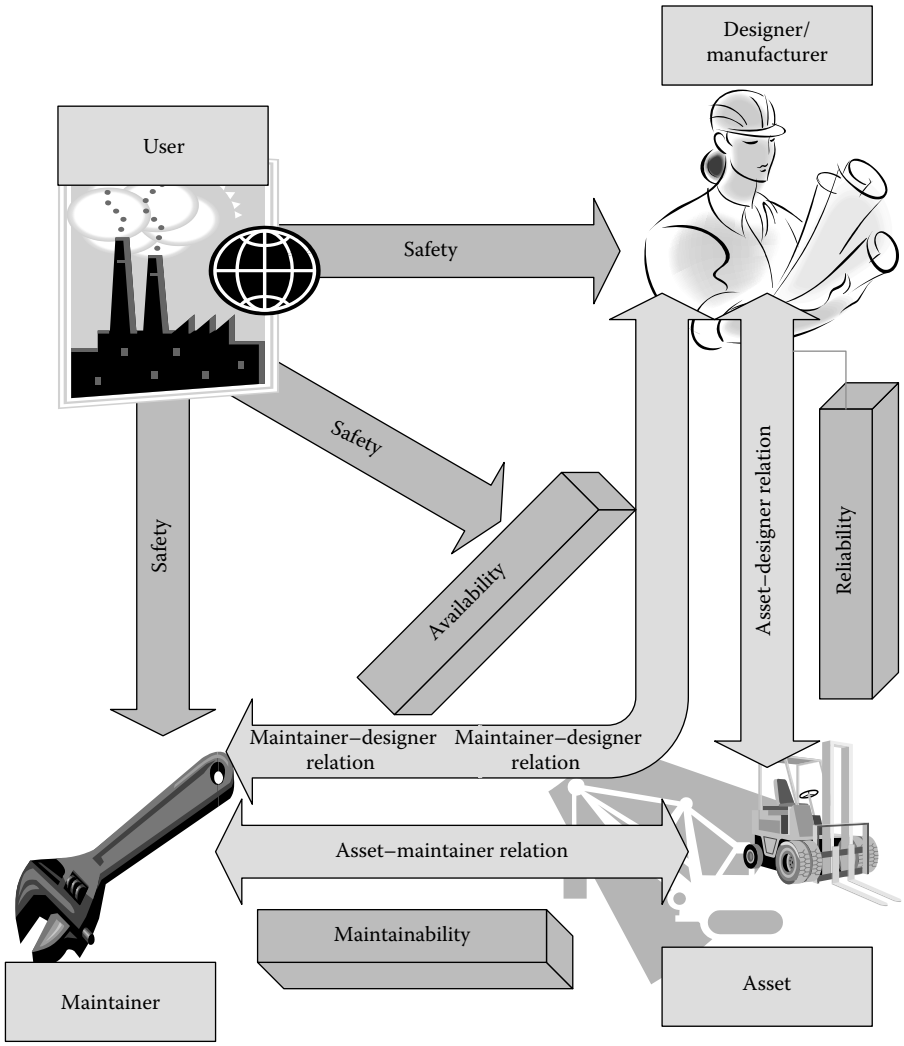

FIGURE 5.2
Relationship between RAMS parameters.

profile of use. The relationships between these parameters are determined in the following ways (Figure 5.2):

1. The relationship between a machine and maintainer is defined by maintainability.

   This is the probability of successfully completing an action of corrective repair, preventive repair, or both, within a defined period of time, at a desired level of confidence, with specified manpower, at predetermined levels of experience, with the suitable technology and tools, test equipment, engineering data, maintenance handbooks, and under specific environmental conditions. It also refers to the probability of being able to repair equipment and return it to its specifications of reference; see Knezevic [171].

   It is calculated by using the inverted repair times to maintain elements of the machine.

2. The relationship between a machine and manufacturer/designer is regulated by reliability.

   This represents the probability that a device lives up to its expected function, during the expected time, when it operates in the environmental conditions for which it has been designed; see Nachlas [232]. It is calculated as the times of failures of the elements of the equipment.

3. An integral relationship between manufacturer and maintainer through the asset, structured as availability.

   This is the real probability of having equipment producing properly during a certain period of time (excluding or adding time depending on the definition applied). Two key parameters are mean time between failure (MTBF) and mean time to restore or repair (MTTR).

To determine the probability that the equipment is operating satisfactorily when required, under stable conditions, the total time considered includes the time of operation, active time of repair, inactive time, time in preventive maintenance (in some cases), administrative time, and logistic time.

5.3.1 Reliability

Reliability is defined in IEC 60050-191 [129] and ISO 8402-2000 [134] as "the probability that a system operates satisfactorily during a determined period of time and in specific conditions of use." The definition accentuates probability, satisfactory operation, time, and specific conditions of operation. Each of these four aspects plays a significant role in the reliability of a system.

Probability is the first element of reliability; it usually takes a simple form, for example, the fraction or percentage created when favorable events are divided by the total number of events. When a number of supposedly identical elements operate under similar conditions, failures may occur at different and unknown moments; the "random mechanism" displayed by these occurrences can be determined by statistical analysis. For this reason, failures are described as probabilistic events, and the definition of reliability depends on concepts derived from the theory of probability.

Satisfactory operation is the second element of reliability. Specific criteria are established to determine what constitutes satisfactory operation. Normally, a combination of qualitative and quantitative factors is required to define the functions the system or product must perform to be considered functional.

Operating time is the third element. It is one of most important as its measurement defines the performance of the system. The parameter of time must be known to evaluate the probability that a task is completed or a given function is performed as predicted. It is of interest, therefore, to have the capacity to consider the probability that an element operates without failure in a determined period of time.

Reliability, expressed in terms of time, includes the following indicators: MTBF, mean time to failure (MTTF), and mean time between maintenance (MTBM).

Specific conditions of operation constitute the fourth element of reliability. These include environmental factors, such as geographic location where the system operates, operating profile, transportation, temperature cycles, humidity, vibrations, and other impacting factors.

Such factors must be considered not only when the system or product is operating but also during periods when the system is in reserve or being transported from one place to

another. Transport, manipulation, and storage are sometimes more critical from the point of view of reliability than conditions of normal operation.

Reliability is an inherent characteristic of the design, and, as such, it is important to consider it in the primary definition of the system and evaluate it throughout the system's life cycle.

Reliability becomes the objective of a system when the user needs the system to operate without failure during a certain period of time. If we look for the real causes of the loss of system reliability, we find most failures are due to the following:

- Human factors, including operator errors
- Improper use of the equipment
- Environmental interactions
- Problems with software
- Insufficient duration of the tests
- Low quality control in the manufacturing process
- Defective installation
- Inadequate maintenance
- Specifications (documentation) unclear

In a program to optimize operational reliability, four factors must be considered: human reliability, reliability of the processes, maintainability of the equipment, and the reliability of the equipment. The variation, together or individually, of any of the four parameters shown in Figure 5.3 will affect the operational reliability of a certain system, as explained by Woodhouse [378].

5.3.2 Maintainability

Like reliability, *maintainability* is an inherent characteristic in the system design. Ideally, a system's design should ensure it can be maintained without great investment of time, money, or other resources (personnel, material, facilities, and equipment).

Maintainability is the capacity of an element or system to be maintained, where maintenance is the series of actions taken to restore an element to, or maintain it in, an effective operating state. Maintainability is simultaneously a parameter of the design and a result of the design.

As a result of the design, maintainability can also be defined as a characteristic expressed in terms of factors of maintenance frequency, times of maintenance, and costs of maintenance.

These terms apply to a number of different indicators or measures. Thus, maintainability can be defined as a combination of factors, such as

1. A characteristic of the design and installation expressed as the probability an element will remain working or will be restored to a specified operating condition within a predetermined period of time, where maintenance follows established procedures and uses established resources.
2. A characteristic of the design and installation expressed as the probability maintenance will not be required more than a certain number of times in a given period,

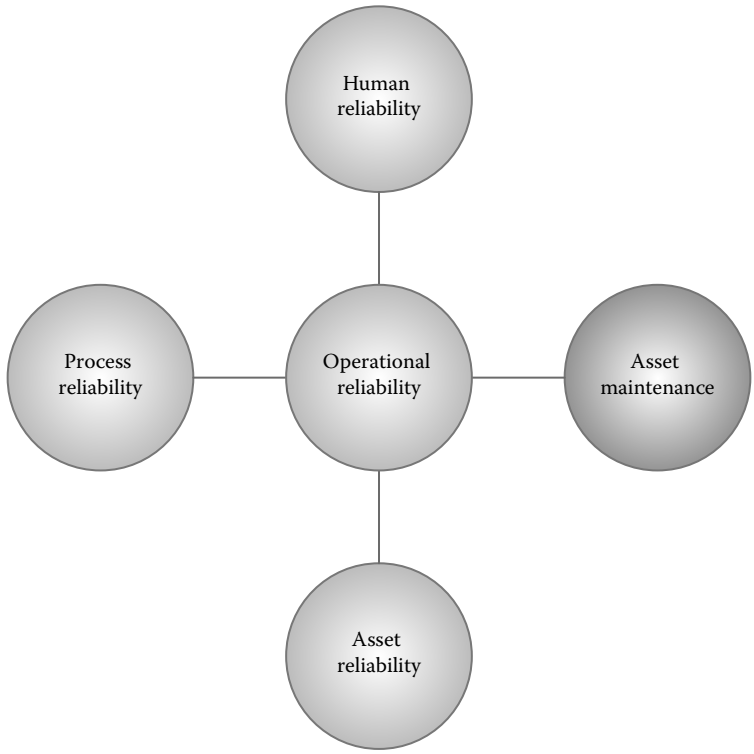

FIGURE 5.3
Operational reliability.

when the system operates or is operated and maintained following established procedures.

3. A characteristic of the design and installation expressed as the probability the cost of the maintenance of a system will not exceed a certain amount of money in a determined period of time, when the system operates or is operated and maintained in agreement with established procedures.

When considered as the objective of a component or system, maintainability is expressed as a requirement to reach a certain specified value.

5.3.3 Availability

The parameter *availability* provides an important measurement of the degree of effectiveness of a system. In general terms, the availability of a system is the probability it will be able to operate when required.

The requirements dominating the system or equipment are associated with its ability to perform when called upon and in certain surroundings. In the latter factor, the surroundings, it is possible to define different measures of availability based on either real conditions of support to the system (spare parts, facilities, etc.) or ideal conditions.

The factors directly affecting a system's availability include their ability to avoid failure (reliability) and their capacity to be maintained (maintainability). Obviously, corrective

maintenance causes a system to be shut down when it is required for operation. But preventive maintenance can also cause nonavailability.

5.3.4 Safety

When applied to a system, safety can be expressed in terms of availability and in measures of the probability of undesired events.

The practical treatment of safety requires the establishment and classification of risk events and the ability to determine their probability of occurring. Using information contained in databases is a better way of doing this than trusting estimations or expert judgments.

The analysis identifies the events of risk in the system quantifying risk in terms of probability. When the components causing unacceptable risks are identified, they must be redesigned. A nuclear plant is a system with obvious safety requirements (stopped, mitigation of accidents, etc.).

Among the diverse measures of the quality of a system, the evaluation of reliability is key. It is crucial throughout the service life of a system and can be considered within the frame of ILS.

In short, the knowledge and measurement of the reliability of components and systems are necessary in the development and operation of modern systems. The analysis of reliability rests on solid mathematical tools; it also calls for the creation of probability models, but the analyst does not always have sufficient data to design these.

5.4 Analysis of Reliability, Availability, and Maintainability

5.4.1 Introduction

RAMS analysis allows us to foresee, for a determined period of time, a system's availability and production based on its configuration, the trustworthiness of its components, and the philosophy of maintenance. Note that, unlike most of the literature, UNE-EN 60300-1:1996 [357] identifies four RAMS parameters.

The analysis builds on the selection of the times that characterize the diverse equipment of the production system, taken from generic databases of the industry, experience, and expert opinion. These times constitute the germ of the documentary system; later analysis will extract the parameters and indicators.

A simulation model considers the configuration of the equipment, glitches, partial and total repairs, shutdowns, and planned maintenance. Once constructed, the RAMS model allows us to infer the impact of availability and production deferred, including new policies of maintenance, changes in the maintainability of the equipment, application of new technologies, changes in the configuration of the equipment within the production processes, changes in the policy of inventories, and introduction of new methods of production.

Measuring data and visualizing indicators allows us to see the difference between RAMS analysis and predicted RAMS parameters. Based on this and following the suggested improvements resulting from the audit, we will be able to predict the future behavior

of the system. The deviations of the control scoreboard from the predictions will lead to improvements in the predictive system, making it more precise in the future.

A RAMS study will identify the probability of various deterioration processes affecting the equipment, subsystems, and systems associated with production. In other words, by measuring the established parameters, the study will predict shut downs or failures. Additionally, it will identify actions that will decrease their occurrence and note the economic implications. Finally, it will compare the situation to "Best Practices" to help establish optimal maintenance strategies.

The process leads to the development of a list of the criticality of elements or equipment. This list allows us to determine the impact of these elements on availability and deferred production, establish actions that mitigate the risk, and optimize the performance of the business.

5.4.2 General Model of RAMS Analysis

Figure 5.4 shows a scheme of the general model of a RAMS study.

As indicated in Figure 5.4, RAMS analysis begins with the estimation of failure rates of components or equipment. The information can be specific or generic. Using MIL HDBK 217-E [215], the U.S. Department of Defense determines the failure rate of electronic components with high accuracy. For mechanical elements, there is much more information and there is no need for the use of referential values to establish failure rates; for example, the

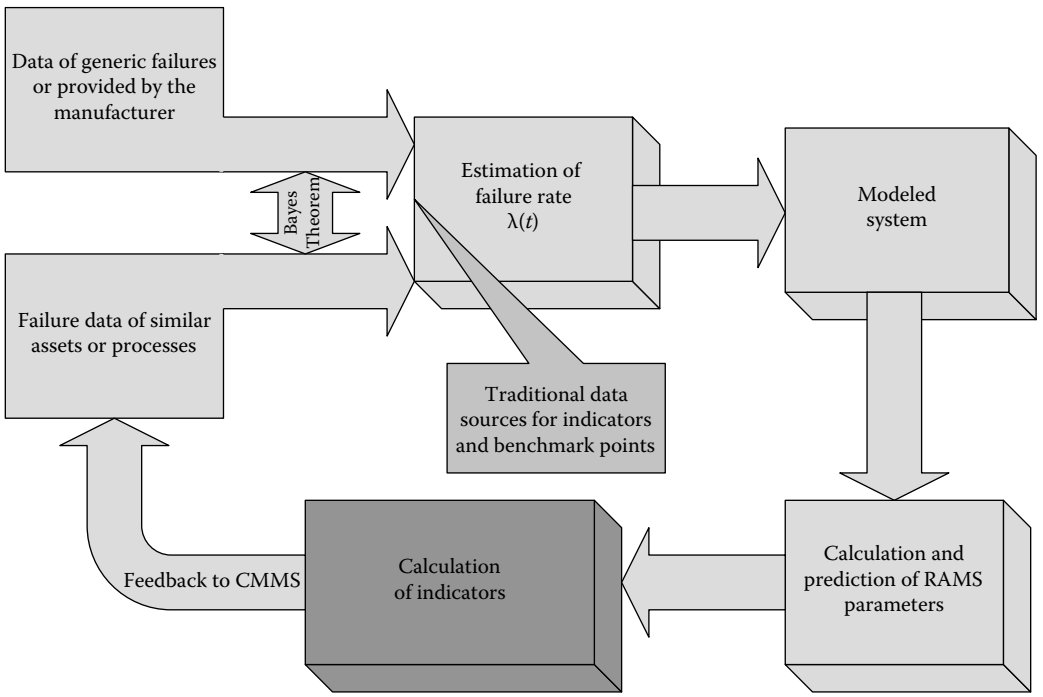

FIGURE 5.4
General model of RAMS analysis.

manufacturers of bearings usually provide models of life and degradation based on the operating load and conditions of work. The second and, in many cases, the main source of intelligence is evidence, including information on failures of similar systems or results of benchmarking between analogous companies or sectors; this evidence is stored in databases, such as CMMS; these data are mined to model the system.

These two sources of intelligence are not incompatible and can be integrated for richer analysis. Bayes theorem allows a combination of structured and mathematically supported forms, including the experience of others (previous knowledge) and a company's own experience (evidence). As a result, representative failure rates especially tailored to the operating reality of the process being analyzed (improved or updated knowledge) are obtained.

Following UNE-EN 61078:1996 [358], the information is used to create a model of availability that combines the architecture of the system and the philosophy of operation. The analysis requires interviews with the personnel of the various participating departments to verify the representativeness of the model. It is important that the model represents all relevant entities and dependencies.

Once the model is developed and the data are validated, the established indicators are measured and compared with the benchmarks, and various scenarios based on improvements in the system are simulated. These scenes correspond to changes of architecture (new configurations of the equipment, introduction of new technology, changes in the design), new plans of maintenance or optimization of existing ones, new policies of inventory, acquisition of equipment, new policies to improve the operating times, and failure rates of the existing equipment, among others. The simulations allow us to verify the impact of proposed changes on the reliability and availability of the system under study.

A RAMS analysis is developed in three stages, as shown in Figure 5.5. The first activity (Stage 1) consists of locating the failure and repair rates of the components or equipment that comprises of the system, along with the work orders for planned and unplanned maintenance, taking the following steps:

- *Historical data summary*: Many companies looking for the continuous improvement of their processes make an effort to harvest data on failures (type and frequency) and repairs. The amount and quality of this type of information are crucial because they reduce uncertainty in the analysis.
- *Compilation of opinions of experts*: In cases where there are insufficient data, certain methodologies allow the harvesting of information from experts. Technicians or workers who have years of experience on a particular system of piece of equipment are a rich source of intelligence; in such cases, adapted management prevents knowledge loss.
- *Search and adjustment of generic information*: To obtain reliable results, it is extremely important to complement a company's information on the failures in its system with generic data on dependability from recognized international databases when they exist. It is vital to adapt this information to the operating conditions under analysis, selecting only those failures that can occur in the environment being studied.
- *Revision and validation of databases*: The work team must validate the derived information on dependability for each element of the system. This stage includes a set of formal interviews with personnel associated with the process (operators,

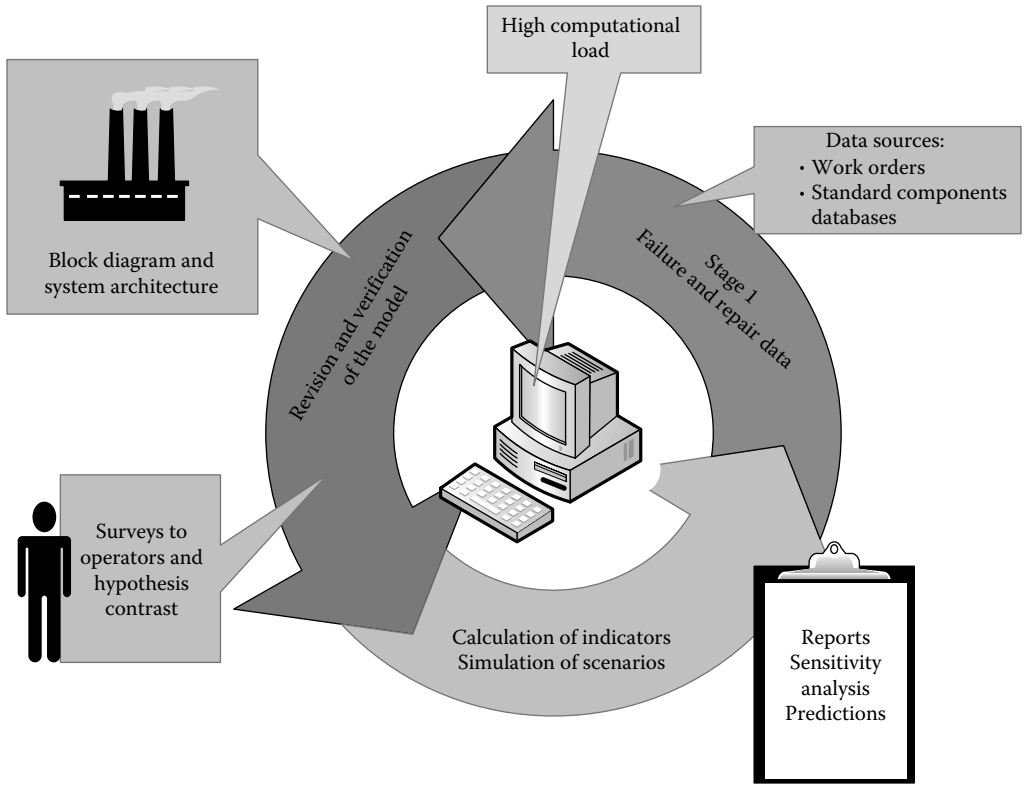

FIGURE 5.5
Stages of a RAMS analysis.

maintainers, analysts, programmers, engineers). As a result of the interviews, functional diagrams, diagrams of process, operating records and failures, plans of maintenance, and other sources of intelligence can be revised.

With all the information obtained in the previous steps, we obtain a representative estimation of the rates of failure and repair that are characteristic of the system or process being studied. From this Bayesian process, we can obtain a mathematical expression for the failure rates.

The second activity (Stage 2) is related to the revision and verification of the architecture of the model; it comprises of the following steps:

- *Construction of a block diagram*: The configuration of the production system must be shown in block models; this requires the detailed revision of the functional diagrams and diagrams of process created in the first state. UNE-EN 61078 [358] proposes basing the diagram on the success of the system.
- *Revision of the representativeness of the model*: Verifying the representativeness of the outlined model with respect to the production system under study. The model is discussed in meetings with experts.

The third activity (Stage 3) combines the results obtained in Stages 1 and 2. Information on failure and repair rates derived in Stage 1 is introduced to the model obtained in Stage 2.

The final modeling process begins by simulating situations, calculating indicators that compose the control scoreboard, and performing sensitivity analysis to establish the impact of each component of the system on dependability and the indicators representing it.

5.4.3 Results of RAMS Analysis

The result of this model is a probability distribution of availability for each simulation and the related indicators. In summary, from a RAMS analysis, these outcomes may be generated:

- Prediction of availability for a determined period of time
- Database with technical information, operating data, and system dependability data
- RAMS model of the system
- Hierarchized list of equipment and critical systems as a function of their impact on availability
- List of technical recommendations to mitigate risk and increasing availability

Additionally, the model allows sensitivity analysis to identify the equipment and systems with high impact on nonavailability. This gives production management the knowledge they need on risk and the costs of intervention due to planned and unplanned maintenance so that they can propose mitigating actions.

RAMS analysis combines various traditional dependability methodologies, including failure mode effect analysis, inspection based on risks, reliability-centered maintenance, among others. With this analysis, we can

- Perform integral diagnoses with information from the elements that integrate the process, system, or equipment (e.g., historical data of failures and repairs, data of operating conditions, and engineering data)
- Infer probabilistically all feasible scenarios of production through periods of both normal operation and unwanted events, based on the configuration of the system, the dependability of its components, and the maintenance philosophy
- Identify concrete actions to diminish or to mitigate the occurrence of unwanted events and take the risk to tolerable levels
- Explore the economic implications of each possible risk scenario and design plans and optimal strategies
- Compare the cost of a maintenance action or strategy against the level of risk reduction or improvement in the performance as a result of this action

RAMS analysis of a productive system is not easy. It requires tools and methodologies of calculation with a complexity similar to the complexity of the analyzed process. Results depend on the representativeness of the model; it must model the real behavior

of the system within its operating context. The preparation of the control scoreboard using RAMS parameters presents a major stumbling block because it demands complex functional and mathematical modeling. An error in the model or the stored data results in the erroneous estimation of the parameters and all indicators derived from them. Finally, the human factor is key in both data collection and knowledge management.

5.4.4 Relationships between RAMS Parameters

As noted, RAMS parameters are related. In a repairable system, there is a relationship between availability, reliability, and maintainability, and this is easily expressed as constant rates (exponential distributions) in the following form:

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

If MTBF is directly proportional to reliability R, and MTTR inversely proportional to maintainability M, we can rewrite the previous equation as

$$A = \frac{R}{R + (1/M)}$$

This expression gives rise to graphical representation as shown in Figure 5.6.

Figure 5.6 contours correspond to constant values of A. If we clear M from the earlier equation, we have

$$M = \left(\frac{A}{1-A}\right)\frac{1}{R}$$

Now deriving M partially with respect to R, we obtain

$$\frac{\partial M}{\partial R} = \left(\frac{A}{1-A}\right)\left(\frac{-1}{R^2}\right)$$

That is, for certain availability A, if R increases, M falls proportionally to R^2.

It is important to emphasize the A5 point or the upper vertex of the three-dimensional surface shown in Figure 5.6. This corresponds with the maximum availability that, in principle, can be reached through reliability and maintainability. In other words, it is the limit we can aspire to reach with the present design and logistical support. At a mathematical level, it may seem obvious, but availability cannot grow indefinitely. This is something to remember when we are determining the indicators and the goals of availability.

Figure 5.7 represents a series of *isocost* curves juxtaposed to the previously mentioned ones of constant availability. For a fixed total cost, a $B_i a$ curve is constructed with the values of reliability and maintainability resulting in that cost. Obviously, the curves

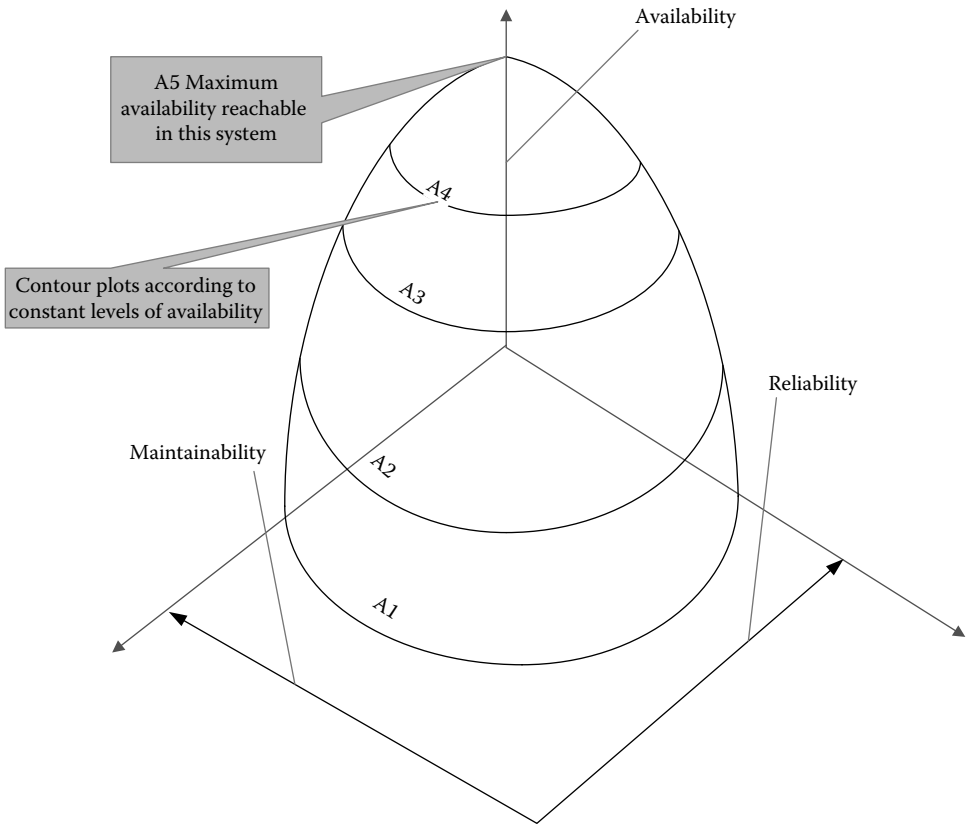

FIGURE 5.6
Availability versus reliability and maintainability.

do not represent the availability reached with each value of M and R. Superposing the isocost curves over the contours of availability results in the following graphic representation.

Note the tangential points P. Each expresses the optimal combination of R and M for a certain availability. For example, P_1 identifies the economically optimal values of R_1 and M_1 required to reach availability A1. Therefore, the line connecting the tangential points indicates the optimal way to improve availability.

That is, at a conceptual level, to improve the parameter of system availability, the process must follow an analysis of alternatives.

5.5 Reliability

5.5.1 Introduction

Reliability in standards IEC 60050-191 [129] and ISO 8402-200052 [134] is defined as "the capacity of a component or system to develop the required function, under certain environmental conditions and of operation, and by a certain time." This definition allows us

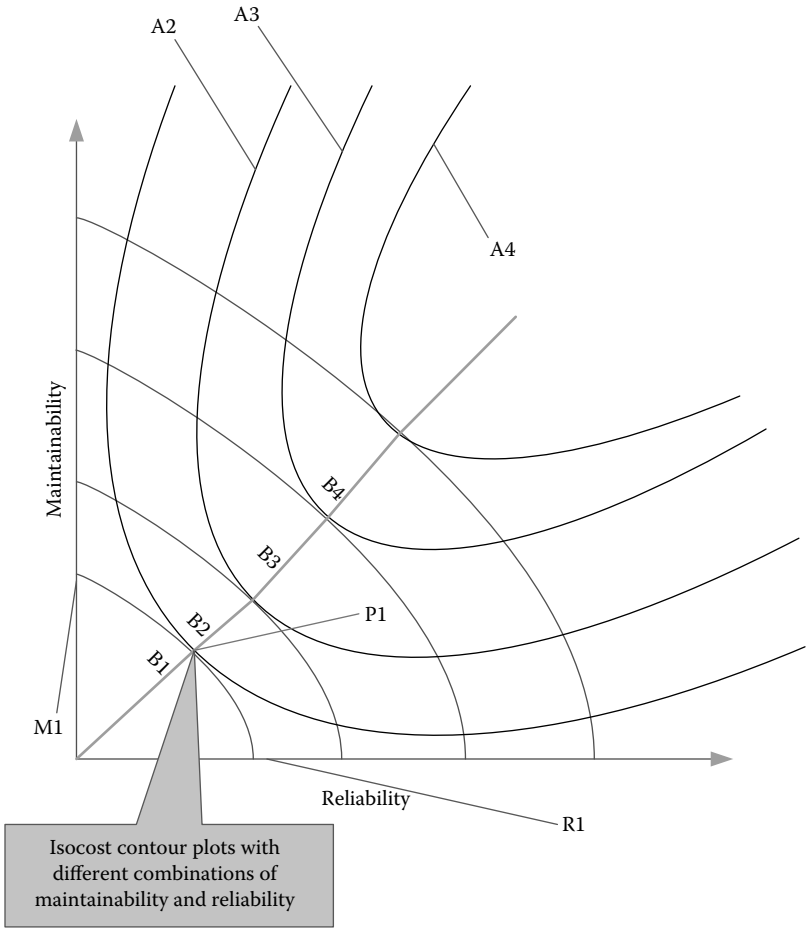

FIGURE 5.7
Isocost curves versus constant availability.

to differentiate between a system's operating reliability and its evolution after a failure, or "the probability of an object to develop the function required under certain conditions and during a certain time, without treating both as aspects of dependability."

5.5.2 Reliability Function

The reliability function, $f(t)$, is the probability density function of the variable "time until the failure" or the time of operating life and is expressed as

$$F(t) = \int_0^t f(t)dt$$

where the distribution function of the variable giving the probability of the time to failure is smaller than or just as small as t. This is called the *unreliability function* in reliability analysis.

The probability that an element does not fail before time t gives us

$$R(t) = 1 - F(t) = \int_t^{\infty} f(t)dt$$

which is a reliability function.

By dividing the previous equation, we get

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

The resulting equation can be used for the risk function.

5.5.3 Average Failure Rate

Using the reliability function, the probability of failure between t_1 and t_2 can be expressed as

$$\int_{t_1}^{\infty} f(t)dt - \int_{t_2}^{\infty} f(t)dt = R(t_1) - R(t_2)$$

The rate of failures in the interval between t_1 and t_2 is defined as the quotient of the probability of the failure occurring in the interval, if it has not happened before t_1, divided by the length of the interval, as shown in the following equation:

$$\lambda(t; t_2 - t_1) = \frac{R(t_1) - R(t_2)}{(t_2 - t_1)R(t_1)}$$

5.5.4 Instantaneous Failure Rate or Risk Rate

The instantaneous rate of failure is defined as the limit of the average rate of failure when the time interval tends to zero. Thus, we have

$$h(t) = \lim_{\Delta t \to 0} \left[\frac{R(t_1) - R(t_2)}{(t_2 - t_1)R(t_1)} \right] = \frac{-1}{R(t)} \left[\frac{dR(t)}{dt} \right] = \frac{f(t)}{R(t)}$$

This constitutes a fundamental relationship in reliability analysis; if we know the value of the density of failures at moment t and the function of reliability at the same moment, we can determine the risk function at that moment. The importance of this relationship resides in the independence of the probability distribution of the variable time until failure. Following the previous argument, if the rate of risk is

$$h(t) = \lim_{\Delta t \to 0} \left[\frac{\Pr(\text{a component of age } t \text{ fails in the interval } t, t + \Delta t \text{ if survived after } t)}{\Delta t} \right]$$

then $h(t)dt$ represents the probability that a component with age t fails in the interval $(t, t + dt)$.

Using the concept of conditional probability, we seek the probability that the failure will occur in the interval (t; $t + \Delta t$) supposing the equipment or system has survived to time t. This conditional probability is expressed by

$$\Pr(t < \tau \le t + \Delta t \mid \tau > t) = \frac{\Pr(t < \tau \le t + \Delta t)}{\Pr(\tau > t)} = \frac{R(t) - R(t + \Delta t)}{R(t)}$$

Now if we divide the previous expression by Δt, we obtain the average rate of failure. Following the same procedure as before, we get the same expression of $h(t)$.

Thus, the risk function is not simply a measurement of the change in survival rate by the unit of change in time.

5.5.5 Relationship between the Function of Reliability and the Rate of Risk

The equation

$$h(t) = \frac{-1}{R(t)}\left[\frac{dR(t)}{dt}\right]$$

can be written as

$$\left[\frac{dR(t)}{R(t)}\right] = -h(t)dt$$

$$\int_0^t \frac{dR(t)}{R(t)}dt = -\int_0^t h(t)dt = -H(t)$$

$$\ln R(t) - \ln R(0) = -\int_0^t h(t)dt \Rightarrow \ln R(t) = -\int_0^t h(t)dt$$

$$R(t) = \exp\left[-\int_0^t h(t)dt\right]$$

This results in the general expression of reliability based on the failure rate, as proposed by UNE-EN 61703:2003 [359].

5.5.6 Distinction between Failure Rate and Risk Rate

A certain degree of confusion exists in the literature on the difference between "failure rate," which denotes the *average rate of failure*, and "instantaneous rate of failure," which includes the *rate of risk*. These are often considered synonymous but are not, and using *failure rate* to refer to both causes problems. The overuse of the model of probability distribution for the variable time to failure is likely to blame for the confusion; while the numeric values of the rates match, this obviously does not mean the concept is the same.

5.5.7 Bathtub Curve

The behavior of nonrepairable devices can resemble that of humans; in both, the most risk occurs at the beginning (human infancy) and the end of life (old age). As the term suggests, the curve showing the rate of risk throughout a system's or a human's lifetime takes the form of a bathtub. In early years, there may be problems due to unexpected birth/design defects. From this point, the rate decreases until failures (loss of life) take place by chance (flat rate).Then, as the system or human ages, the risk rate grows. Obviously, the optimum period of usage comes in the central period. Techniques of determining this are proposed in UNE 200004-1 [341] and UNE 2000042 [342] (Figure 5.8).

There are a variety of options to determine the bathtub curve for any given system. One of the most intuitive is a density function such as

$$f(t) = k_1 f_1(t) + k_2 f_2(t) + k_3 f_3(t)$$

where $k_1 f_1(t)$, $k_2 f_2(t)$, and $k_3 f_3(t)$ correspond to the probabilities of early-stage failure, midlife failure (chance), or failure due to aging (wearing down), respectively.

The literature establishes that in complex systems, the behavior of the fault rate as shown in the bathtub curve is practically constant, Arata [11]. Thus, RAMS analysis is preceded by the bathtub curve analysis of each subsystem of the equipment to distinguish its stage and select the best maintenance for this stage. As a result of the analysis, a failure rate is obtained; the more complex the system is, the more constant its failure rate will be.

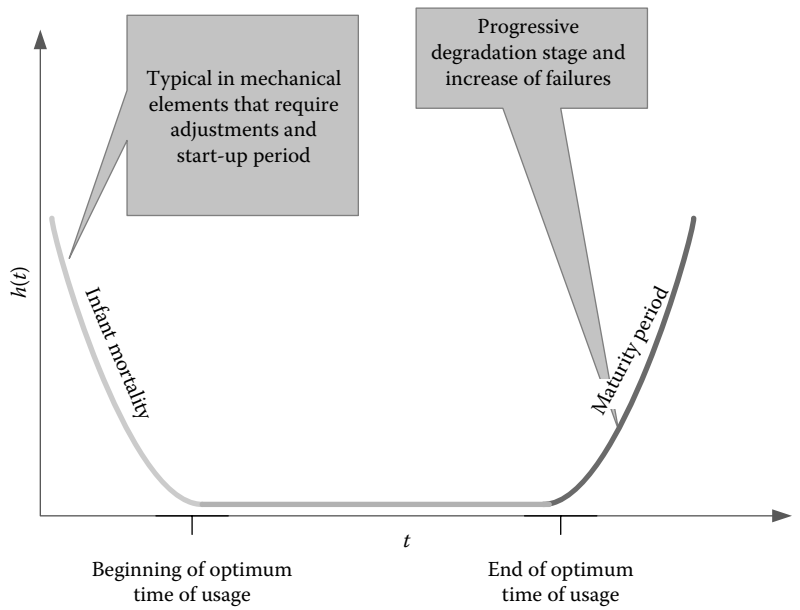

FIGURE 5.8
Bathtub curve.

5.5.8 Average Life

We call T the "time of life" variable with density function $f(t)$. The mathematical expression of *average life* is

$$\mu = E[T] = \int_0^\infty t f(t) dt$$

The following equation relates average life to reliability $R(t)$; this is a more practical expression of average life

$$\int_0^\infty t f(t) dt = \int_0^\infty t \left[-\frac{dR(t)}{dt} \right] dt$$

When l'Hôpital's Rule is applied, the following is obtained:

$$\mu = \int_0^\infty R(t) dt$$

5.5.9 Probability Distributions

This section looks at models of probability distribution used in the analysis of reliability.

5.5.9.1 Normal or De Gaussian Distribution

There are two main applications of this model of distribution. One is the analysis of components that present failures due to wearing down. The failure distribution due to age and wear fits a normal distribution reasonably well.

Another application is the dispersion of characteristics of components due to differences in manufacturing. More specifically, elements constructed with the same specifications may exhibit different behaviors. Deriving from this, an application used by engineers is quality control. The application of this distribution follows the theorem of the central limit, which says the sum of a great number of variates with finite average and variances has a normal distribution.

The density function of the normal distribution is

$$f(t) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[-\frac{1}{2} \left(\frac{t-\mu}{\sigma} \right)^2 \right]$$

where

μ is the population average
σ is the population standard deviation

This distribution can show a certain anomaly as a model of times of failure. It is symmetrical with respect to the average, and its left tail, in theory, reaches infinity (negative).

That is, times of failure start at $t = 0$. This defect actually is not so serious since negative values of t are undesirable. The value of the average μ must be 3 or 4 times greater than the standard deviation σ, and this is a common occurrence.

A change of variable (standardization) allows us to use the tabs values of the normal distribution. The density function, once transformed, turns out to be

$$f(z) = \frac{1}{(2\pi)^{1/2}} \exp\left[-\frac{z^2}{2}\right]$$

$$z = \frac{t-\mu}{\sigma}$$

$$f(t) = \frac{1}{\sigma} f(z)$$

The distribution has an average of zero and a standard deviation of 1; it is denoted as N [0; 1].

5.5.9.2 Distribution Log-Normal

The log-normal or normal logarithmic distribution corresponds to a variety whose Napierian logarithm is distributed according to the normal or Gaussian model.

This distribution has its main application in maintainability analysis, specifically in the analysis of repair times. Repair times generally concentrate around an average time but can extend further, a situation modeled by the right tail of the distribution. See the corresponding chapter for a detailed study.

In reliability analysis, the log-normal distribution is used to model the times of failures of semiconductors and mechanical components that may suffer fatigue.

The density function of this distribution has the form

$$f(t) = \frac{1}{\sigma t (2\pi)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{\ln t - \mu}{\sigma}\right)^2\right]; \quad \text{for } t \geq 0$$

where the average is

$$\exp\left(\mu + \frac{\sigma^2}{2}\right)$$

and the standard deviation is

$$[\exp(2\mu + 2\sigma^2) - \exp(2\mu + \sigma^2)]^{1/2}$$

with μ and σ the average and the standard deviation respectively of the variable ln t.

If variable t follows a log-normal distribution and variable $t' = \ln t$ follows a normal distribution, the results are the following:

$$f(t) = \frac{f(t')}{t} = \frac{f(z)}{\sigma \cdot t}$$

with z being the variable $N(0; 1)$.

The following practical expression is used to calculate reliability:

$$R(t) = \Pr\left(z > \frac{\ln t - \mu}{\sigma} \right)$$

5.5.9.3 Relationship with the Normal Distribution

The median of the log-normal distribution is T_{50} (point representing 50% of the failures). If t is log-normal with parameters (T_{50}, σ), then $X = \ln t$ is the normal variable with average $\ln T_{50}$ and standard deviation σ.

Of this form, we can say

$$E[t] = T_{50} e^{\sigma^2/2}$$

$$\mathrm{Var}[t] = T_{50} e^{\sigma^2} \left(e^{\sigma^2} - 1 \right)$$

and its density function can be written as

$$f(t) = \frac{1}{\sigma t (2\pi)^{1/2}} \exp\left[-\frac{1}{2} \left(\frac{\ln t - \ln T_{50}}{\sigma} \right)^2 \right]; \quad \text{for } t \geq 0$$

the parameter σ gives us the following additional information:

- High values ($\sigma \geq 2$) represent high failure rate at the beginning but decreasing over time.
- Low values ($\sigma \leq 0.5$) represent an increasing failure rate (wearing away).
- Values next to 1 represent a flat failure rate.

5.5.9.4 Exponential Distribution

This is probably the most frequently used distribution in the analysis of reliability, especially for electronic components and equipment. Because the distribution has a *constant risk rate*, its applicability is limited to those components whose instantaneous rate of failure stays practically constant with the age and those for whom early failures have been eliminated.

The extensive use of this model is justified by the following:

- It is easy to estimate its unique parameter λ.
- Its mathematical treatment is relatively simple.
- It is a reproductive distribution. That is, the sum of its exponentially distributed independent variables is also distributed according to an exponential model.

The practical applicability of this distribution has been and continues to be the topic of much discussion since to fail exponentially, a device has to be insensitive to age and use. If this is indeed the case, if a component has not failed, it must be as good as new.

With some reservations, we can say that the applicability of this distribution is justified in the following cases:

1. In bled components with early failures and with a very long life; these are often electronic components (but not empty valves)
2. In bled components that are replaced before they wear down
3. In very complex repairable systems without dominant redundancies

The density of failures is given by

$$f(t) = \lambda \exp\left[-\lambda t\right], \quad \text{for } t \geq 0$$

where λ is the rate of risk $h(t)$, the so-called "failure rate."

The reliability function is

$$R(t) = e^{-\lambda t}$$

where the average life is $1/\lambda$, and the mean time between failures MTBF = $1/\lambda$.

If the function of reliability $R(t)$ is expressed using the Taylor series, and for the case of a small failure rate, we get

$$R(t) \cong 1 - \lambda t$$

Consequently, the distribution function is

$$F(t) \cong \lambda \cdot t$$

If we consider the proportion p of the number of failures in a period of time t_0, for a certain number of samples, we have

$$\hat{\lambda} \cdot t_0 = p = \frac{\text{Number of failures}}{\text{Number of samples}}$$

or

$$\hat{\lambda} = \frac{p}{t_0}$$

5.5.9.5 Gamma Distribution

The gamma distribution is used in reliability for cases where partial failures can exist without catastrophic failure. That is, a series of components can fail without losing the function of the device.

The distribution also models the time to their failure, when the time between failures can be modeled by an exponential distribution.

The failure density has the form

$$f(t) = \frac{\lambda}{\Gamma(r)}(\lambda t)^{r-1} e^{-\lambda t}, \quad \text{for } t \geq 0$$

where

r is the form parameter

λ is the parameter of scale

$$\text{average} = \frac{r}{\lambda}$$

$$\text{std_des} = \frac{r^{1/2}}{\lambda}$$

where

λ is the failure rate of total failure

r is the number of partial failures or events that generate total failure

$\Gamma(r)$ is the gamma function expressed by

$$\Gamma(r) = \int_0^\infty x^{r-1} e^{-x}\, dx$$

When $(r - 1)$ is a positive whole number (the most frequent case in reliability analysis), the gamma function takes the value $(r - 1)!$; it then has an *Erlang distribution* with the density function

$$f(t) = \frac{\lambda \cdot (\lambda t)^{r-1}}{(r-1)!} e^{-\lambda t}, \quad \text{for } t \geq 0$$

If $r = 1$, the distribution is exponential, as described earlier.

5.5.9.6 Weibull Distribution

In reliability analyses, the Weibull distribution has almost universal applicability; because of its two parameters, it can adjust to almost any model.

The density function is expressed as

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t-\gamma}{\eta}\right)^{\beta}\right]$$

where

β is the shape parameter

η is the parameter of scale or *characteristic life* (time in which 63.2% of the population will have failed)

γ is the minimum life (only considers $t \geq \gamma$. If $\gamma = 0$, the failure possibility starts at $t = 0$)

This is the only distribution that can be used to represent any one of the three typical periods of a machine: early failure (failure rate decreasing), lifetime utility (random and constant failure), and wearing down (failure rate increasing), according to Kelly and Harris [169].

In most situations, the parameter γ is zero (this presupposes it is possible to have failure represented as $t = 0$ or failure in the beginning); for the density function, the survival rate and the rate of risk respectively will be

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$$

with the average expressed as

$$\mu = \eta\Gamma\left(1+\frac{1}{\beta}\right)$$

The Weibull distribution takes one of the following forms:

- $\beta < 1$ Gamma
- $\beta = 1$ Exponential
- $\beta = 2$ Log-normal
- $\beta = 3{,}5$ Normal (approximately)

This implies it can be used to identify other statistical distributions, as will be seen later.

The relationship between the various values of parameter β and the function instantaneous failure rate $h(t)$ is one of the following:

- When $\beta < 1$, $h(t)$ is decreasing, as in early stages or infancy.
- When $\beta = 1$, $h(t)$ is constant and equal to $1/\eta$. The distribution for $\gamma = 0$ is the exponential distribution for the average η.
- When $\beta > 1$, $h(t)$ is increasing, as in the period of wearing down. For $\beta = 2$, the function $h(t)$ is linear.

5.5.10 Estimation of Parameters

5.5.10.1 Nonparametric Methods

The main advantage of nonparametric methods of estimation in reliability analysis is that they do not require suppositions about the model or the form of the probability distribution. In addition, they are usually simpler to calculate.

UNE 200001-3-5:2002 [339] describes the concepts and methods of estimating reliability, beginning with a truncation in time or number of failures. Let us assume data from a test

of n equal components in which the times of the failures of each component have been registered. This data set $\{t\}$ constitutes a sample of size n of the distribution of life of that type of component. Clearly, statistical methods are applicable both to select the appropriate model of probability distribution and to determine or estimate its parameters.

5.5.10.1.1 Censured Samples

The data used to estimate the parameters of probability distributions usually are obtained from *life tests*; this requires obtaining a component sample of n of the interest population in operating conditions and environmental surroundings most similar to the real conditions. If the test ends before all components have failed, the *sample is type I censured*. Another real possibility is that r components will have failed ($r < n$) when the test ends; in this case, the *sample is type II censured*.

In type I censorship, the number of failures obtained in the test is a variety; in type II censorship, the variety is the time between failures or the total time of the test.

Type I censorship is also called *right censored*. This occurs when data originate from outside the laboratory. That is, the sample comprises of information on the components in a normal condition and excludes data on end of life. The treatment of this information is very interesting; the inclusion of incomplete data (the censored time of component life is greater than or equal to a certain value) provides a more complete sample than if such data were excluded.

Censorship can also be double. That is, the registry of the times of failure is as much right censored as left censored. This happens when collected data do not originate from controlled tests in the laboratory but are obtained from historical and operating data.

5.5.10.1.2 Life Table Method

Life tables are used for older and more frequently used components. Their properties are studied from a statistical point of view, especially censured data.

Life tables are a generalization of tables of frequency allocation and extend censured data. Thus, the proportion of items that survive a certain time t_i, constitutes an estimation of the probability of survival to time t_i.

The data generally are grouped in intervals, according to the times of failure of each individual in the sample, along with the time of its retirement from use. The time scale is divided into $k + 1$ intervals $I_j = [t_{j-1}, t_j)$, where $j = 1, \ldots, k + 1$, with $t_0=0$, $t_k = T$, $t_{k+1} = \infty$, and where T is the least upper bound of the observed interval.

5.5.10.1.3 Nonparametric Estimation of the Survival Function

Using the Kaplan–Meier probability estimate, survival can be estimated as *the product limit*.

Suppose we have n individual sand k times of failure. If the time between times of failure k is more or less equal, we call this d_j. In addition, if the censored time for individual L_i agrees with a noncensored time, we enter them as equals. If the censored time of individual L_i is less than or equal to an already registered time t_j, we enter it as individual "risk" to time t_j and express it as the risk to n_j individuals at time t_j. Then, the survival function is

$$\hat{R}(t) = \prod_{j:t_j<t} \frac{n_j - d_j}{n_j}$$

where, as noted earlier,

n_j is the number of surviving individuals at t_j

d_j is the number of individuals with times of life equal to t_j

5.5.10.1.4 Graphical Method for the Weibull Distribution

The method of maximum probability can be applied to obtain the parameters of shape and scale of the Weibull distribution, but the procedure is difficult since the estimations are obtained by solving a pair of quite complicated nonlinear simultaneous equations.

Instead of those purely analytical methods alternatives that give very good results, we can opt for more intuitive methods, for example, the application of the method of minimum squares.

For functions of density and reliability of survival, the Weibull distribution has the following:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

If we apply natural logarithms on both sides of the reliability function, we have

$$-\ln R(t) = \left(\frac{t}{\eta}\right)^{\beta}$$

$$\ln(-\ln R(t)) = -\beta \ln \eta + \beta \ln t$$

If we apply the least-squares method, we need to estimate the reliability function based on life test data. One way to accomplish this is to submit a random sample of n devices to a proof of life, counting the number of survivors at the end of each interval of time (a day, a week, a month, etc.). If we call "i" the indicator of corresponding interval time for the partition performed on the total test time (or data collection), an estimate of the proportion of survivors at time "i" time is

$$\hat{R}(i) = \frac{n_i}{n}$$

where

n_i is the number of survivors at the end of the ith observation interval
n is the total number of devices tested

Now, we can calculate ratios from the data and adjust a straight line by least squares so that

$$\underbrace{\ln(-\ln R(i))}_{Y} = \underbrace{-\beta \ln \eta}_{a} + \underbrace{\beta \ln i}_{bX}$$

where the data for the adjustment will be

$$y_i = \ln(-\ln R(i))$$

$$x_i = \ln i$$

If we call "*a*" the *y*-axis (intercept) and *b* the slope of the line, the parameter estimates will be

$$a = -\hat{\beta} \ln \hat{\eta}$$

$$b = \hat{\beta}$$

or

$$\hat{\eta} = \exp\left(-\frac{a}{b}\right)$$

$$\hat{\beta} = b$$

Another way of putting it is the time to failure obtained without using the concept of *i*th interval, that is, working directly with the ordered failure times t_i. This can be estimated as follows:

$$\hat{R}(t_i) = \frac{n_i}{n}$$

where
n_i is the number of survivors after the *i*th failure
n is the total number of devices tested

Now, we can calculate proportions from the data and adjust a straight line by least squares so that

$$\underbrace{\ln(-\ln \widehat{R}(t_i))}_{Y} = \underbrace{-\beta \ln \eta}_{a} + \underbrace{\beta \ln t_i}_{bX}$$

where the data for the adjustment will be

$$y_i = \ln(-\ln \widehat{R}(t_i))$$

$$x_i = \ln t_i$$

Clearly, if we call "*a*" the *y*-axis (intercept) and *b* the slope of the straight line, the parameter estimates will be

$$a = -\hat{\beta} \ln \hat{\eta}$$

$$b = \hat{\beta}$$

or

$$\hat{\eta} = \exp\left(-\frac{a}{b}\right)$$

$$\hat{\beta} = b$$

5.5.10.2 Parametric Methods

We have seen that the theoretical probability models able to analyze component and system reliability are based on mathematical expressions that are defined once the value of the component or the system's parameters is known. By observing the behavior of the component (in this case, its behavior toward the failure event), we can infer the value of those parameters. The problem is the number of observations that must be made to ensure certainty in the values assigned to the parameters. As any sampling activity requires time and money, parameter estimation processes are based on the observation of a part, *the sample*, of the total set of components, or *population*.

From n observations, or in other words, from *a sample of size n*, and the values obtained in the variable (usually the time to failure), certain functions are built; these are called *statistics* and they allow us to infer values of the unknown parameters.

There are many methods to obtain these statistics; one objective in the work of many researchers is to define new functions to obtain such values.

Another consideration is the relationship between the sample size and population size; more specifically, an infinite population may extract endless random samples of size n. If we extract all possible random samples (at least those differing in an observed element) and calculate the statistical value, we obtain the *distribution of statistical sampling*. This is a random variable since its outcome depends on a random experiment. The importance of size n of the sample seems obvious. Intuitively the larger the sample, the more information will be contributed to the statistics. For this reason, there is special emphasis on sample sizes; generally, values above n 30 are considered *large samples*.

5.5.10.2.1 Statistics Distribution

We have defined the concept of statistics as a function of the sampling variables. Certain fundamental considerations about the behavior of statistics should be noted if they are to be used as estimators.

5.5.10.2.1.1 Sample Mean The sample mean is defined as

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

where x_i is the ith value observed in the sample.

5.5.10.2.1.2 Variance and Quasi-Variance Sample Variance sample is defined as

$$s^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

Quasi-variance sample is defined as

$$s_1^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$$

Taking n to infinity tends to follow a normal distribution. If $n \geq 30$, $N \geq 2n$ (where N is the size of the population) and the population has a finite mean and variance, the sample can be considered normally distributed.

5.5.10.2.2 Population Mean and Variance Estimators

An important property is the following: *For any form of the population distribution, the sample mean is an unbiased estimator of the population mean, and the sample quasi-variance is an unbiased estimator of the population variance.*

So, for any distribution, we have

$$\hat{\mu} = \overline{x}$$

$$\hat{\sigma}^2 = s_1^2$$

where the former is the estimated parameter value and the latter is the estimator.

5.5.10.2.3 Size n of the Sample

This is a population parameter estimate from n observations of variable values, through which a particular function (estimate) can infer the true value of the unknown parameter. One of the first problems encountered is the determination of sample size n, to comply with at least some assurance of the goodness of the estimation. We frequently want to consider the following:

- *Confidence level*: The level of assurance about the certainty of a particular statistical statement under specified conditions
- *Signification level*: Degree of uncertainty about a particular statistical statement and under the same conditions as those specified to determine the level of confidence

If we call the signification level α, the confidence level is $1 - \alpha$.

We want accuracy when estimating a parameter; therefore, we must consider two aspects:

- *Confidence level* $1 - \alpha$: For example, the confidence level of 95%.
- *Accuracy requirement*: The maximum deviation in the estimation based on the true value of the parameter. This deviation can be set in absolute terms or relative value.

5.5.11 Methods of Distribution

The distribution of reliabilities is one of the initial tasks of component and system design. Generally, the global aim of reliability (minimum requirement to achieve) should be shared, or distributed, to a component-level or subset. It should distinguish between the allocation and distribution of reliability.

The distribution of reliability is the process of assigning reliability objectives to subsystems during system design. There are algorithms to accomplish this; the most popular is the ARINC method described by Lloyd and Lipow [191]. The main difficulty with this method is that the distribution task is based on subjective criteria.

One way to increase the reliability of the system is by introducing redundancies in locations of chosen components. That is, the system configuration is altered by replacing a single component having two or more copies in parallel. The problem of selecting the components for which this is done is called reliability allocation.

5.5.11.1 AGREE Method

The AGREE (Advisory Group on the Reliability Electronic Equipment) method is based on the complexity of the components or subsystems, defined in terms of modules. Thus, the basic formula is as follows:

$$\lambda_i = \frac{N_i[-\ln R(t)]}{N w_i t_i}$$

where
t is the mission duration
t_i is the duration of operation of each subsystem
N_i is the number of modules in the ith subsystem
N is the total number of modules in the system ($N = \sum N_i$)
w_i is the importance factor of the ith subsystem (within of range from 0 to 1)

- Will be 1 if the subsystem should work to make the system work
- Will be 0 if failure of the subsystem does not affect the operation of the system

$R(t)$ is the reliability target for the mission duration t
Reliability for the ith subsystem is determined by

$$R_i(t_i) = 1 - \frac{1 - [R(t)]^{N_i/N}}{w_i}$$

This method tends to give erroneous results in cases of very low importance factors, but gives a good approximation for values close to 1.

5.5.11.2 Distribution with Reference Information

When the reliability information of a system of identical characteristics is available (equal number of subsystems and components), based on the reliability values achieved, we can determine the distribution using the following formula:

$$R_i = \left[\frac{R}{R_{\text{ref}}}\right]^{1/n} \cdot R_{\text{ref}(i)}$$

where
R is the reliability objective of our system
R_{ref} is the reference system reliability
$R_{\text{ref}(i)}$ is the reference subsystem i reliability
R_i is the calculated reliability for our i subsystem
n is the number of subsystems

5.5.11.3 Method Based on Failure Rates

This method, for serial and constant failure rate systems, can be used when the information of failure rates of similar components is available.

We define the factor

$$\omega_i = \frac{\lambda_i}{\sum_{j=1}^{n} \lambda_j} = \frac{\lambda_i}{\lambda}$$

The maximum failure rate target will be

$$\hat{\lambda}_i = \omega_i \lambda_{objective}$$

5.6 Maintainability

5.6.1 Introduction

Maintainability can be defined as the measure of the ability of a component to be preserved, repaired, and returned to the initial specific conditions; maintenance is performed by personnel with specified skill levels using established procedures and resources in each level of maintenance and repair.

This definition has been used to develop procedures for predicting maintainability. Each procedure uses quantitative measures to indicate system maintainability. However, all measures have a specific relationship with the distribution of system total down time.

Maintainability, like reliability, is inherent to the system design. A system should be designed so that it can be maintained without large investments of time, money, or other resources (staff, materials, facilities, equipment).

Maintainability is the ability of a component or system to be maintained, with maintenance defined as the series of actions to reintegrate or maintain an element in effective operating condition. Maintainability is both a design parameter and a result of design.

Maintainability can be expressed in terms of frequency of maintenance, maintenance time, and maintenance costs.

Finally, maintainability can be defined as a combination of factors such as

1. A design and installation feature expressed as the probability that an item will continue to operate or be restored to its specified operating condition within a specified period of time, when maintenance is performed according to established procedures and resources
2. A design and installation feature expressed as the probability that maintenance will not be required more than a certain number of times over a period of time when the system operates or is operated and maintained in accordance with established procedures
3. A design and installation feature expressed as the probability that the cost of maintaining a system will not exceed a certain amount of money in a given period of time, when the system operates or is operated and maintained according to established procedures

The UNE_200001-3-4:1999 [338] standard requires we consider the following factors in the specification of the requirements of maintainability:

- Operating conditions and environment where the equipment is used
- Qualifications and responsibilities of staff responsible for the operation and maintenance of the equipment
- Maintenance policy to be applied, the procedures used, and the agreed-upon logistics

Maintainability, therefore, requires the consideration of various factors related to the system, and maintainability measures typically include a combination of the following temporary measures:

1. *MTBM*: Mean time between maintenance performed on equipment or systems, including preventive maintenance time (scheduled) and corrective (unplanned).
2. *MTBR*: Mean time between replacements of equipment or systems due to maintenance action.
3. *M*: Average time of active maintenance.
4. *Mct*: Mean time for corrective maintenance; this is the arithmetic average time spent on the various maintenance tasks and is equivalent to MTTR.
5. *Mpt*: Mean time for preventive maintenance; this is the arithmetic average time spent on the different tasks of preventive maintenance.
6. *Mmax*: Maximum time to corrective maintenance; this is specified at 90%–95% of the upper end of the range, with confidence level of 90% or 95%.
7. *MDT*: Downtime due to maintenance; this is the average total time the equipment or system is unable to perform its functions. The MDT includes half-active maintenance (M), logistic delay time (LDT), and administrative delay time (ADT).
8. *MMH/OH*: Maintenance man-hours per hour of operation of the system/equipment.
9. *MC/OH*: Cost of maintenance per hour of operation of the system/equipment.
10. *MC/MA*: Maintenance costs for maintenance action.

In practice, maintainability, converted into target system/component, results in the expression of these earlier measures (one or more) as requirements to achieve a certain value.

5.6.2 The Need to Predict Maintainability

The purpose of prediction according to UNE 20863:1996 [348] may vary. It may be used to provide a basis for drafting a specification, analyze a design, or plan maintenance. It can also serve to highlight the weaknesses of a system and the organization of maintenance and suggest possible improvements.

Therefore, the purpose of prediction and the relationship between the prediction and any other part of the program of reliability, maintainability, and availability should be clear.

We must gather all information needed to make the prediction, including

1. System or equipment type/support/module/component and specification, including its development
2. Maintenance logistics policy
3. Maintenance level (in case of maintainability prediction)

When the prediction includes behavioral assumptions and staff qualifications, they should be described and quantified properly to allow a good measure of the system or equipment. In the case of maintainability, reference data such as mean time to active repair at different levels will be required.

The prediction of the expected number of hours a system or device will be in inoperative state or "down" during maintenance is of vital importance to the user because of the adverse effect of excessive time "down" for production or service.

Further, once the operating requirements of a system are fixed, it is imperative to predict maintainability in the design phase as soon as possible in quantitative terms. This prediction should be continually updated while advancing the design.

A significant advantage of maintainability prediction is that it indicates areas of inadequate maintainability to the designer; this, in turn, justifies product improvement and modification or design change. Maintainability prediction also allows the user to create an early budget if the scheduled downtime, quantity and qualifications of personnel, and tools and test equipment are appropriate and consistent with the needs of the operating system.

This implies that performing maintainability studies in the design phase provides valuable information for maintenance planning and production both in estimating operational availability and in quantifying the human and material resources necessary to conserve equipment resources.

5.6.3 Maintainability Measures

Each maintainability prediction procedure relies on the use of reliability and maintainability data and also on experience with similar systems and components under similar conditions of use and operation. It is usual to assume the applicability of the "principle of transferability" whereby the data accumulated from one system can be used to predict the maintainability of a comparable system being developed or designed. This procedure is justified when the degree of similarity between systems can be reasonably established.

During the early design phase of the life cycle, similarities can normally be established in very general terms. But as the design will be redefined in the final stages of the life cycle, similarities are acceptable only if the ratio of the functions carried out at the team level to the times of maintenance tasks, levels (locations where performed) of maintenance is high—not to mention the level of training of maintenance staff.

The recovery process of a system that is inoperative due to failure can be described only in probabilistic terms. Therefore, maintainability is defined by the random variable "recovery time" or TTR (time to restore or time to repair) and its probability distribution. From this model, maintainability typically involves

1. Maintainability function
2. Percentage of recovery time
3. Mean recovery time

5.6.4 Maintainability Function

The distribution function of the random variable TTR is called *maintainability function*. This function expresses the probability that the system operation is recovered at time *t*. That is, if we call *M*(*t*) according to maintainability, we have

$$M(t) = \Pr(\text{TTR} \le t) = \int_0^t m(t)dt$$

where *m*(*t*) is the density function of the TTR variable.

The most common distributions for this variable are

- Exponential
- Normal
- Log-normal
- Weibull

5.6.5 Percentage of Recovery Time

This is the time spent on maintenance with probability *p*. Mathematically, we can express it as

$$\text{TTR}_p = t \Rightarrow \Pr(\text{TTR} \le t) = p$$

The *p* percentages used most often are 90% and 95%.

5.6.6 Mean Recovery Time

The mean or expected recovery time is expressed by the TTR variable. The mean recovery time is expressed mathematically as

$$E(\text{TTR}) = \int_0^\infty t \cdot m(t)dt$$

This measure is known as the *mean time to recovery* or MTTR.

Among all the indicators that can be used in a management system, some stand out and are called world-class indicators. MTTR is considered world class.

5.6.7 Measures Based on Labor Hours

These measures are based on the TTR variable and, consequently, on the time spent on maintenance. This is extremely important in the analysis and evaluation of maintainability.

Obviously, the objective is to have effective systems and high availability with high levels of efficiency. To achieve this objective, maintenance times must be the lowest possible, without forgetting costs. That is, a possible reduction of time is often possible by increasing the maintenance staff. This may have implications not only for the direct cost but also on the need for more highly qualified personnel. For a more detailed assessment of the situation, therefore, it is useful to consider labor hours using the following measures:

1. Maintenance labor hours per system operative hour (MLH/OH)
2. Maintenance labor hours per system operation cycle (MLH/cycle)
3. Maintenance labor hours per month (MLH/month)
4. Maintenance labor hours per maintenance task (MLH/MT)

These factors may be expressed in terms of average values. For example, if we call MLH_C the average corrective maintenance hours, we can calculate the following practical expression:

$$MLH_C = \frac{\sum(\lambda_i)(MLH_i)}{\sum \lambda_i}$$

where
λ_i is the failure rate of the *i*th element
MLH_i is the average maintenance labor hours necessary to repair the *i*th element

5.6.8 Measures Based on Maintenance Frequency

Considering preventive maintenance leads to the establishment of joint measures for average values of corrective and preventive maintenance times. The measures used in practice are as given in the following text.

5.6.8.1 Mean Time between Maintenance Actions

The mean time between all maintenance actions MTBM, preventive and corrective maintenance, can be calculated as

$$MTBM = \frac{1}{(1/MTBM_C) + (1/MTBM_P)}$$

where $MTBM_C$ and $MTBM_P$ are the mean times of corrective and preventive maintenance, respectively. The reciprocal of these mean times represents the maintenance rate in terms of maintenance actions per hour of system operation. Otherwise, the value of the $MTBM_C$ must be very close to the value of the MTBF, considering a failure rate that includes primary failures, secondary failures, induced failures, etc.

5.6.8.2 Mean Time between Replacement

MTBR is an important factor in determining the spare parts needs.

MTBR applies to corrective and preventative maintenance where component substitution is required. Clearly, improving the maintainability will maximize this factor.

5.6.9 Measurements Based on Maintenance Costs

For the vast majority of systems/equipment of great complexity, maintenance costs are very important in the life cycle cost. Experience shows that decisions made in the early stages of the life cycle have the greatest impact on the life cycle cost, making it essential to consider the overall cost as one of the design parameters of the system/product.

The following indices can be used to consider the maintenance cost:

1. Maintenance cost per action (MU/action); note that MU is a monetary unit.
2. Maintenance cost per hour of system operation (MU/H).
3. Maintenance cost per month (MU/month).
4. Ratio of maintenance cost and total life cycle cost.

5.6.10 Logistics Factors Affecting Maintainability

Many other logistical factors influence the maintainability of a system and must be considered as well:

1. *Supply response*: Measured as the probability of having a spare part available when it is needed
2. *Effectiveness of test equipment and support*: Measured as equipment reliability and availability
3. Availability of maintenance facilities
4. Transportation times between maintenance facilities
5. Effectiveness of the maintenance organization and its staff

5.6.11 Data Analysis

In the statistical analysis of reliability, sampling the time to failure is generally not possible, either because it is uneconomical or the data are excessively large. In the analysis of maintainability, obtaining data is much easier and all statistical methods are applicable. The problem is to obtain a reasonably large set of data.

UNE 20654-3:1996 [344] proposes obtaining maintainability data from various sources such as

- Historical data from similar devices
- Design and manufacture data of the device
- Sources from demonstration trials of the device and operating data

These can be expressed as specifically adapted values (actual, planned, estimated, extrapolated) of maintainability basic measures. Points to consider for each data source are indicated later.

5.6.11.1 Historical Data

Historical data are based on experience (e.g., use, repair, computer support center). To make use of these data, we need to know the device on which they are based and the reasons for the data collection. It is necessary to define the methods used for data collection and levels of aptitude and training of the maintenance staff. We also need to discuss discrepancies that may affect the application of the data to the device. Historical data are used during the conceptual definition and the establishment of specifications. In the later phases of the device life cycle, the information can be considered in conjunction with the actual data of the device itself.

5.6.11.2 Data Obtained from the Design or Manufacturing Processes

If data on maintainability are generated during the design or manufacturing processes (e.g., testing during development, production, and assembly), the method for data collection should be specified. We need to understand how it was chosen and applied, along with any possible limitations in the accuracy of the data.

Data obtained from the design or manufacturing processes can be used as a basis for

- Qualification and acceptance of the device from the point of view of the maintainability requirements
- Review of the relevance of historical data and the validity of previous estimates of maintainability

5.6.11.3 Data Obtained from Demonstration Models

Data on maintainability can be obtained from tests conducted on demonstration models, prototypes, or production equipment in a real or simulated environment, or data may be generated during use of the device (e.g., support center, repair, operation). As explained in the following section, there are various techniques of verifying maintainability. Comparing data obtained from demonstration testing with data from real operations is essential to support activities in the commissioning phase of the device.

5.6.11.3.1 MTTR Analysis

For UNE 20654-1:1992 [343], a main objective is finding out the time during which a device is out of service because of maintenance. It is obviously desirable to reduce this time to a minimum, and a wide range of options are available for this purpose, depending on the situation.

Active repair time is often used to specify maintainability and comprises of the following different elements:

- Diagnosis (failure detection, localization of the cause, etc.)
- Technical delays (classical technical delays include commissioning, cooling, interpretation and organization of information, interpreting readings of the measuring devices, etc.)
- Repair (disassembling, exchange, installation, adjustment, etc.)
- Final assessment (verification procedures as needed)

Sometimes, the analyst only needs the estimated MTTR, so the calculation is extremely simple. In this case, we can make a point estimate of the average population parameter through statistical analysis. That is, we have

$$\text{MTTR}^* = \sum \frac{ttr_i}{n}$$

where ttr_i is the sample data from a sample of size n.

5.6.12 Maintainability Allocation

The assignment (allocation) of maintainability is a process that breaks down and distributes the system requirements among its components, so once the assigned requirements are assembled, the global requirements at the system level are covered.

The allocation of these system requirements at lower levels allows the objectives of the subsystem and component design to be achieved, avoiding unnecessary effort and achieving the required goals. In cases where this fulfillment is not possible, it is necessary to review the allocation, entering into an iterative process.

The process achieves the following:

- Allows distribution of the maintainability requirements at lower levels of the system
- Allows designers and contractors to apply the appropriate objectives to subsystems and components
- Provides benchmarks to assess the level of achievement of maintainability
- Prevents or reduces excessive or inappropriate design efforts
- Allows the initial assessment of the feasibility of achieving maintainability requirements in a particular design approach

There are several ways to assign the maintainability target set for all elements of a system. The reality is that none fully satisfies any situation, so the subject is open to research.

UNE 20654-6:2000 [346] proposes a method where available additional design data are used; functional decomposition can be performed on subsets to which failure rate values are assigned. This method can be applied to any system in which it may be assumed the time for corrective maintenance is a log-normal distribution and where sufficient design details are available, for example, during the definition phase or at the end. Applying this method requires the specification of a maximum allowable time for active corrective maintenance.

Among the different methods using expert judgment, the one proposed by Blanchard [28] can be used when the maintainability of the elements of a system is unknown and also when it is known. Blanchard [28] and the British Standard [32] propose a method of allocating maintainability incorporating the contribution of component failure rate to the failure rate of the overall system and the requirement for maintainability (usually MTTR) of the system. The methodology applies the general principle whereby the elements with higher contributions to the system failure rate have a lower MTTR target

allocation. Thus, the average time for corrective maintenance is calculated by using failure rates to weigh the average time for each family or group of equal elements of the system. Thus, we have

$$\bar{M} = \frac{\sum_{i=1}^{k} n_i \lambda_i \bar{M}_i}{\sum_{i=1}^{k} n_i \lambda_i}$$

where

k is the number of different elements in the system (families)
n_i is the number of ith elements (number of elements "i")
λ_i is the failure rate of ith elements
M_i is the mean maintenance time for elements in the "i" family

Based on the British Standard [32], we can distinguish three methods.

5.6.12.1 Method 1: New Design

The first method handles the new design cases where the maintainability characteristics of the various components and elements are not yet known.

Letting M be the target of mean time to repair (also of the mean time of active corrective maintenance) for the system, the distribution of this objective for ith element is

$$M_i = \frac{M \sum_{i=1}^{k} n_i \lambda_i}{k n_i \lambda_i}$$

where

k is the number of different elements in the system (families)
n_i is the number of ith elements (number of elements "i")
λ_i is the failure rate of ith elements

For high values of n and k, this method gives unrealistic values since the M_i figures are very low.

5.6.12.2 Method 2: Partially New Design

In the second instance, it is assumed we have knowledge, in terms of maintainability, of the behavior of at least I families or groups of like components (where $I < k$). Then, for these particular circumstances, we have

$$M_j = \frac{M \sum_{i=1}^{k} n_i \lambda_i - \sum_{i=1}^{I} n_i \lambda_i M_i}{(k - I) n_j \lambda_j}; \quad j = I + 1, \ldots, k$$

5.6.12.3 Method 3: Design with Prior Knowledge

Finally, when we have prior knowledge for k families, we have

$$M = \frac{\sum_{i=1}^{k} M_i n_i \lambda_i}{\sum_{i=1}^{k} n_i \lambda_i}$$

In this case, we need to check compliance with the target value. If the calculated value of M with the previous formula is less than or equal to the target, we are within requirements. Otherwise, we need to check the values of M_i of the different families.

This formula is also valid to replace the first method. Equivalent to the method proposed by Blanchard, it uses expert judgment to estimate the values of M_i of families and see if these are within targets.

5.6.13 Maintainability Prediction

One of the most important and interesting applications of maintainability is the *prediction* or estimate of the earlier proposed factors. Generally, as in any prediction activity, there are many varied difficulties. Probably, the biggest is the lack of information (i.e., data on the execution times of maintenance tasks and subtasks) but this does not preclude the application of the methodology. In the initial life cycle phases and/or with poor data collection, knowledge of maintainability plays an important role.

Clearly, if no information is available, we need to rely on expert judgment or use other system data as a reference.

In what follows, we present a method that generally gives good practical results and has the advantage of being very similar to the block diagrams used in reliability analysis. In our analysis, the variable is the TTR; the maintenance task or tasks under study are modeled on it.

5.6.13.1 Block Diagram of the Maintenance Activity

As in reliability block diagrams, we break the maintenance activity down into tasks or subtask components. In other words, the overall task or activity maintenance is represented schematically by a diagram in which each block represents one of the component's activities. If we can model the activity of maintenance according to the key mission, as proposed by UNE-EN 61078:1996 [358], we can make an analogy between the success of the repair and reliability using the decomposition methodology proposed in the standard.

It is necessary to establish a classification for priority activities. Thus, we distinguish the following:

1. *Sequential activities*: These are part of an overall maintenance activity; they are mutually dependent and must be performed in a predetermined order. Their representation in the block diagram of activities corresponds to the serial block configuration.
2. *Simultaneous activities*: These are mutually independent and are performed in a concurrent manner over time. The block diagram shows a parallel configuration.

3. *Combined activities*: Some activities are performed sequentially, others simultaneously. This is the most common configuration. The block diagram is a mixed, sequential, and concurrent model.

5.6.13.2 Analysis of the Maintenance Task

We have seen that one of the best ways to approach the maintainability study of a system or component is by analyzing the TTR variable. The aim now is to break down that variable into its components, always referring to the random completion times of each maintenance task, and then perform aggregation.

Let us first define the variables that intervene in the breakdown:

- *TCAi*: Random variable representing the time to complete the *i* activity
- *na*: Number of activities that make up the maintenance task

5.6.13.2.1 Maintainability Function for Simultaneous Tasks

For simultaneous tasks, maintainability can be obtained from the intersection of events defined as the probability that a task will be completed in a time less than or equal to *t*, expressed as

$$\begin{aligned} M(t) &= \Pr(\text{TTR} \le t) = \\ &= \Pr\left[(\text{TCA1} \le t) \cap (\text{TCA2} \le t) \cap \cdots \cap (\text{TCA}na \le t)\right] = \\ &= \Pr(\text{TCA1} \le t) \cdot \Pr(\text{TCA2} \le t) \cdot \cdots \cdot \Pr(\text{TCA}na \le t) \end{aligned}$$

5.6.13.2.2 Maintainability Function for Sequential Tasks

When we work with sequential tasks, the total execution time is the sum of the times of each of the activities; therefore, the maintainability function will be

$$\begin{aligned} M(t) &= \Pr(\text{TTR} \le t) = \\ &= \Pr\left[(\text{TCA1} + \text{TCA2} + \cdots + \text{TCA}na) \le t)\right] \end{aligned}$$

This simply expresses the *na*th convolution of the activity component time.

In general, the calculation of the previous expression is very complex; although we can easily assign probability distributions to TCA*I* variables, treating the convolution analytically can be difficult.

5.6.13.2.3 Maintainability Function for Combined Tasks

Most maintenance tasks belong to this group. The function is expressed in a maintenance block diagram, as specified before, and treated as a combination of tasks.

5.6.13.3 Prediction at the Initial Stages of the Life Cycle

Prediction in the early stages of the life cycle, or more precisely early in the design, such as feasibility analysis, is characterized by the lack of data and the inability to perform

maintainability tests. It is necessary to have alternatives to traditional analytical methods, either through estimates by experts or a mathematical model.

The latter is the purpose of this section. Here, we develop a system based on the MIL-HDBK-472 [216] model. The philosophy of the method is based on the consideration that the time for a system repair represents the aggregation of the repair times of individual system components. The times of identical components are considered approximately equal and can be estimated from a random sample. That is, if our goal is to determine the mean time to repair, we will take a sample of system repair times and calculate the arithmetic mean; the repair times from the sample will consist of the time used to repair some system components. Statistically, the size and composition of the sample should be representative of the "population," or in other words, representative of the composition of the system behavior and the failure of its components.

Therefore, the first thing to decide is *the sample size*, *N*, as in any process of random sampling. This size will depend on the accuracy, *k*, we want to achieve in the estimates. The relationship is expressed as

$$N = \left[C_x \frac{z}{k} \right]^2$$

where

C_x is the variation coefficient (ratio of the standard deviation and the population mean, i.e., at system level)
z is the confidence level expressed in terms of the normal distribution or Gauss
k is the desired accuracy in the analysis also expressed in percentage terms

Now, this sample size is decomposed into representative subsamples of the system. To do this, we must first consider the number of different kinds of components and quantity, *Q*, of the same components that make up each class. Thus, the size of each subsample for each class or type of component will be

$$n_i = \text{Entero}(K_i \cdot N)$$

where *K* is

$$K_i = \frac{Q_i \lambda_i}{\sum Q_i \lambda_i}$$

where λ is the failure rate of the components that constitute the class "*i*."

From this, we obtain the samples required to determine the mean time to repair systems. This process is relevant to the calculation of indicators as creating indiscriminate arithmetic means can ignore population statistics and their validity, consuming excess resources in data collection and processing.

The last step is to estimate repair times. We follow the MTTR approach proposed in MIL-HDBK-472 [216], which gives MTTR in minutes. The MTTR model depends on three

parameters, A, B, and C, where A, B, and C depend on the physical design characteristics, support requirements, and maintenance personnel requirements, respectively.

The calculation of these coefficients is performed using the corresponding checklists, where each question/criterion is assigned a score from 0 to 4. These lists are reproduced next.

List A
Physical Design Characteristics

Criteria	Description
1. External access	Accessibility in relation to visual inspection and handling
2. External support	Consideration of whether the external fasteners require special tools
3. Internal support	Consideration if the internal supports, require special tools or excessive time
4. Internal accessibility	Inner packaging and accessibility in relation to visual inspection and manipulation in the maintenance
5. Modularity and packaging	Easy access to parts that need to be dismantled or assembled
6. Parts replacement	Ease with which a component can be replaced
7. Sensors and displays	Availability of the necessary information on the state of operation or failure of the system from improperly installed displays
8. Capacity self-test	Existence of indicators and alarms to facilitate troubleshooting and isolate faults
9. Test requirements	The need to use inspection points/tests to carry out the maintenance
10. Ease of checks	Ease of use and clarity of checkpoints
11. Identification	Clear identification and labeling of the important parts for easy maintenance
12. Calibration requirements or adjustment	Extension of requirements/calibration/adjustment
13. Ease in check	Consideration of whether the removal of the component failure identified for testing/verification is needed
14. Capacity to protect from damage	Consideration of the existence of devices that avoid or minimize damage in the event of failure (fuses)
15. Personnel safety	Safety of maintenance staff during tasks

List B
Support Requirements

Criteria	Description
1. Test equipment requirements	If needed to complete the maintenance and for how long
2. Connectors/adapters test equipment	Consideration of needs and special tools for manipulation
3. Accessories for handling	Need for accessories or aids such as arms, pulleys, etc. to handle maintenance
4. Visual communication	Consideration of whether the visual communication of maintenance personnel for tasks is possible
5. Maintenance/operation staff	Consideration of the need for maintenance and operation staff to interact
6. Number of maintenance staff	Number of people needed to perform the task
7. Need for supervision services	Need for the presence of supervisory personnel or persons established contractually

List C Maintenance Staff Requirements	
Criteria	**Description**
1. Physical strength	Physical capacity required to perform the tasks (arms, legs, porters, etc.)
2. Physical effort	Amount of energy required
3. Skill	Need for dexterity and coordination
4. Visual resolution/acuity	Need for visual acuity to perform the task
5. Memory	Need for familiarity with procedures, tools, etc.
6. Logic and deduction	Need for logical reasoning and inference by maintenance staff to perform the task
7. Organization	Consideration of the need for planning management tasks for maintenance effectiveness
8. Alert	Need for and availability of alert staff
9. Patience, concentration, and persistence	Need for special mental states in terms of concentration, etc. to perform the tasks
10. Independence and aptitude	Need for initiative and independence of maintenance staff

5.7 Availability

5.7.1 Introduction

An additional parameter is needed for the probability that the component/system is operating at a given moment t (i.e., has not failed or has been restored after failure). This indicator is availability. Availability is a performance criterion for repairable systems that considers the reliability and maintainability of a component or system. It is defined as "a measure of the percentage of the degree to which the machinery and equipment is in working order at the time it is needed." This definition includes the equipment itself, the process performed, and the facilities and operations around it. It has several meanings and ways of being calculated on the basis of its use.

5.7.2 Availability Classifications

The definition of availability is flexible and is based on what types of failures are being considered in the analysis. Classifications of availability include

- Instant or punctual availability
- Average availability
- Asymptotic availability
- Inherent availability
- Accomplished or achieved availability
- Operational availability

5.7.2.1 Instant Availability, A(t)

Instant availability is the probability that a system (or component) will be operational (running) at time t, as defined by Smith and Hinchcliffer [297]. It is very similar to the

reliability function to the extent that it gives the probability of a system to function at a given time t. Unlike reliability, the instant availability measurement incorporates maintenance information. At any given time t, the system will be operational if the following conditions are met

1. Probability of survival to at least time t

$$A_0(t) = R(t)$$

Operation		**Repair**	
Failure distribution (density; distribution)	$f(t)$; $F(t)$	Repair distribution (density; distribution)	$g(t)$; $G(t)$
Reliability	$R(t) = 1 - F(t)$	Complementarity	$W(t) = 1 - G(t)$
Risk rate (failures)	$h(t)$	Risk rate (repairs)	$k(t)$

2. Probability of a failure–repair cycle by time t

Now, let us calculate the probability that between 0 and t, one cycle of failure–repair has occurred, and at time t, the component is available because the repair has been completed.

Operation	**Failure**	**Repair**	**Operation**
$t = 0$	u	$u + du$	vt

$$A_1(t) = \int_0^t \left[\int_0^v R(u)h(u)W(v-u)k(v-u)du \right] R(t-v)dv$$

Simplifying this gives

$$A_1(t) = \int_0^t \left[\int_0^v f(u)g(v-u)du \right] A_0(t-v)dv$$

3. Probability of being in repair on t, having occurred two cycles of failure-repair

The probability of being in repair at time t, after two periods of normal operation and an intermediate repair, will be equal to the probability of failure in the period 0 to "u," subsequent repair from u to v, that is, $g(v - u)$, multiplied by the probability that v is a period of operation after a failure and a subsequent repair in t.

Operation	**Failure**	**Repair**	**Operation**	**Failure**	**Reparation**
$t = 0$	u	$u + du$	v		t
				A_1	
		A_2			

Thus, we have

$$A_2(t) = \int_0^t \left[\int_0^v R(u)h(u)W(v-u)k(v-u)du \right] A_1(t-v)dv =$$

$$= \int_0^t \left[\int_0^v f(u)g(v-u)du \right] A_1(t-v)dv$$

where

$R(u)$ is the probability the equipment will be working at least until u
$h(u)du$ is the probability that the failure occurs after u in a long interval du
$W(v - u)$ is the probability that the repair is not made before v
$k(v - u)$ is the probability that the repair is made after v
$A_1(t - v)$ is the probability of a failure–repair cycle occurring from v to t, with the equipment subsequently in operation

That is, time t is the sum of the first cycle time plus the second cycle time, or

$$T = T_{C1} + T_{C2}$$

These are obviously two random variables. We can, therefore, raise the distribution of the variable T to be the convolution of distributions of the variables T_{C1} and T_{C2}.

This is expressed as

$$D(t) = \int_0^t d_{TC1}(v)D_{TC2}(t-v)dv$$

with "d" the probability density function and "D" the distribution function.

In our case, this will be

$$d_{TC1}(v) = \int_0^v R(u)h(u)W(v-u)k(v-u)du = \int_0^v f(u)g(v-u)du$$

$$D_{TC2}(t-v) = A_1(t-v)$$

If

$$I(v) = \int_0^v f(u)g(v-u)du$$

then

$$A_1(t) = \int_0^t \left[\int_0^v f(u)g(v-u)du \right] A_0(t-v)dv$$

$$A_2(t) = \int_0^t I(v)A_1(t-v)dv$$

$$A_J(t) = \int_0^t I(v)A_{J-1}(t-v)dv$$

The general case will be

$$A(t) = A_0(t) + A_1(t) + A_2(t) + \cdots + A_J(t) + \cdots$$

giving us the *instant availability of a repairable component* expressed as

$$A(t) = \sum_{k=1}^{\infty} \int_0^t f_k(t-u) \cdot R(u)du$$

That is, the probability of being active in t will be the union of the following events, mutually exclusive, expressed as the sum of these probabilities:

1. Probability of not having any failure, at least until $t(A_0)$
2. Probability of one failure and one repair and being active in $t(A_1)$
3. Probability of one failure, one repair, operation, second failure, second repair, and operation, at least until $t(A_2)$
4. Probability of J failures, J repairs, and operation, at least until $t(A_J)$

5.7.2.2 Average Availability, $\bar{A}(t)$

The average availability is the proportion of time during a period of time that the system is available for use. It represents the mean value of the instantaneous availability during the period (0, T].

The expression for calculating the average availability is

$$Am(t) = \frac{\int_0^t A(u)du}{t}$$

In the case of exponential distributions, we have the expression:

$$Am(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{t(\lambda+\mu)^2}\left[1 - \exp\left(-(\lambda+\mu)t\right)\right]$$

5.7.2.3 Asymptotic Availability, Am(∞)

The system's asymptotic availability is the limit of the instant availability as a function of time when this approaches infinity:

$$A(\infty) = \lim_{t\to\infty} A(t)$$

The instant availability function begins to reach a steady state after a period about four times the average time to failure. This is illustrated in Figure 5.9.

As we have seen, in the case of exponential distributions (failure and repair), the asymptotic availability ($t \to \infty$) is

$$Am(\infty) = A_{\infty} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{\mu}{\lambda + \mu}$$

Therefore, a higher expression is valid according to O'Connor [240] when the time interval is appreciably higher than MTBF. If this assumption is not valid, the numerical simulation is applied to define the availability using probability distributions of reliability and maintainability, according to Lewis [188].

The ascending and descending of the two graphs shows the so-called infant mortality when the equipment trend toward failure stabilizes, that is, availability in the early stages is strongly influenced by the reliability of the system and its temporal behavior.

Therefore, the availability steady state can be regarded as a point at which the stabilizing system availability is a constant value. However, this steady state cannot be used as the sole indicator for some systems.

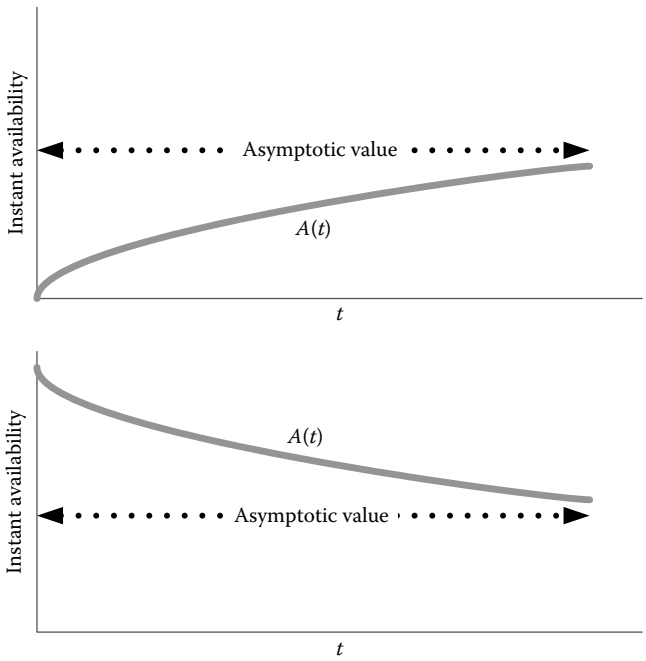

FIGURE 5.9
Availability reaching the stabilization point at a constant value.

5.7.2.4 Inherent Availability, A_I

Inherent availability is the probability that a system or component, when used in the proper conditions and with ideal support (spare parts, maintenance), can operate satisfactorily at any moment when required. The system downtime for corrective maintenance is in a steady state, so inherent availability denotes the level of availability only for corrective maintenance; see ESREDA [96]. Inherent availability is exclusively determined by the equipment design. It is assumed that the spare parts and labor are 100% available, without delay. Logistics, administrative delays, or expected inactivity are excluded, as is inactivity due to preventive maintenance. Only inactivity due to corrective maintenance is included. Inherent availability is typically deduced through analysis of engineering design. Inherent availability fulfills the need to distinguish between expected performance and unexpected failures.

This measure of availability has the following characteristics:

1. The influence of preventative maintenance is *not* considered.
2. The real condition of the system's logistical support is *not* considered.

The aim of this measure is to highlight the operational readiness of the system in *isolation from the influence of logistical support*.

This operating arrangement contemplates corrective maintenance; it is an idealization and in an environment with real logistical support, it can decrease in value.

Its application is mainly aimed at specifying requirements for a new system, which does not yet have a definition of logistical support.

The expression for calculation is as follows:

$$A_i = \frac{\text{MTBF}}{\text{MTBF} + \text{Mct}}$$

where, as already defined,

MTBF is the mean time between failures

Mct is the mean time of corrective active maintenance (in practice, the MTTR)

It should be remembered that neither the logistical delays nor the administrative delays are included in this last factor.

The MTTR can be represented as follows (remember that the MTTR represents only corrective actions):

$$A_I = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}$$

5.7.2.5 Achieved Availability, A_A

Achieved availability is the probability that the equipment operates satisfactorily at a given point in time when used under ideal conditions and with impeccable logistic support (i.e., personnel, tools, and spare parts are instantly available). It excludes the logistics, the waiting time generated, and the time of administrative inactivity. It includes time for preventive and corrective maintenance. The achieved availability is defined as the level of

availability reached for the current operational performance of preventive and corrective maintenance. Achieved availability is very similar to inherent availability except that preventive maintenance (PM) stops are also included. Specifically, it is the steady state when considering the availability of corrective and preventive measures of system inactivity. It can be calculated by the mean time between maintenance actions, MTBM, and mean downtime due to maintenance, $\bar{M}$, as explained by Ebeling [87]:

$$A_A = \frac{\text{MTBM}}{\text{MTBM} + \bar{M}}$$

This definition complies with the need to distinguish when equipment availability is due to planned or unplanned actions. The shape of the availability curve is determined by the plant design. Maintenance strategies have a direct effect on availability and are an ideal indicator of the performance of preventive maintenance program.

One of the objectives of this availability based in maintenance operations is to find the optimal curve and operate at that level. It is essential to know the location and shape of the curve of availability achieved. Otherwise, it is not possible to determine what is reasonable and possible for operational availability and, therefore, for the production of the plant. If the curve of this availability is unknown, operations management and manufacturing may try to achieve performance beyond what is possible. The result is overspending, with excessive investment in maintenance resources that negatively impacts the budget.

The achievable availability is the result of several factors:

- Plant design determines the shape and location of achievable availability curve. Therefore, it establishes the availability that can be achieved.
- Maintenance strategies determine the location of the plant in the availability curve. Therefore, they establish the real achieved availability.

5.7.2.6 Operational Availability, A_o

Operational availability is a measure of the average availability in a time period that includes all sources of inactivity, such as administrative inactivity and inactivity due to logistic problems. It is the probability of equipment performing satisfactorily at a given point in the time when it is used in a real environment with operational support. This includes time due to logistics, activity and potential activity time, inactivity or expected administrative delays, and both preventive and corrective maintenance.

The operational availability is the availability that the customer actually experiences. It is essentially *a posteriori* definition of availability based on actual events that have occurred in the system. The previous definitions, *a priori*, are estimates based on models of system failure and statistical distributions of downtime. The operational availability is, therefore, the proportion of system uptime and total time, mathematically equivalent to

$$A_o = \frac{\text{Uptime}}{\text{Operating cycle}}$$

where the operating cycle is the period of operation under investigation and uptime is the total time the system was working during the operating cycle.

As stated, the operational availability is the probability that a system or equipment, when used under the established conditions and in the actual operating environment, can operate satisfactorily at any moment when required.

This measure of availability best fits or expresses the degree of confidence that a system will meet its operating demand. Therefore, to determine it, we need a deep knowledge of the system's expected response and the logistical support it will receive.

This measurement expresses the degree of system efficiency with regard to its behavior in the face of failure; it also reflects the adequacy of the logistical support in the existing maintenance policies and resourcing (facilities, supplies, personnel).

The general expression for its calculation, based on known parameters, is

$$A_o = \frac{\text{MTBM}}{\text{MTBM} + \text{MDT}}$$

where

MTBM is the mean time between maintenance
MDT is the mean time of stops in maintenance

Operational availability isolates the effectiveness and efficiency of maintenance operations. It is the actual level of availability realized in day-to-day facility operation, that is, plant maintenance that reflects resource levels and organization effectiveness. The operational availability is the experienced performance in a plant at a certain production level.

The difference between operational and achievable availability is the inclusion of logistical support maintenance. Achieved availability assumes resources are 100% available and no administrative delays occur.

5.7.3 Reliability Terms

The terms of reliability are graphics and theoretically defined on Figure 5.10.

Cycle time, that is the time between two failure, can be decomposed as proposed by the Spanish standard xxxxxxxx in a series means are times that are part of the data collections more frequent to incorporate into work orders and reports issued interventions.

5.7.4 Failure Time

The total failure time, according to SMRP, can be decomposed as in Figure 5.11.

These times can be represented as follows in Figure 5.12.

5.7.5 Definition of Time

We need a clear definition of time that does not lead to double interpretations. This is rarely achieved despite attempts to normalize the definition. For example, UNE EN 13306:2002 [354] defines some times as availability and others as unavailability, giving rise to various interpretations that precludes their use in a metric for benchmarking.

This problem has led to the widespread use of a limited number of indicators known as world class, including MTBF and MTTR. These are globally accepted and agreed-upon definitions. It is not a problem of a correct or incorrect definition of time but, rather, its use in metrics.

To calculate the different availabilities, the following definitions of time are proposed:

Total time (A): Maximum amount of time available (24 hours a day, 7 days a week) in the observation period, as agreed upon (i.e., calendar time).

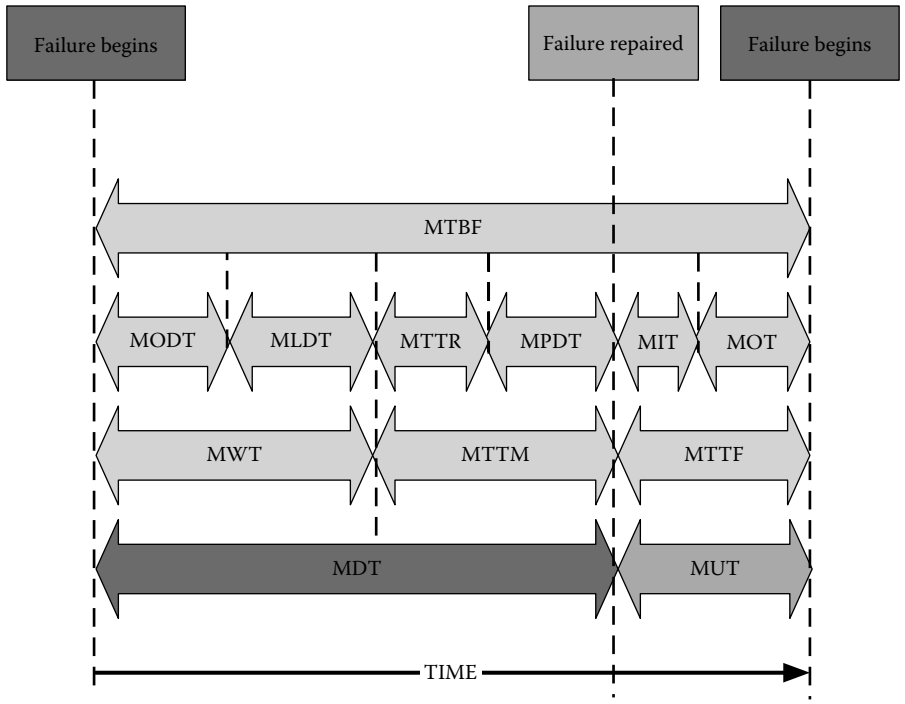

FIGURE 5.10
Times displayed in a failure and repair process. MTBF, mean time between failures; MODT, mean operative downtime; MLDT, mean logistic downtime; MTTR, mean time to repair; MPDT, mean preventative maintenance downtime; MIT, mean idle time; MOT, mean operational time; MWT, mean waiting time; MTTM, mean time to maintain; MTTF, mean time to failure; MDT, mean downtime; MUT, mean uptime.

Plant stop time (B): Time the facility is closed for operation.

Operating time (C): Time the facility is open and ready to produce.

Planned unavailability (D): Planned time for scheduled maintenance, tests or experiments; time for any foreseeable repairs or improvements; mainly composed of preventive and predictive maintenance.

Planned production stops (BR): Expected time when production interruptions occur, such as breaks, lunches, meetings, etc.

Operating time (E): Available time for normal operation of equipment.

Delay time (F): Time consumed by unexpected events that keep the equipment from operating, not including failures; including but not limited to processing difficulties (unless a turnkey system), operational errors, errors in materials flow (blockage or shortage), and raw materials outside specifications.

Repair time (H): Time when equipment is unable to operate due to a malfunction and subsequent repair of one or more of its components; malfunction occurs spontaneously, causing the equipment to end its operation. Note that equipment malfunction does not include process malfunctions (unless it is a turnkey system); the waiting time for the necessary parts from the supplier is not included in the repair time (H). To calculate equipment availability, the waiting time of the maintenance staff for the required part is included in delays (F).

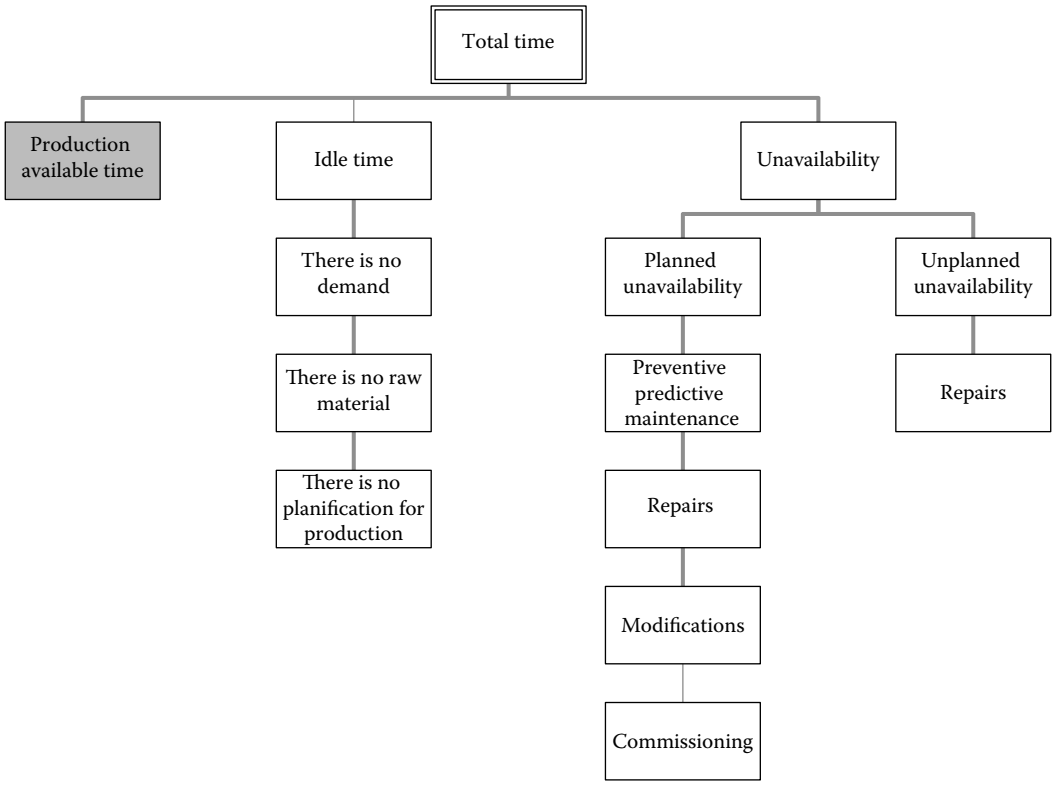

FIGURE 5.11
Failure time decomposed according SMRP.

The repair time includes the following items:

- H(1): Inactivity failure: time to find the failure and its cause
- H(2): Logistics inactivity of the parties
- H(3): Repair inactivity: time to repair and test

Production time (I): Time when equipment is producing or the time of potential production (G), less time to repair (H)

Process time out of cycle: Moment when the equipment is not in the normal cycle of production activities, including machine preparation (part configuration) for operation and production of parts, within the process of inspections, operator settings, replacement of perishable tools and/or supplies, and cleaning (removing junk, cleaning chips, weld spatter, etc.)

Cycle time (K): Also called activity time or uptime; time when equipment is in operation and production (in the cycle), or the production time (I) less process time out of cycle (J)

5.7.6 Method for Calculating Availability

Unfortunately, it is not always the case that the time of failure of the systems and its repair time should be perfectly parameterized and modeled with their probability distributions.

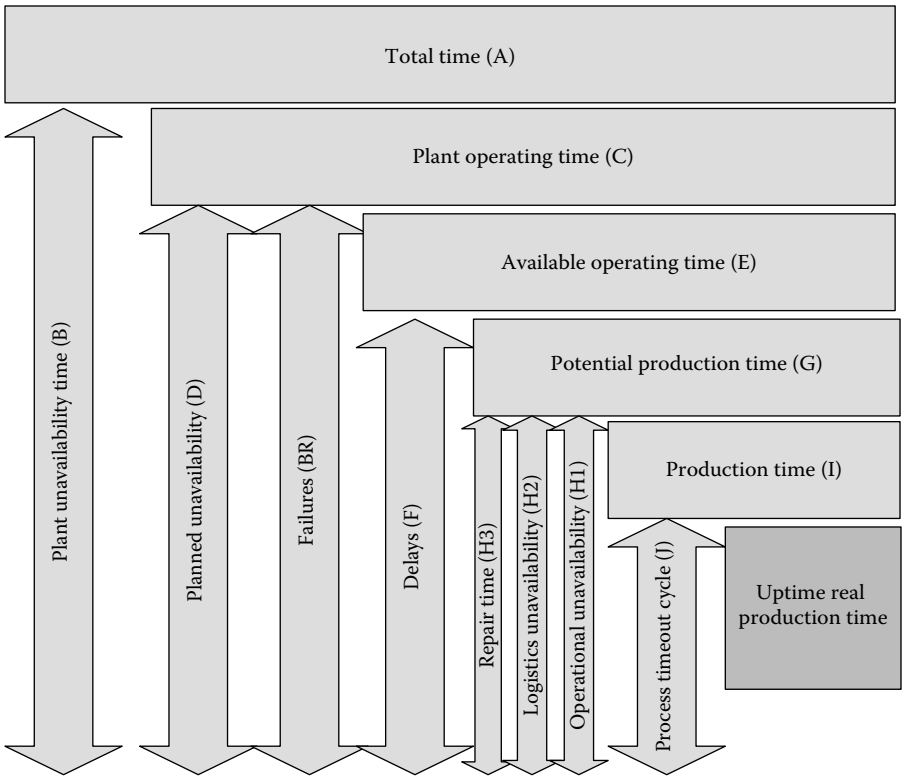

FIGURE 5.12
Temporary distribution diagram for availability.

If present, calculating the exact availability is the result of a state diagram using Markov analysis.

Markov analysis uses a transition diagram as a graphical representation of the system reliability characteristics, modeling system behavior over time. In this type of analysis, a system is considered as comprising a series of units, each of which has only two states: broken and functional. For the system as a whole, however, there may be a number of different states, each determined by a combination of operational and functional units. Thus, as a unit fails or is repaired, the system moves from one state to another. This kind of model is usually called a continuous time model with discrete states.

Markov analysis allows modeling the events of failure/restoration graphically. The process of failure/restoration is represented by symbols of transition from state to state, as described in UNE 21406:1997 [349]. The sum of all transition probabilities is unity, which means that at any point the system must be represented by one and only one state of the state transition diagram. If for practical reasons states with low probability are omitted, this requirement is fulfilled only approximately.

UNE 21406:1997 [349] proposes the following metrics for a maintenance state diagram:

- The probability of being in one or more states
- The transition speed (input or output) between the states
- The time spent by the system in each state

From these measurements, we can establish availability. Availability is not more than the sum of the probabilities of being in a state that allows system operation, that is, meeting operational objectives.

If there is a lack of data, we must estimate the availability based on the documentation generated from maintenance work orders and operators. The proposed availability calculation is structured as shown in the flowchart in Figure 5.13.

- Normally, the operation records are accumulated chronologically. A complex control system will identify the occurrence of failures of different systems more easily.
- The first stage is to identify operating time to failures and the time required to repair. The times should be carefully selected because in complex systems, performance loss or failure conditions can be caused by another component. We must be especially careful determining the cause of failure.

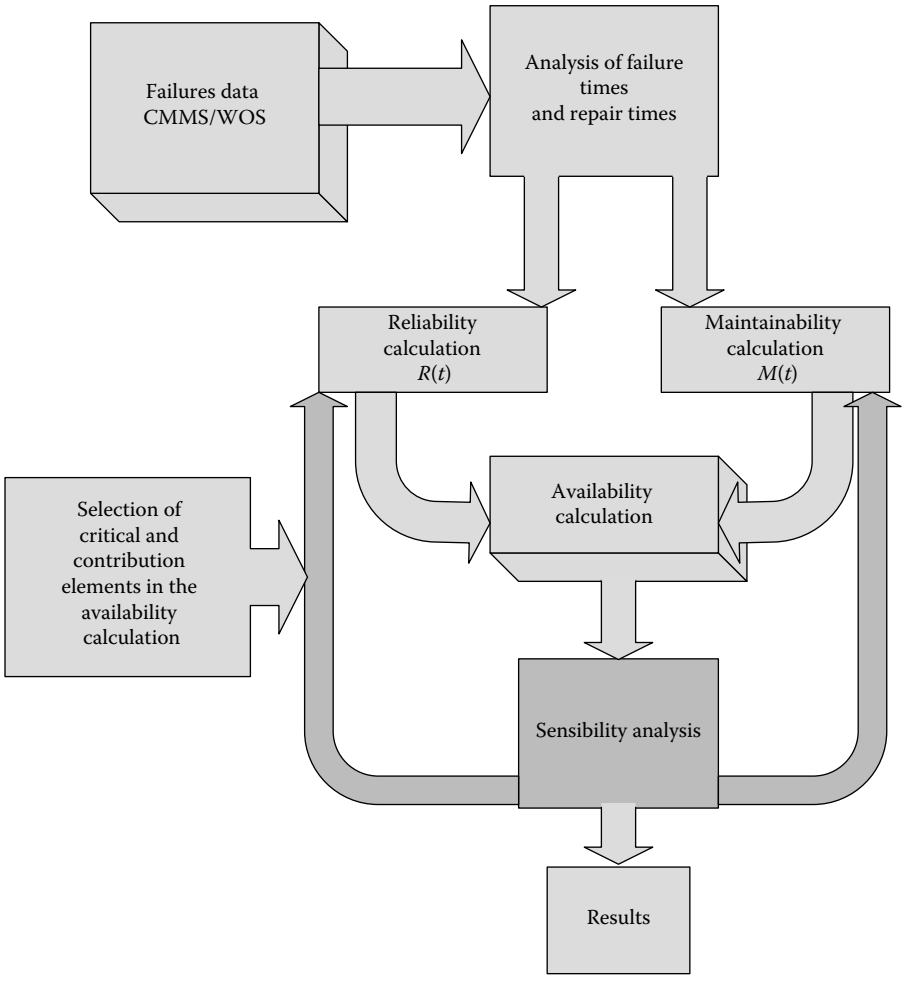

FIGURE 5.13
Flowchart of availability calculation.

- The second stage is to calculate the system maintainability and reliability. Systems capable of being repaired have a maintainability modeled by a Weibull or log-normal distribution, with repair times depending on various factors such as the skills of maintenance staff or the availability of spare parts.
- The third stage is to calculate the system operational availability using the ratio of the average of the mean time between failures and the system operating cycle.
- The fourth stage is sensitivity analysis; the procedure is repeated using software that will increase the number of repetitions to fit the data; RELIASOFT [281].
- Finally, the results of the calculations can be presented as indicators of operating performance.

5.7.7 Time Parameters for Monitoring and Diagnostics

One of the important activities at the level of generating indicators is the correct measurement of time associated with preventive and corrective maintenance. Preventive planning can minimize corrective maintenance and, consequently, improve customer service, increase the availability of resources, and significantly reduce repair costs, system downtime, cost of spare parts, etc.

It is important to be aware of the importance of the accuracy and reliability of the data on the time required for preventive and corrective interventions. The value of the scorecard lies in the validity of the data. The following parameters are important:

1. Mean response time
2. Mean time for action on the machine
3. Time to repair
4. Mean time to diagnose
5. Mean time between failures
6. Mean time of commissioning
7. Availability

5.8 Safety

5.8.1 Introduction

Safety is a fourth RAMS parameter. If a system is functionally safe, that is, reliable, it will act in the manner for which it has been designed.

Reliability assumes a system operates correctly, or in other words, that it is safe. Safety is a complex reality, ranging from strictly technical details to various types of human and social effects.

The complexity of safety requires its classification or systematic structuring. The three most common levels of classification are

1. Work safety
2. Safety of industrial products
3. Safety of industrial processes and facilities

Safety can be subjective. "Safe" and "unsafe" are adjectives often applied rather lightly and not necessarily corresponding to the rigorous analysis we require. In fact, their use is frequently not governed by physical laws but by the decisions of individuals, leading to subjectivity, even uncertainty as to meaning. The human factor will always be present in all activities related to safety, including industrial safety, but the goal is to reduce uncertainty to very low limits.

5.8.2 Safety Structure

5.8.2.1 Work Safety

Work or occupational safety is extremely important to organizations. Obviously, work safety is intended to protect workers; hence the importance attributed to it by organizations.

It is necessary to articulate what we mean by occupational safety; otherwise, provisions would be limited to statements of objectives and goodwill and not extend to technical details. At the top of this regulatory pyramid are protection laws; these set limits to maintain a certain level of security and provide a system of penalties for individuals or companies who violate these laws. In many cases, these regulations impose minimum or maximum values that are easily measurable. This is the concept, for example, in determinations of the maximum allowable concentrations of toxic chemicals or radioactive products.

Some voluntary standards and codes of practice are applicable to the various industrial sectors, generated by professional associations and/or individual companies. Voluntary standards provide more detailed requirements and provisions applicable to a specific work place. In some cases, this includes prevention plans and emergency plans.

A work and occupational safety program must also inquire about the origins of risk and consider how to limit them, setting maximum allowable levels. Risks include voltage, temperature, pressure, decibels, radiation exposure, or the concentrations of various products. Analyzing how to ensure these limits will not be surpassed is an important part of job safety.

Ultimately, companies and workers are responsible for work safety in their facilities; they are well-qualified to analyze the origins of risk, and if they do so, this can be an unbeatable protection policy.

5.8.2.2 Product Safety

Users have a completely different approach to safety even if the risk sources are similar. Work safety refers to occupationally exposed persons, but people do not have to have any qualifications to use a product.

This means products must have the appropriate design and manufacturing techniques to ensure they perform as intended, especially security features. In the traditional administrative system in most Western countries, homologation is commonly used and is still necessary in some types of products. Through homologation, a company is granted *a priori* a permit to market a product, based on the testing of a prototype or on appropriate checks.

Today, prior homologation is not required for products. Rather, the marketing of products is the responsibility of the manufacturer or importer; the product must have an EC mark, indicating the product meets all applicable EU directives.

Manufacturers or importers cannot fix the EC marking irresponsibly, however; they have to prepare a technical file showing all tests and trials have been carried out in compliance with the directives; this includes quality assurance of the production process or products. Technical performance modules must declare the applicable directives are met.

Furthermore, a declaration of conformity with the directives must be explicitly made by the manufacturer or importer.

Before the EU harmonization achieved by the so-called new approach and global approach, each country had its own technical legislation. Generally, all industrial products had to pass a premarket homologation before commercialization. Homologation is a technical requirement that involves a series of tests to verify compliance with regulations. Apparently, this procedure offers better guarantees of protection to the public but carries a significant commercial disadvantage, and greater security is only apparent. It is only apparent because products may not be identical to the approved prototype.

Logically, to ensure that safety guarantees are real, public authorities have to complement them with a sample control of industrial products; this process should be accompanied by a sanctioning capacity.

5.8.2.3 Serious Accidents

A third area of safety concerns serious accidents, understood as those affecting the general public or the human environment, such as the emission of toxic substances from industrial installations, or abnormal amounts of energy output. The release of energy is often accompanied by dangerous phenomena such as noise, explosions, and fires. These energy emissions can stimulate the dispersion of toxic agents, raising the accident to catastrophic levels.

Broadly speaking, we can differentiate two industrial areas in which such accidents are especially relevant: toxic chemicals and radioactive products.

A company requires the capacity to react to disasters of any kind, including the development of evacuation plans. At the same time, it must work to prevent industrial accidents and to limit their effects if they occur. In the case of major accidents, we will have problems related to the safety of the general public, including maintaining public order. This explains why many of the issues relating to safety after a major accident are envisaged primarily from the perspective of civil protection, forgetting that in some cases, the most effective protection is created at the root of the facility and processes.

We need to develop standard review plans for each installation type, similar to the nuclear industry. The latter industry has produced safety guides and performance specifications after systematic analysis of nuclear safety criteria. Great efforts have been made, and the industry has very detailed plans, standards, and physical specifications for various system physical variables. The notions of quality found in the nuclear industry should permeate other fields.

5.8.3 Risks Analysis

According to UNE 200001-3-9 [340], risk analysis seeks to answer three fundamental questions:

1. What can go wrong?
2. What is the probability of this happening?
3. What are the consequences?

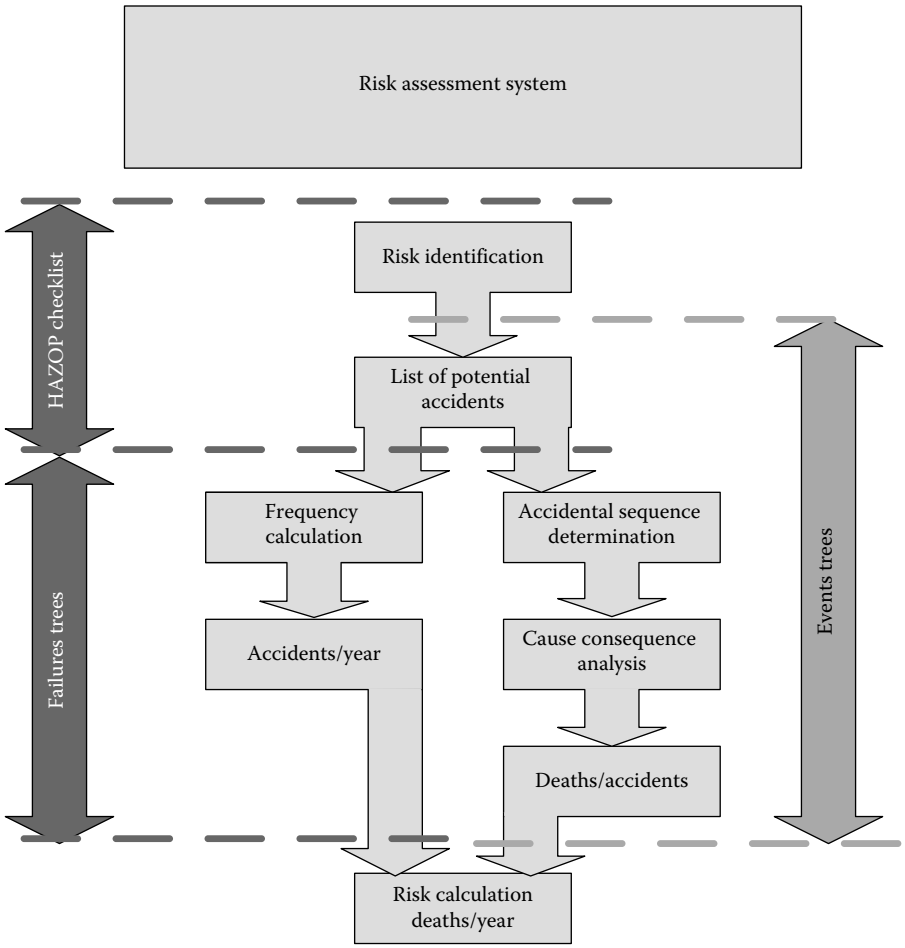

FIGURE 5.14
Risk assessment system.

To conduct safety studies of facilities potentially susceptible to serious accidents and to carry out a full cost–benefit analysis, we need a tool to characterize accidental events. The various methodologies to assess risks are shown in Figure 5.14.

One of the most common techniques is Hazard and Operability Analysis (HAZOP). HAZOP systematically investigates the operating condition of a plant and determines the risks associated with breakdowns or mechanical failures.

An accident hypothesis list should cover the full spectrum of reasonably expected issues. Each hypothesis can lead to an event tree showing how the accident sequence may occur; a cause–consequence analysis associates the hypothesis with certain effects, including deaths or damage to people, things, or the environment.

The event tree is essentially qualitative; it can only approximately determine deaths and other associated damage with a particular type of accident.

We should supplement this with an estimate of the frequency of accidents using failure analysis trees.

Fault tree analysis aims at identifying and analyzing the conditions and factors that cause or contribute to the occurrence of a specific undesirable event, usually an event that

significantly affects the proper functioning of the system, its economy, security, or other required features.

According to UNE 21925:1994 [350], a failure tree is particularly useful for the analysis of complex systems comprising several functionally related or dependent subsystems with different operating objectives. This is especially true when the design of the system requires the involvement of many specialized design groups. Examples of such systems are nuclear power plants, airplanes, communication systems, chemical and industrial processes, etc.

The accident hypothesis should include whether failures are sequential or parallel and associate a failure rate with various initiating events. The hypothesized number of incidents per year must be complemented with the probability of success of the various safety features.

The failure rates of the elements, components, and subsystems usually follow a Poisson statistical distribution, while the probability of success or the ability of a safety system to tackle the negative effects is binomial, that is, success/failure.

5.8.3.1 Binomial Distribution

A binomial distribution is applicable to those situations where there are only two possible results and the probability of these basic events remains constant. This distribution is widely used in reliability and quality analysis and is expressed as

$$f(x) = \binom{n}{x} p^x q^{n-x} \quad \text{with} \binom{n}{x} = \frac{n!}{(n-x)!\,x!}$$

where

$f(x)$ is the probability of getting x number of events in n experiment attempts or repetitions
n is the repeats or tests performed
p is the probability of occurrence of the event in question
q is the probability of the opposite event

Therefore, $q = 1 - p$.

The distribution function will give us the probability of r events in n attempts, expressed as

$$F(x;r) = \sum_{x=0}^{r} \binom{n}{x} p^x q^{n-x}$$

5.8.3.2 Poisson Distribution

The Poisson distribution is used quite often in reliability analysis and can be considered an extension of the binomial distribution when n tends to infinity.

If events occur according to a Poisson distribution, the occurrence occurs at a constant rate and the number of events in a time interval is independent of what occurred at any other interval.

The amount function will give the probability of x occurrences within a predetermined time interval. It is expressed as

$$f(x) = \frac{a^x e^{-a}}{x!}$$

where x is, for example, the number of failures and the number of expected failures (mathematical expectation).

For the purpose of its use in reliability, the practical expression is as follows:

$$f(x;\lambda,t) = \frac{(\lambda t)^x e^{-\lambda t}}{x!}$$

where

λ is the instant failure rate or risk rate, which is constant in this distribution
T is the length of time interval considered
X is the number of failures

The safety function or the probability of zero failures at time t is

$$S(t) = \frac{(\lambda t)^0 e^{-\lambda t}}{0!} = e^{-\lambda t}$$

obviously corresponding to the exponential distribution.

5.8.3.3 Poisson Process

The Poisson process is a stochastic process, with a random variable whose distribution depends on a parameter t, usually the time. In the Poisson process, an event can happen randomly at any time under the following conditions:

- The number of times the event occurs in a time interval of length t is not dependent on what has gone before that interval or the initial time interval.
- The probability of the event occurring in the interval dt is proportional to dt. The probability an event occurs more than once in the dt interval is an infinitesimal dt.

Under these conditions, the probability of an event occurring r times during an interval of duration t is

$$\Pr(t) = \frac{e^{-\lambda t}(\lambda t)^r}{r!}$$

This expression matches a Poisson distribution.

When the event analyzed is the failure of a repairable component with repair time zero, the Poisson process describes the exponential case. That is, the probability t no failure occurs in an interval of duration t is

$$P_0(t) = e^{-\lambda t}$$

or the reliability function expression (or survival) of an exponential distribution.

The probability of r failures in duration t, corresponding to the density function of the *Erlang distribution* (the density function of a Gamma distribution with parameter r), is expressed as

$$f(t) = \frac{\lambda}{(r-1)!}(\lambda t)^{r-1} e^{-\lambda t}$$

With this we can draw the following practical conclusions, when the terms of a Poisson process are met:

- The probability distribution of the random variable "number of failures in an interval of duration t" is a Poisson distribution.
- The probability distribution of the random variable "time between consecutive failures" is an exponential distribution.
- The probability distribution of the random variable "time to reach consecutive failures r" is a Erlang distribution.

It is not easy to determine the characteristics or statistics of these distributions, either Poisson or binomial. In some cases, there are not enough historical data to determine the true failure rate.

Typically, there are three stages in the life of a component, usually described as the bathtub curve. In the first stage of the bathtub curve, the failure rate is high due to the failure occurrence called birth defects associated with the manufacture of materials or installation. Usually, in expensive facilities and a high rate of danger, this period is closely monitored, with nondestructive testing and inspections of various kinds. In the bathtub curve, the initial period is followed by one where failure rates diminish and remain constant over time. Near the end of life, the failure rate soars again.

Similarly, in the binomial distributions characterizing the success or failure of a safety system whose function is needed at any given moment, there is large uncertainty. These systems are usually very distinctive and individualized, so there is not enough information about them. Proper maintenance and periodic verification of their functionality ensures their reliability—much more so than if they were neglected. In any case, and noting the uncertainties of the statistical models, using failures trees can determine the probability of an accident and its consequences, including, for example, the number of deaths likely to be caused.

Combining the latter with the number of accidents expected in a given period, for example, 1 year, we can calculate the risk in terms of deaths per year (or other type of damage per year). With this, the overall risk analysis is completed.

One advantage of this methodology is that it allows us to identify the events with higher impact and determine the ways accidents usually occur. In other words, this methodology allows us to determine which security features in certain elements and subsystems should be improved.

5.8.4 Safety Reliability Analysis

Any given installation will have a series of safety systems. It is possible to carry out probabilistic analysis to determine the degree of uncertainty and possible damaging consequences associated with specific projects.

Logically, to increase the safety of a project, it should be in a specific installation. Increasing safety measures will increase the real cost of investment but also will also increase the level of security, or alternatively, decrease the level of insecurity, and save hypothetical costs. These costs are hypothetical and only appear in the reality of accidents, which in principle cannot be predicted deterministically. A given installation may have no accidents throughout its lifetime, while another similar facility, despite spending more money on security systems, may have accidents.

The useful life of a given installation can be known only after the fact, not at the time of a project. Therefore, it is feasible and advisable to perform reliability safety analysis. In such an analysis, for a given design and a certain level of safety investment, we can determine the foreseeable consequences of hypothetical accidents.

This assessment has substantial cost–benefits; while the analysis is hypothetical, uncertainty is reduced, as are the catastrophic consequences that can result from breakdowns, human failure, etc.

To determine the costs of a lack of safety, we can use reliability analysis: failures trees can determine the probabilities of occurrence of various events in the operation of the facility, and event trees can establish the possible consequences of certain failures.

In both cases, failure trees and event trees, there is always a probability component. The accuracy of the calculations is fundamentally linked to the precision with which we can identify the statistical type of the components and subsystems, as noted before.

In the field of consequence analysis, it is essential to establish the likely propagation of the accident, from a chain-reaction failure of various toxic substances and explosives or different process lines, following an initial event. In general, the accumulation of combustible or explosive materials in a particular area may lead to consequences that amplify a relatively meaningless incident.

For example, the use of welding torches in fuel storage facilities, or in proximity to inflammable substances, in some cases not sufficiently assessed for their potential to catch fire, can lead to spectacular fires.

One technique used in probabilistic analysis, for example, in probabilistic safety, is FMEA or Found Modes, Effects, and Criticality Analysis (FMECA) based on the detection of failure modes and the analysis of the effects of failure and criticality, that is, if a failure has a direct impact on the safety functions of the plant.

FAMECA can be considered an extension of FMEA. FMEA is a starting point, the level (component or subset) that provides basic information on failures (primary failure modes). From the basic characteristics of the failures of the elements and the functional structure of the system, FMEA determines the relationship between the elements' failures, malfunctions, operating constraints, and performance degradation or system integrity. Assessing secondary failures or higher-order systems or subsystems considered failures can create a chronological sequence of events

FMEA is limited to a qualitative analysis of the failure modes of the physical support (hardware) and, thus, does not include human error or logistical support (software), although systems are normally subject to both. Criticality describes the sequence of the severity of failure. The establishment of categories or levels of criticality is a function of the damage and loss of ability of the system to function and, sometimes, the failure probability. It is preferable to proceed to the analysis of this probability separately [347].

The study of criticality and the calculation of the probability of failure modes are logical consequences of FMEA. The criticality analysis of identified failure modes is generally known as FMECA and is widely used in security.

The FMECA method is applied in

- A project
- Construction and assembly
- Operation
- Dismantling and disposal

This method requires the use of failure trees and event trees, looking at criticality condition, based on the assessment of the effects of an accident or breakdown on the safety features of the plant, that is, if they affect the firefighting equipment, the monitoring of the physical and chemical variables, locking systems, confinement of toxic products, etc.

The FMECA method should be particularly rigorous in the analysis of human errors even when they are associated with a high level of uncertainty. For human failure, it should also distinguish different levels of criticality. In this field, specialists have different opinions; there is not a single recipe for success. However, we must try to reduce the burden of responsibility and limit the potential for accidents.

UNE 20812:1995 [347] recommends performing FMECA using forms or tables designed for the system being studied; they should be prepared in accordance with the objectives and stored for subsequent operations.

Failures such as the total rupture of a storage tank rarely occur suddenly and catastrophically. Failures usually occur during a process, particularly during transportation and decanting of toxic or flammable materials.

To study failure sequences, Boolean algebra can be used to model the binomial distribution in each subsystem or safety component. A reported failure may have certain consequences depending on the reaction of safety systems. Boolean expressions, following Boolean algebra, can be associated with a set of logical diagrams to express the operation state or failure of the various systems.

This is not the appropriate place to develop the properties of Boolean algebra and its use to calculate the probabilities of the various processes. However, both manual calculation and computational calculation can create logic diagrams of increasing complexity to represent all system variables characterizing various safety equipment.

Probabilistic safety analysis has multiple uses. It serves to evaluate the degree of uncertainty associated with a particular plant working under given conditions. It can also determine the possible pathways or amplifications of more frequent events leading to serious consequences. This allows us to modify a project and enhance the safety features in high-risk areas.

Using various accident scenarios, we can configure the set of relations damage/probability, which determines the risk characteristics of the installation. Depending on the accident tolerance permitted, both by the public and by the regulatory authority, security systems may have to narrow the maximum possible consequences; in other situations, the reverse will occur. For example, a disaster with a major impact on the population, and logically on the economy, is truly disastrous; although it has a very low probability, it should be avoided.

Another key aspect of reliability safety analysis is the formulation of appropriate external and internal emergency plans. To be representative, they must consider the most likely accidental events and how these events can be amplified in severity.

In the case of past catastrophic accidents, this type of analysis is increasingly desirable. It can study the events that have already occurred and suggest ways to prevent further ones.

5.9 Information Management for Failure Analysis

5.9.1 Introduction

As we have repeatedly said, information on maintenance is critical. It allows us to know the status of the behavior of a plant and its machinery over time, facilitating decision-making in the event of a new equipment failure. Some experts say information leads to "knowledge." In industrial plants, especially in the maintenance function, companies seeking to improve their competitive edge increasingly need to conserve and make better use of the knowledge produced by past experience.

To improve the functioning of equipment, it is important to have a good record of information as well as knowledge acquired from previous experiences. This involves changing work habits and creating a new attitude about the importance of records, especially their use in new problems, and the transfer of experience to coworkers.

5.9.2 Study of Failure Information

A first step in improving fault analysis is the appropriate use of information and building failure databases. Without data, it is not possible to take a close look at the causes of failure.

There are two types of databases for faults:

1. *Qualitative*: Failure analysis data
2. *Quantitative*: Historic data on the operation and the intervention time

The first set of information has details of the failure and the corresponding corrective and preventive maintenance. The second mainly concerns temporary indicators MTBF and MTTR; it also has to do with the improvement of equipment, but through the conclusions reached by trend analysis and the management of large volumes of data.

UNE 200001-3-2:2001 [337] says the following data sources are usually available:

- Preventive and corrective maintenance
- Repair activities ("*in situ*," in the workshop)
- Claims
- Measures of performance (e.g., reports of anomalies, traffic measures, operating records, and environmental measures)
- Inventory information (e.g., stored product lists, installation lists, modifications, and regularly updated databases for configuration control)

5.9.3 Work Order Data Management System

The failure data management system is created to preserve the knowledge gathered through the experiences of equipment failure and intervention. A failure information system must contain at least the following information as proposed by UNE-EN 13460:2003 [355]:

- Dates and times when failures occur
- Equipment where the fault appears
- Classification of failure class: critical, intermediate, or reduced

- Part or component failed
- Form or nature of failure: noise, vibration, heat, wear, etc.
- Product that is processing equipment
- Supplier of raw materials that are transforming
- Failure analysis
- Corrective action taken

This type of information should be consolidated into daily, weekly, and monthly reports to define the priorities for maintenance. The analysis of information should lead to the formulation of actions to prevent recurrence. Using layering techniques, the main problems facing the plant can be analyzed in detail. Stratification can identify what type of materials, raw materials, or machinery suppliers have the greater number of failures, in what turn, and what operator is responsible for operation.

The data mining process is complex and beyond the traditional functions of CMMS. It involves data from other departments and can find a huge plurality of relationships and dependencies.

5.9.4 Using the Pareto Principle for Failure Reporting

Within the troubleshooting phase, it is necessary to identify causes and corrective actions. It is recommended to start the analysis with the construction of a Pareto family grouping by repetitive failures, type of equipment, plant areas, etc. This diagram allows us to select the normal failures and eliminate extrinsic failures and to correct them if possible, but it is not used in reliability studies. It is a rudimentary but useful graphical indicator to purge a large number of work orders and reduce system analysis to a manageable amount of data (Figure 5.15).

Three simultaneous graphics are used to facilitate analysis:

- Pareto diagram by failure family (n)
- Intervention length Pareto diagram (t)
- Product Pareto diagram ($n*t$)

The graph $n*t$ is an availability indicator; it shows how much time is lost by failure type or class. This is the most important graph to select the most critical malfunctions from the viewpoint of stops due to failures.

The graph n allows us to identify the elements or components that require corrective actions in their design, more frequent rigorous inspection and other preventive actions.

Graphic t allows us to analyze the intervention time or maintainability. This Pareto graph can suggest corrective actions for parts supply, workshop repairs, improved assembly methods, or procedures to improve times.

5.9.5 Quantitative Registries: MTBF Board

One of the most useful indicators for the study of equipment behavior is MTBF; it allows us to evaluate the effectiveness and efficiency of preventive maintenance. With this indicator, we can perform studies to improve reliability and maintainability. To prepare this indicator, we need information on interventions, used spare parts, times, etc.

Without this information, the diagnosis becomes more complex, and we may not identify the causes of the problem. Japanese companies frequently use the MTBF table of analysis

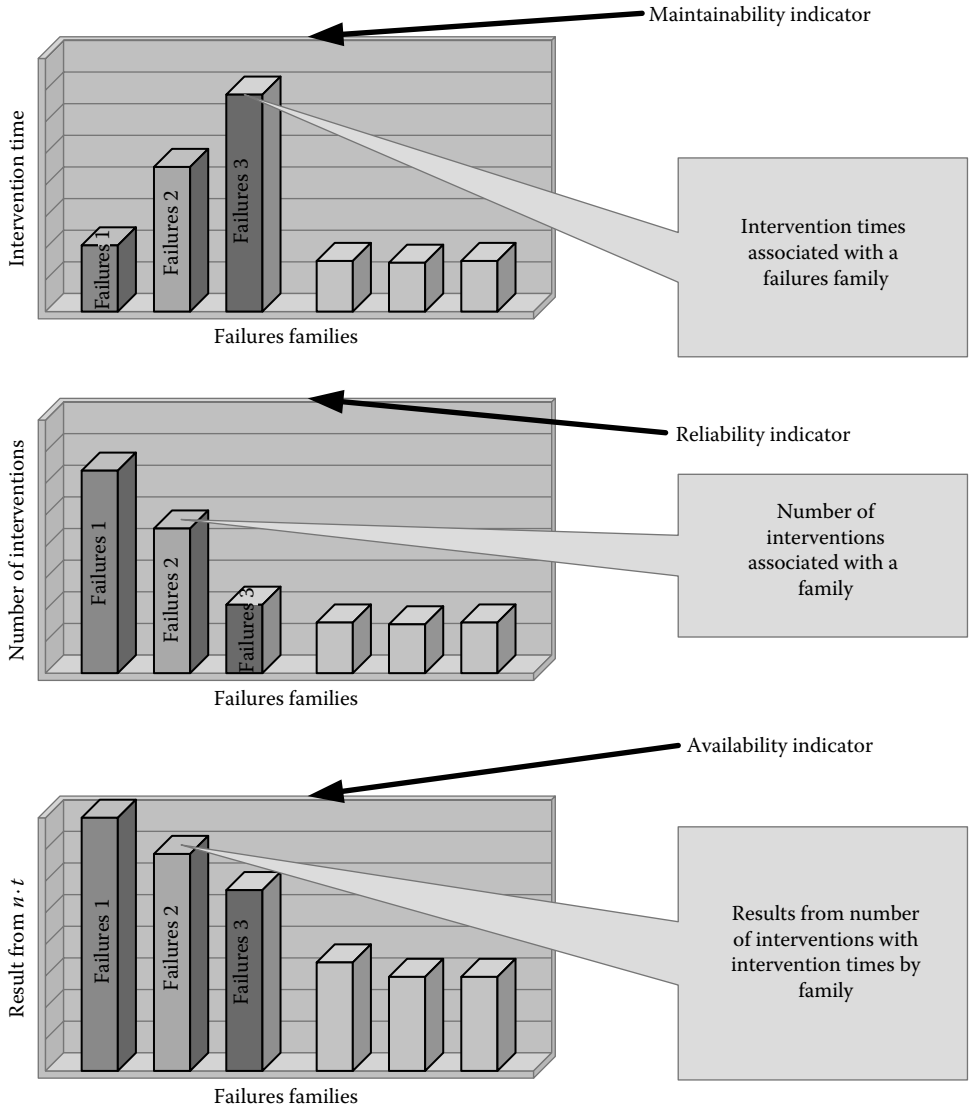

FIGURE 5.15
Using the Pareto principle for failure reporting.

(Figure 5.16) as a departure point to identify the present condition of the equipment of a plant. Such tables are visual systems of control where the activities of planned maintenance, unplanned shutdowns, lubrication, cleaning, and activities related to the care of the equipment are registered. Depending on the facility, these boards are located in visible places so that they can be observed by all the workers. UNE EN 13460:2003 [355] stresses the use of public graphs of control for the MTBF and MTTR of critical machines.

This board is used to

- Select the areas of improvement and reduce maintenance exigencies
- Consider the period of useful life of the asset and used spare parts

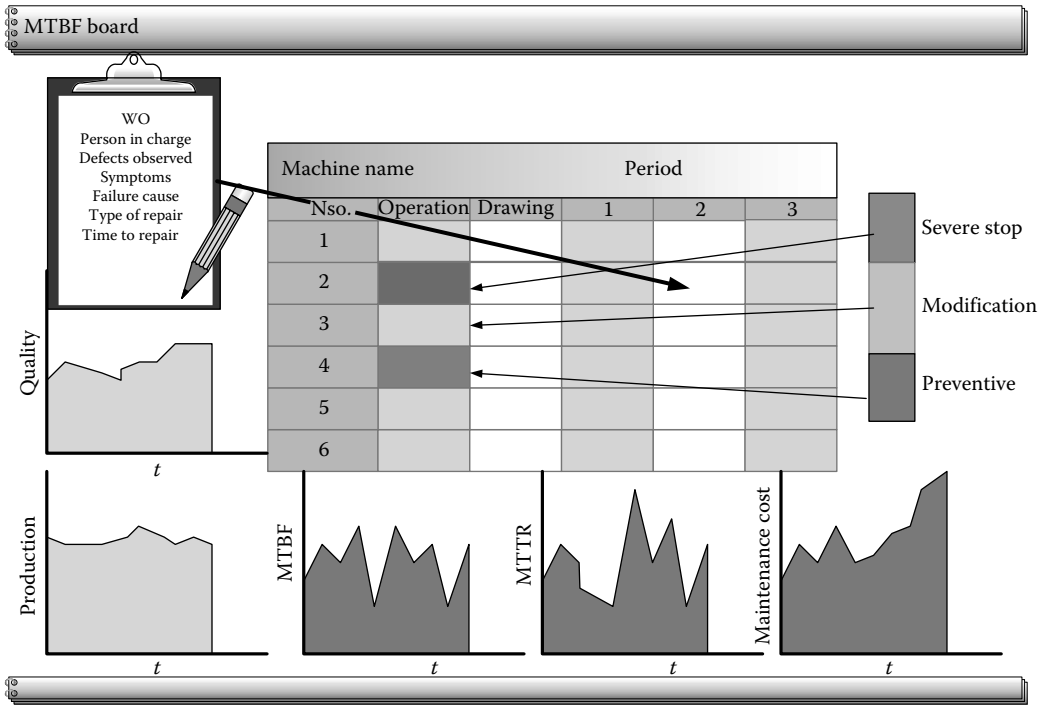

FIGURE 5.16
Board of MTBF analysis.

- Select the points of interest for inspection, along with the determination and modification of inspection standards
- Select possible maintenance to be performed by external personnel
- Show remedial actions have had an effect
- Motivate personnel in the work area

In this table, the index (MTBF) is quickly calculated following the equation:

$$\text{MTBF} = \frac{\text{Operational interval}}{\text{Number of failures in that period}}$$

This form of calculation is not exact; it does not show the variability or dispersion of the individual data. Nevertheless, it can be considered a valuable reference. A calculation method that avoids errors uses a Weibull distribution, but as noted earlier, this distribution requires an advanced statistical treatment through graphical methods or computer science systems.

The MTBF table of analysis must fulfill the following:

1. Data must be easy to interpret and organized on a page. The investigation of historical data is often difficult in companies, but showing all the relevant information on a single page allows the company to observe the behavior of a production line and/or equipment.

2. The data must be taken as a continuous time series to facilitate the analysis of the particular behavior of a certain component or part, the type of remedial actions taken and their effect, as well as the frequency of successive shutdowns or failures.
3. The records of maintenance and the analysis of the benefit of the goals must be performed simultaneously. The maintenance data include information on the extension of the intervals of shutdowns for any component.
4. When a failure occurs, remedial actions should be based on the analysis of similar past experiences. A monthly report of failures will not suffice as it will not include information on failures older than a month. Therefore, the maintenance function must preserve such information.
5. With an adapted design, more information can be registered on a board.
6. The table should facilitate the concentration of maintenance actions. Maintenance reports usually do not indicate where maintenance efforts should be concentrated. Diagrams, symbols, and other markings can highlight critical problems and/or where more failures occur.
7. The table should show the effects of corrective actions. The measures taken for equipment failures are not readily observable. We generally need to wait several weeks, even months, to see the effect of an intervention. The maintainer's reports often indicate what was done, but an MTBF board analysis may indicate the circumstances of some specific measures and their overall effect. A table with this feature can be a very useful tool in understanding the equipment's overall performance.

Ultimately, this board is a rudimentary command box equipped with visual indicators aimed at operators and personnel officers. It uses a few basic indicators to show the desired objectives, becoming an easy way to indoctrinate personnel in the use of RAMS metrics and help them adopt a culture of reliability.

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6

Maintenance Indicators and Scorecard

6.1 Introduction

This chapter discusses the use of indicators for maintenance. Indicators used to support the measurement of maintenance are located within the three following pillars of maintenance:

1. RAMS parameters
2. Maintenance cost model
3. Human factor

Authors such as Wireman, Woodhouse, and Svantesson have made valuable contributions to the field of maintenance metrics, as do UNE-EN standards and SMRP, but they provide batteries of indicators and suggest contradictory approaches. Indicators should be consistent and compatible across families of indices.

The classical way to structure these indicators is perhaps too optimistic because it assumes the accuracy of the data; it also has inconsistent approaches and objectives and lacks a sense of the real purpose of measurement. The lack of vision of how maintenance supports production and the inability to transmit corporate objectives are the main shortcomings of traditional systems.

When sensors and indicators are measured, their logical grouping based on business objectives must be set within a scorecard to make these objectives understandable to all levels of the organization. This proposal follows Blanchard [29] and Kutucuoglu et al. [180]. Maintenance must go beyond the perspective of technical elements of maintaining and improving equipment to focus on the strategic objectives of the organization. The perspective of the global business unit can help integrate maintenance with production policies; one such example is total productive maintenance (TPM); see Nakajima [234].

A balanced scorecard or an integral scorecard is composed of indicators reflecting the organization's overall objectives for maintenance in each of the following areas:

- Client perspective
- Financial perspective
- Internal processes perspective
- Learning and growth perspective

The achievement of the corporate objectives in maintaining each of the four perspectives is measured at every level of the organization using a small number of indicators.

The chapter describes maintenance indicators, their qualities, and the current regulations, analyzing them through the perspective of a balanced scorecard of maintenance.

It explains the use of a hierarchical balanced scorecard as an integrative tool for measuring the performance of the maintenance department and helping it take the strategic line chosen by the management.

Finally, the chapter analyzes the traditionally most commonly used indicators. These are ranked by the method of calculation, document management, and the knowledge needed to control them. The chapter then selects indicators to be incorporated into a scorecard. To create a good scorecard, we must meet three basic requirements:

1. We must establish indicators for everything that can be measured.
2. We cannot use indicators whose objectives may be in conflict, even though their objectives are good for the organization.
3. The indicators must reflect their owners and users, avoiding confusion about objectives and making sure they are applicable.

6.2 Management Indicators

6.2.1 Managerial Indicators

All activities can be measured if they focus on decision-making to monitor management. This ensures that the activities are applicable and allows us to search for signals as to whether the management is meeting its objectives, goals, and responsibilities. The signals are known as management indicators. An indicator, as discussed in the previous chapters, is the quantitative expression of the behavior and performance of a process whose magnitude, when compared to a reference level, may signal a deviation requiring corrective or preventive actions.

To work with maintenance indicators, we must establish a system running from the correct understanding of the facts and figures to making sound decisions to maintain and improve the process.

The concept of management indicators began with the philosophy of "total quality" created in the United States and applied in Japan to measure the efficiency of implementations of TPM. According to Yamashina [381], the implementation of TPM changed the minds of operators and created a mix of production and maintenance. The need to measure intangibles associated with hours of training, increased responsibility for equipment, and improvements thereon led to the development of a set of indicators for maintenance.

Establishing a system of indicators should involve both operational and administrative processes in an organization. Indicators should be derived from performance agreements based on the mission and strategic objectives. However, the indicators alone have reduced validity; their validity lies in the conceptual framework of the scorecard in which they are inserted.

Basically, an indicator is a measure of the status of a process or event at a given time. The indicators together can provide a picture of the process status, the business status, the machine status, or the production availability of a factory.

If they are employed in a timely manner and continually updated, indicators allow control over a given situation; it is possible to predict and act based on positive or negative trends in the overall performance.

Indicators are a key form of feedback; they monitor the progress or the execution of a project. Through the use of indicators, an organization can visualize how well the objectives of the maintenance department are aligned with the strategic plans of the organization.

Response time to find the indicators should be quick so that corrective actions can be made in a timely manner. Some indicators trigger immediate responses, while others are medium-term action indicators.

In fact, it is not necessary to continuously monitor all indicators; only the key indicators need be monitored. As mentioned previously and proposed by most authors, a scorecard can measure the overall performance of the department and should receive the highest priority. The number of indicators may be higher or lower, depending on the type of business, its specific needs, or other factors, but the aspects mentioned previously will always be considered.

6.2.2 Benefits of Management Indicators

- *Client satisfaction*: Identifying priorities for a company sets the standard in performance. To the extent that client satisfaction is a priority, the company will inform its staff and link strategies with management indicators so that staff will be alerted and the desired results achieved. It is important for the maintenance department to identify its customers and understand their demands.
- *Monitored process*: Continuous improvement is possible only if there are solid links in the chain comprising the process to be tracked. The measurements are the basic tools to identify opportunities for improvement and to implement the proper actions.
- *Benchmarking*: If an organization seeks to improve its processes, it should understand the overall environment, not just its own inner workings. One way is through benchmarking to evaluate products, processes, and activities and compare them with those of another company. According to Camp [37], it helps to know the best practices of others; comparing different companies will yield more immediate results. This is easier if indicators are used as reference. For maintenance, given the absence of relevant information sources, benchmarking has become a main source of objective performance appraisal.
- *Human factor*: A suitable measurement system of the human factor allows people to know their contribution to organizational goals and to understand what results will support good performance. As mentioned, the human factor is considered one of the three pillars on which the system of indicators is built; it plays a main role in any analysis of the causes of failure of any implementations. Here, staff motivation is essential.

6.2.3 Management Indicators' Features

Management indicators must meet certain requirements and have certain elements to support the management in achieving the objectives:

- *Simplicity*: The ability to define the event to be measured with an inexpensive use of time and resources.
- *Adequacy*: The ease of the measurement to fully describe the phenomenon or effect; it should reflect the magnitude of the event analyzed and indicate the actual deviation from the desired level.
- *Validity in time*: The property of being valid for a desired period.

- *User involvement*: The ability to be involved from the design of the metrics, as well as providing tools and training necessary for execution. This is perhaps the key ingredient in motivating personnel to implement the indicators.
- *Utility*: The possibility of the indicator finding the causes of a particular value and effecting improvement.
- *Opportunity*: The ability for data to be collected on time; the information must also be analyzed quickly to take action.
- *Perception*: The subjective impression that alerts the indicator. We must shun measures that reflect failures, accidents, and so on as negative indicators are a constant reminder of the poor quality of work performed.

Peters and Waterman [265] discuss the behavior change in employees during the measurement process. How operators work to change the values of indicators depends on how the process is introduced. Everyone notices a number that measures performance, and operators will immediately react. Therefore, some authors, such as Rolstadås [288], suggest attaching conceptual characteristics to each indicator, that is, the object for which it has been setup. These objectives include the following:

- Support decision-making
- Evaluate performance of equipment or individuals
- Diagnose problem situations
- Perform benchmarking

6.2.4 Management Indicators and Strategic Planning

Management indicators are a manifestation of the strategic objectives or the mission of an organization. For these indicators, it is necessary to integrate operational and strategic business results as they are relevant to maintenance. They should also reflect the corporate strategy to all employees. Therefore, we suggest the use of integrated indicators in a balanced scorecard as well as a hierarchy of indices.

De Wit and Meyer [69] note that most companies have well-defined strategies for their sales policies, their customer service, their fees, and their vision as is expressed to shareholders or competitors. Yet, it is equally important to have a scorecard for processes falling below sales and customer service in the organizational hierarchy as all factors contribute to success. These should be monitored with an appropriate set of indicators. Hill [121] says it is essential to align the strategy of sales and production with the company's overall goals. Otherwise, indicators may be contradictory and objectives may be conflictual. Once sales policies and production are aligned, Wilson [373] suggests that a specific maintenance strategy must be designed to support both production and the corporate objectives of the company.

6.2.5 Elements of Management Indicators

- *Definition of indicator*: An expression that quantifies the status of the features or facts we want to be controlled.
- *Objective of indicator*: The objective is the purpose of the selected indicator. The goal is improvement; actions to achieve improvement may include maximize,

minimize, delete, and so on. The objectives permit the maintenance department to select and combine preventive and corrective actions in one direction.

- *Use of benchmarks*: The act of measuring is done through comparison; this is not possible if we do not have a baseline to compare the value of an indicator.

The following benchmarks are commonly used.

6.2.5.1 Historical Value

- Historical value shows trends over time.
- It allows designing and calculating expected values for the period.
- It indicates the variation of results showing whether the process is or has been controlled.
- It indicates what has been done but does not indicate the achievable potential.

6.2.5.2 Standard Value

- The standard value indicates the potential of a given system.

6.2.5.3 Theoretical Value

- Also called design, it is mainly used as reference indicators related to machinery and equipment capabilities in production, material consumption, and expected failures.
- It is frequently given by the equipment manufacturer.

6.2.5.4 User Value

This represents the value to customers within a given time.

6.2.5.5 Competition Value

Reference values from competition (i.e., by benchmarking): the comparison only points to where and how quickly a company must improve, saying nothing about the effort.

6.2.5.6 Corporate Policy Value

Depending on its objectives, the company must set an overall policy for competition values and user values. There is no single way to estimate risks; strengths and weaknesses are evaluated, and a policy is set.

Unfortunately, maintenance often lacks data. Historical data are not reliable; theoretical values or standards are not stored; and in the case of old machinery, the manufacturer ignores the evolution of equipment performance over time. Therefore, we usually rely on users to know the demand made on the equipment and on officials and experienced maintenance technicians for information. Based on experience and with adequate benchmarking, common maintenance personnel are able to set more realistic values of reference in the equipment; their involvement, in turn, ensures the success of the measurement system.

6.2.5.7 Determining Values Based on Experience

When we do not have information showing the historical values of an indicator and cannot count on studies of standard values to determine user requirements or competition, a quick way to obtain reference levels is going to the accumulated experience of the group involved in the specific tasks.

6.2.5.8 Responsibility

The responsibility for providing accurate information is one of the most complex tasks in the system. A lack of confidence in the information gathered is one of the main reasons why managers are wary of indicators extracted from this information; this generates distrust in the whole system.

6.2.5.9 Measurement Points

We must define the way to obtain and create data, identifying the sites and times where measurements should be made and determining how to make the measurements, who does the readings, and what the procedure is to obtain samples. This allows us to establish guidelines for accuracy, timeliness, and reliability.

6.2.5.10 Frequency

We must define the period for the measurement and decide how to present the data when performing specific readings and finding specific averages. The periodicity of maintenance measures is vastly different; some may be every few seconds, while others are bimonthly or semiannually. In addition, there may be different users and scorecards for different levels of the hierarchy. Nevertheless, maintenance performance indicators have many characteristics in common and pursue the purpose expressed in the strategic plan of the organization.

6.2.5.11 Processing System and Decision-Making

The information system, usually computerized maintenance management system (CMMS), must ensure the data obtained from the collection of historical readings are adequately presented and correctly used when making decisions; see Labib [181].

A report must contain not only the current value of the indicator but it must also reflect the reference level. We must distinguish between users who are presented with the results in order to capture only those indicators relevant to the recipient and not overwhelm users with excessive or superfluous information.

Condition-based maintenance (CBM) indicators should be structured in such a way that information must rise to the correct hierarchical levels. The debugging of technical information and its extraction for cause–effect analysis is a fundamental task of indicators.

6.2.6 Types of Indicators

There are different classifications of indicators, depending on the author (see, e.g., López and Gadea [194], Douwe et al. [76], etc.). Classifications noted by most authors are the following.

6.2.6.1 Operational Performance Indicators

These relate investment with production, giving an idea of what to expect for a particular set of resources, or, alternatively, what resources are needed to produce certain amounts with certain quality levels, opportunity, and so on. Productivity indicators are indicators of return on investment in business. They give an idea of how much can be produced from a given set of investment resources.

6.2.6.2 Effectiveness Indicators

These indicators relate production to use. When effectiveness is evaluated, the performance of a service or product is analyzed from the perspective of its users.

6.2.6.3 Cost-Effectiveness Indicators

Cost-effective indicators relate use to investment. These indices connect customer feedback on the performance of the service or product (i.e., effectiveness) with the resource costs of providing that product or service.

6.2.6.4 Impact Indicators

This relates the use of the business, its services, or products with its potential use. Such indicators help to answer the question: Is the business achieving what it set out to achieve?

6.2.7 Indicator Selection

It is important to adjust the set of indicators for each process so that each is aligned with its respective business unit and, therefore, with the mission of the organization, to ensure effectiveness. Martorell et al. [202] and Kaplan and Norton [154] agree that performance indicators should be aligned with corporate objectives. But as will be seen later, other qualities are also important, such as the number of indicators, the ease of the process, and the rejection or acceptance by end users.

Some indicators monitored in a company are limited to a specific time because they support the ultimate solution of a problem or the completion of a project, with a well-established beginning and end. When the project or problem ends, the objective is reached; the indicator may no longer be relevant and its continued monitoring is not justified. In the infancy stage of machinery, faults can cause problems; accordingly, new machines are more closely monitored (see Figure 6.1).

It is important to develop criteria for the selection of indicators to be monitored continuously. Monitoring is costly when not supported by a real benefit. Four basic questions must be answered to appraise the suitability of each indicator and to determine whether it is worth investing the resources required for its implementation:

- Is it easy to measure?
- Does it measure quickly?
- Does it provide relevant information expressed in a simple way?
- Is it easily plotted?

	Review	Approach	Purpose
Strategic planning	Global organizational performance	Long-term	Scope of the vision and mission of the organization
Functional planning	Performance of functional areas	Short- and medium-term	Support functional areas to achieve the strategic goals of the organization
Operational planning	Individual performance of employees, equipment, products, services, and processes	Daily (weekly, daily, hours)	Aligning the performance of employees and equipment with the goals of the organization and functional areas

FIGURE 6.1
Dimensions of Management Indicators.

These questions will provide information on whether the selected indicators have the following characteristics, as suggested by López [193], Burcher and Stevens [34], and Miller [217]:

- *Relevance*: The indicator is suitable for what we want to measure.
- *Objectivity*: The indicator lacks ambiguity.
- *Univocal*: Changes expressed by the indicator do not allow misinterpretation.
- *Sensitivity*: The indicator identifies small variations.
- *Accuracy*: The margin of error is sufficiently acceptable.
- *Fidelity*: Indicator qualities are maintained over time.
- *Accessibility*: Measurement has an acceptable cost and results are easy to interpret and calculate.

If the indicator meets these requirements, it is appropriate. These questions obviously must be asked at different hierarchical levels, especially the first question on relevance. Crucial data for a mid-level technician or even the maintenance manager may not be relevant to the CEO.

Since a picture is worth a thousand words, the indicators should be set by creating a simple chart, reflecting the starting value and the goal to achieve, the historical evolution of the index, and a breakdown of progress in the various periods.

But as discussed previously, a goal may not be achieved if the process lacks input from those who are responsible. Each indicator should be complemented by an action plan that includes the following activities:

- Development of preconceived actions
- Investment in structures and equipment
- Staff training and awareness

- Implementation of participatory groups to suggest improvement
- Redesign of operations by relevant groups
- Provision of outside technical assistance

Remember that any management system should measure the degree of compliance with the planned objectives for a given period and detect certain trends over that period in order to evaluate the goals achieved, to make the necessary corrections, or to counter detected deviations. It is important to know the impact of delays when new methodologies or technologies are being implemented. Emiliani [92] emphasizes that TPM implementations or training activities can have a delayed impact of 5 years before results or changes in trends are seen.

The need to measure the degree of compliance with the goals and the extent to which the objectives are achieved suggests the use of performance indicators. Sumanth [311] defines efficiency as the "proportion of the generated results related to the prescribed results." These indicators will obtain information on the degree to which goals are achieved (technical achievement, efficiency, etc.) and whether their cost is within the organization's estimation of resource consumption.

The most appropriate indicators must reflect the following aspects:

- The organization's characteristics
- The ability of the management level to use the information
- The breadth of information according to the hierarchical level for which it is intended
- The ability of the factors influencing the target to be measured
- The ability to identify trends

The measurement of objectives is not limited to identifying and understanding the values reflected in the system indicators. We must also establish what factors have influenced the results measured by each indicator; that is, if a company has set unavailability (downtime) for annual planned maintenance at a certain value and the figure is lower at year end, it is necessary to establish whether this was due to failure of the plan or greater efficiency in maintenance work. This suggests that, in addition to a main indicator (unavailable for planned maintenance), there must be secondary indicators explaining the reasons for the increase or decrease in value. The need to understand the trends of certain indicators of the system is also justified because they serve as tools for the analysis and forecasting of evolution and help to plan new reference values for these indicators.

To meet the needs of the management system, the following provisions are required:

- A set of key indicators to comprehensively analyze the fulfillment of the objectives set by management
- A system of secondary indicators to assess the impact of the major factors that can influence the main indicators
- A systematic method of obtaining information showing the degree of compliance of key indicators, trends in their behavior and prognosis of their evolution

6.2.8 Continuous Improvement

Continuous improvement involves creating new sets of values that improve quality and productivity over time. It is necessary for any innovation to be accompanied by feedback, to determine how the innovation can be improved, and thus to start the cycle again. This way of working requires time, however, and may not achieve short-term objectives.

Working with a continuous improvement philosophy allows improved quality, higher productivity, and equipment that will be more reliable, standardized, and competitive in the future. In maintenance, reliability improvement, through modified maintenance, is only realizable with a scorecard that allows monitoring improvements and providing appropriate feedback to the improvement team. Similarly, investment in new maintenance projects and decisions on major repairs or overhauls necessarily entail the use of indicators and an improvement cycle; see Zohrul Kabir [387].

The use of an improvement cycle in a maintenance scorecard achieves a reduction in the following:

- Inventories
- Response times
- Maintenance costs per produced unit
- Redesign time, improvements for standardization, and defined processes
- Space and energy required

In short, continuous improvement is a journey toward excellence; this, in turn, ensures the survival of enterprises on a general level and the fulfillment of objectives in such departments as maintenance, when applied to that department's internal processes, on a more specific level. The continuous and systematic application of the Plan Do Check Act (PDCA) cycle, explained in the following, allows higher levels of performance through the rational use of indicators. In maintenance, indicators measuring performance lead to improvements in the department's effectiveness and efficiency; therefore, the use of maintenance indices is linked to the cycle of continuous improvement.

Continuous improvement based on the PDCA cycle is outlined in Figure 6.2.

The PDCA model helps a company or a department to adopt and monitor processes, as long as these are endless processes, that is, an action is planned, the action is taken, results are checked, and results are acted upon to restart the process.

The PDCA creates a dynamic relationship between people and processes based on the establishment, maintenance, and improvement of performance indicators, a task accomplished by defining project specifications, the process's technical specifications, and operating procedures.

Using PDCA, maintenance management takes the following steps:

- *PLAN*: The goal is defined, along with the methods to establish appropriate performance indicators.
- *DO*: The task is executed and data are collected, but not before going through a training process.
- *CHECK*: The results of the executed task and measurements are evaluated, problems resulting from noncompliance with the tasks are identified, and deviations in the indicators are observed.
- *ACT*: Based on the evaluation, actions are taken to achieve compliance with the goals and return the indicators to normal values.

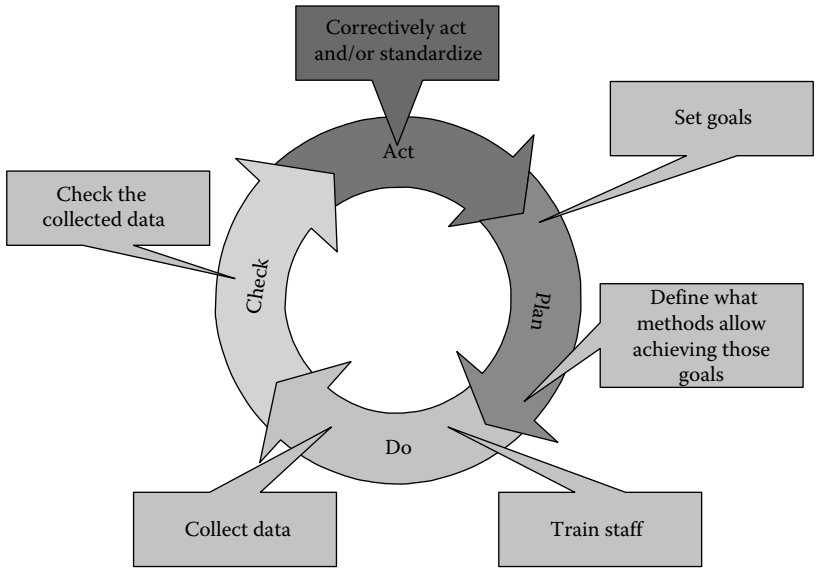


FIGURE 6.2
PDCA cycle.

6.2.9 Balanced Scorecard and Balance in Management Indicators

Given the complexity of analysis and synthesis, especially addressing the problems of the company as a set of interrelated subsystems, we need to consider models that integrate the subsystems to represent the entity as a whole and not as the sum of its parts. This concept, called "enterprise integration," facilitates the flow of materials, information, decisions, and control across the organization, linking the functions of information systems, resources, applications, and people to improve communication, cooperation, and coordination of the current subsystems, so they behave as a whole and operate in alignment with the company's strategy; see Ortiz [252]. As indicators must be able to measure integration, the balanced scorecard is specifically applicable.

The "balanced scorecard" (BSC) is a multidimensional approach to measuring the corporate performance of a company, where organizational performance is seen from four perspectives: financial, customer, internal processes, and learning and growth. Although there are four common perspectives, their usefulness in any given case depends on the type of company, circumstances, and strategic business units, among others. In most cases, the four perspectives can be expressed as the following:

1. Shareholder perspective is expressed as financial goals: profits on capital, profits over net assets, performance, and so on.
2. Customer perspective is expressed as client goals: market share, number of complaints or returns, and so on.
3. Internal company perspective or internal processes is expressed as operational process goals: order delivery time, product development cycle time, cost per production unit, and so on.
4. Learning and growth perspective is expressed as goals for learning and innovation, based on the number of trained people working period rotations, number of innovations in products or processes per year, and so on.

Applying the BSC method to the maintenance scorecard requires identifying the actors involved, that is, customers, shareholders, and so on, in order to define the relationships between them.

The maintenance function must set its management systems and measurement within its strategies and capabilities. Unfortunately, while many companies have clear strategies on relationships with customers, competition, and organizational strengths, they measure staff performance only with financial indicators. The BSC and management indicators consider the financial perspective as a critical point of organizational performance and business, but use a more comprehensive and integrated set of measures linking the current customer, internal processes, and employees, with the goal of developing performance that ensures long-term success.

The set of balanced measures is a convenient way to communicate the vision and strategy of a company within a coherent set of performance measures. Measurements should also be used for the following:

- Define the strategy
- Communicate strategy
- Ensure the employees and the organization work toward a common goal

In general, BSC is used as a communication system (information and learning) and as a control system. In the maintenance case, with a BSC, employees are involved in company strategy; they know what the company expects of the department and, in particular, of them (Figure 6.3).

The four perspectives allow a balance between short- and long-term objectives, between desired outcomes and performance drivers and catalysts of these results, and between measures of difficult objectives and measures of more easily achievable ones. Kaplan [153]

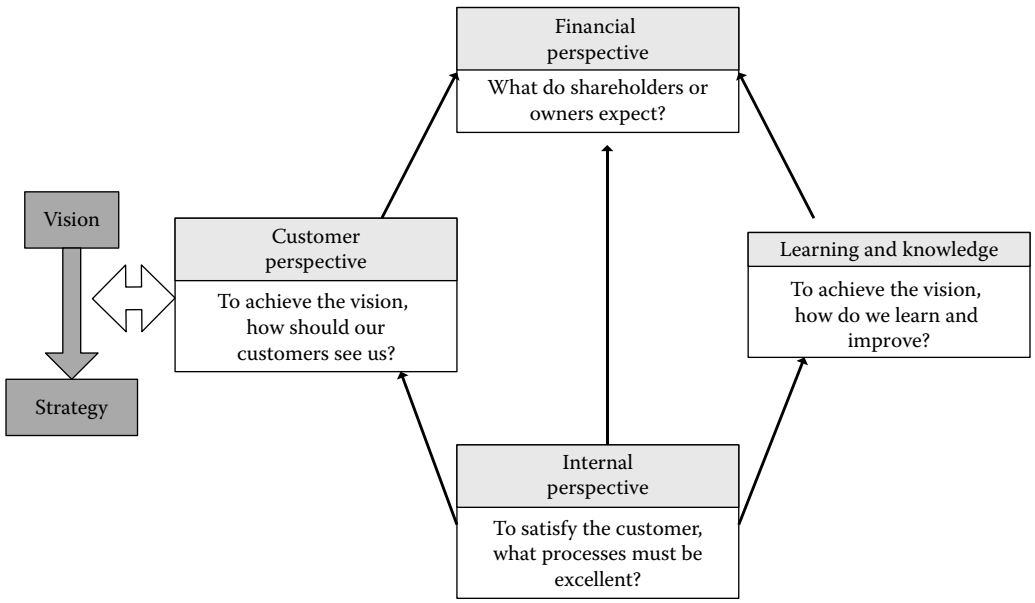


FIGURE 6.3
Balanced scorecard.

notes that long-term financial indicators show only commercial transactions and no internal conditions of the company. This biased view can be greatly expanded with the use of BSC.

6.2.10 Implementation of a System of Indicators

The procedure to set up a system of indicators in an organization is as follows:

1. Create a working group of indicators (PLAN). As discussed, the human factor is relevant, and employee participation in the generation, measurement, and valuation of indicators ensures program success.
2. Identify activities to be measured (PLAN). Multilevel composition and multidisciplinary activities are necessary for scorecards.
3. Establish a measurement procedure, including setting objective, allocating responsibilities, and preparing system administration (PLAN).
4. Carry out the process (DO).
5. Monitor the actions taken to measure results and implement corrective actions (VERIFY).
6. Increase the number of indicators by a reasonable amount (MANAGE). Indicators should be dynamic, as some may expire, while others should be adapted in their conception or measurement based on structural changes.

Any methodology that enables us to implement a system of management indicators should consider the elements associated with an indicator; it must allow proper feedback, present clear information, and be complemented by other management tools to analyze results, and establish improvement points, thus supporting previous decisions. If possible, its relationship with other indicators should be clear. Hierarchical indicators have a common base, that is, RAMS parameters constitute the upper levels, with different contributions of particular information from other levels.

The elements of any indicator are the following:

- *Objective*: Shows the improvement sought
- *Definition*: Should be simple and clear and include only one feature
- *Responsibility*: Indicates the indicator's proprietary area and the actions arising therein
- *Resources*: Personnel, instruments, software, and so on
- *Periodicity*: Indicator must accommodate variations, according to decisions on changes in it
- *Benchmark*: Can be historical data, an established standard, a client requirement, competition, or a figure agreed upon by the consensus of the working group
- *Reading points*: Should be clear when measurement will be done, that is, at the beginning (baselines), at an intermediate stage, or at the end of the process

Finally, it is relevant to know the methodological form of the maintenance function. Reliability-centered maintenance (RCM) methods have a high technical component associated with an important statistical content, but they lack the abilities and skills required

by TPM; see Solomon Associates [304]. Many of the latest methodologies have a high human factor; therefore, the content of the indicators must be shaped to measure intangibles associated with such methods. Normally, the indicators and the associated references are the result of benchmarking, not simply mathematical calculations.

6.2.11 UNE 66175:2003: Guide for the Implementation of Indicators

6.2.11.1 Justification of the Guide

Standards UNE 66175 [352] and UNE-EN 15341 [356] give information for the quality management of indicators. They do not regulate any aspect, however, and are rarely implemented in organizations. Some authors, for example, Wisner and Eakins [376], blame the low impact of these regulatory standards to the lack of attention paid to them by researchers and the general public, not to mention the authorities' lack of interest in enforcing them. These are, therefore, teaching documents. In many cases, however, they are not disseminated to users.

Although it does not deal with the criteria of the BSC defined by Kaplan and Norton and does not insist on the balanced integration of objectives, UNE 66175 [352] can be used as a guide to establish a scorecard, in particular, to define the characteristics of the indicators selected by an organization. The only bibliographical reference to a scorecard is to a French document on "tableaux de bord" and it only indirectly suggests the use of a scorecard. It designs a scheme of continuous improvement that can be assimilated with the Deming circle, using such terms as "conceptual framework" to refer to the "strategy" of the organization. For the conceptual framework, it identifies the main lines of action and the needs of the organization based on the strategy of the organization.

UNE 66174 [351] uses the following definitions:

- *Indicator*: Data or set of data that help measure objectively the evolution of a process or an activity
- *Objective*: Something striven for or an intended result

6.2.11.2 Characteristics of the Indicators

Indicators should meet the following objectives:

- Be measurable
- Be achievable
- Be coordinated
- Be challenging
- Be able to engage staff
- Be developed in action plans

The indicators must also

- Refer to important or critical processes
- Represent a direct relationship with the process
- Be quantifiable through numerical data or a classification value
- Be profitable

- Be able to define the changes over time through comparison
- Be reliable so users have confidence in their validity
- Be easy to maintain and use
- Not interfere with other indicators but remain compatible with them
- Allow information in real time

An inherent characteristic of a scorecard is the small number of indicators used; many authors suggest five, six, or eight measures, but what is more relevant, according to Ravindran et al. [277], is determining the key performance indicators (KPIs) that will model the behavior of the target system, in this case, the maintenance function. These KPIs will be sensitive to the strategies and actions of the maintenance function, reflecting positive and negative deviations.

According to Bertalanffy, following the General Theory of Systems [21], a system will have certain general principles. To see maintenance as a system, we need to know its properties as a whole system, and not just the properties of its various subsystems. As Figure 6.4 shows, the use of performance measures represents a systematic approach to the maintenance function; Miser and Quade [218].

Goals must be set at different levels to establish action plans and achieve them. The objectives will respond to the question: what should be achieved? And the action plans will respond to the question: how do we do this?

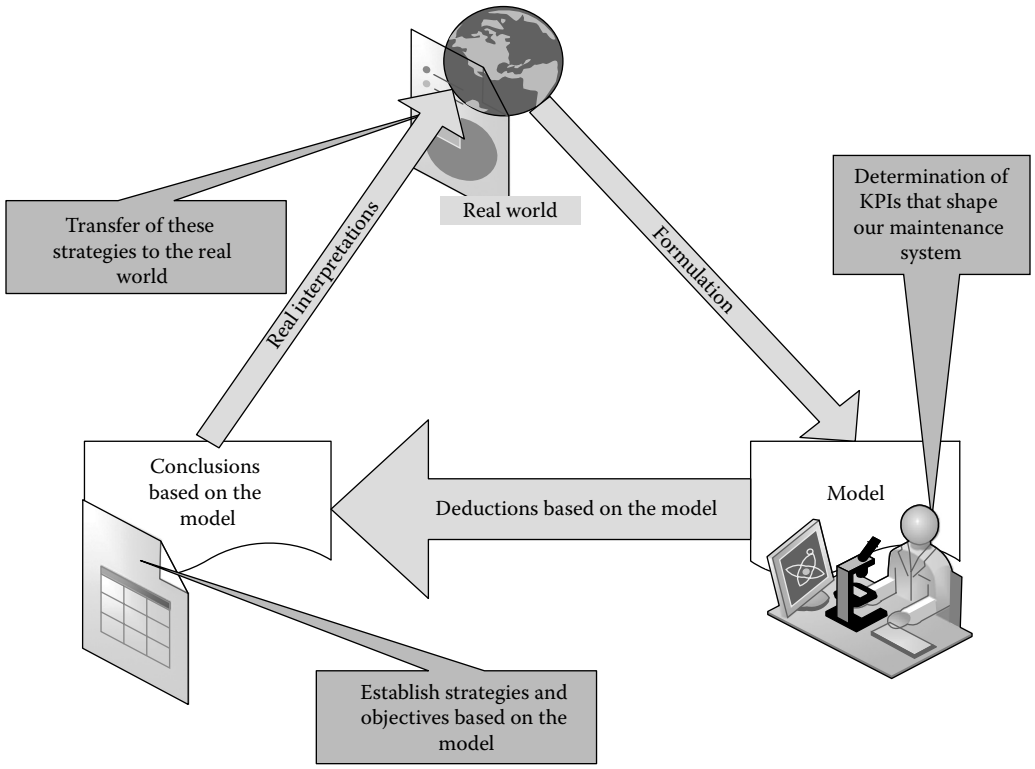


FIGURE 6.4
Model by Ravindran et al. (Adapted from Ravindran, A. et al., *Operations Research, Principles and Practice*, 2nd edn., John Wiley & Sons, New York, 1987.)

6.2.11.3 Indicator and Scorecard Design

The establishment of a scorecard will take the following sequence of steps:

1. Indicator selection
2. Name of indicator
3. Calculation form and information sources
4. Representation mode
5. Establishment of responsibilities
6. Definition of limits and tolerances

We must look for a cost-effective approach as resources are always limited in the selection of indicators. We should consider the following criteria to find the priority indicators for monitoring and decision-making; see Idhammar [127]:

- Relationship between indicators and objectives
- Evolution of critical factors in implementation of the strategy
- Situation of the organization
- Cost of resources required to establish the indicators
- Reliability of calculation of indicators
- Staff motivation

The name of the indicator should be responsive to the objectives and not lend itself to misinterpretation.

The method of calculating the indicator should clearly establish the sources used to obtain the data for computation, that is, monthly, quarterly, annually; numerical, percentage, ratio, and so on.

It is important to specify the scope of the indicator: whether it refers to all or a part, and to specify the adjustments following occasional variations in the data.

The indicators and improvements can be presented numerically or graphically.

It is advisable to define the responsibilities for gathering information, analyzing effects, and communicating results to the relevant persons.

The limits of the indicators may be represented by their minimal or maximal approximation of the parameter to be achieved, their nominal value, or their achievement of successive values over time.

An interesting finding of the top figure is the dynamic nature of the indicators, that is, the need to establish a circle of improvement. Their definition, scope, and reference values may change, or they may simply have expired. In maintenance, the use of different methodologies and technologies, along with the mixture of external and internal work, may require various adaptations of the scorecard over the lifetime of the productive assets.

6.2.11.4 Construction and Implementation of the Scorecard

A scorecard must show results that do not conform to the limits established in advance and warn about areas moving toward risk. When decisions are made, it will help to

assign responsibilities and facilitate communication between the various factors involved. Aspects to consider in the construction of a scorecard are as follows:

- Submit only the information that is necessary in a simple, effective, and summary form. A small number of indicators are suggested; for example, 25 are too many.
- Highlight what is relevant to the organization.
- Simplify representation using graphs, tables, curves, and so on.
- Unify development to facilitate finding results in specific departments.

It is necessary to involve the people affected through development training courses, communication, and motivation. Training in the objectives and the operation of the system must include an active awareness of responsibility, along with the design and implementation of the system, the exploitation of the information, and subsequent improvements. It should offer information about the actions that must be performed by the staff to prevent or correct deviations and keep indicators at planned levels. It is important to emphasize the degree of the relationship between staff activities and the results of the indicators to enhance motivation. Effective communication predisposes staff to accept the system and to become involved in its development, understanding the usefulness of their participation, and appreciating the impact of their efforts. Good communication will

- Provide information about the indicators as a tool to monitor the organization's progress, not as a disciplinary tool
- Explain how results are obtained and evaluated
- Make the indicators understandable to the personnel involved

6.2.11.5 Assessment of Indicators

Once the system is setup, we recommend validating the indicators to determine whether they are useful and profitable. To this end, a survey can collect feedback from users in the following areas:

- Usefulness of the indicator in decision-making
- Links with the objective
- Compatibility with the rest of the indicators
- Cost of collecting and developing information
- Reliability of data in relation to time
- Clarity of representation
- Possible redundancy with other operators
- Adequacy of the established frequency
- Simplicity in obtaining the information
- Leveraging of computer media
- Ideal disclosure of the results

We strongly recommend validating the whole scorecard in the following aspects:

- Link between the scorecard and an overview of the global process
- Ability of the scorecard to highlight critical aspects of the process
- Clear appreciation of the differences between results obtained and programmed
- Utility of the scorecard for decision-making
- Profitability of the scorecard

The validation of indicators should be continued over time to confirm that they remain relevant and meet the defined objectives. However, using surveys for validation may not be useful given the emotions often reflected in the answers.

An indicator can lose its validity when the organization has defined new objectives, changed the circumstances and expectations, or changed the customer. As in other processes, the system of indicators and the scorecard must undergo a process of continuous improvement, maintaining, modifying, and deleting indicators or creating new ones, when the circumstances warrant, using a methodology similar to other improvement actions in the organization's management system; the steps are plotted in Figure 6.5.

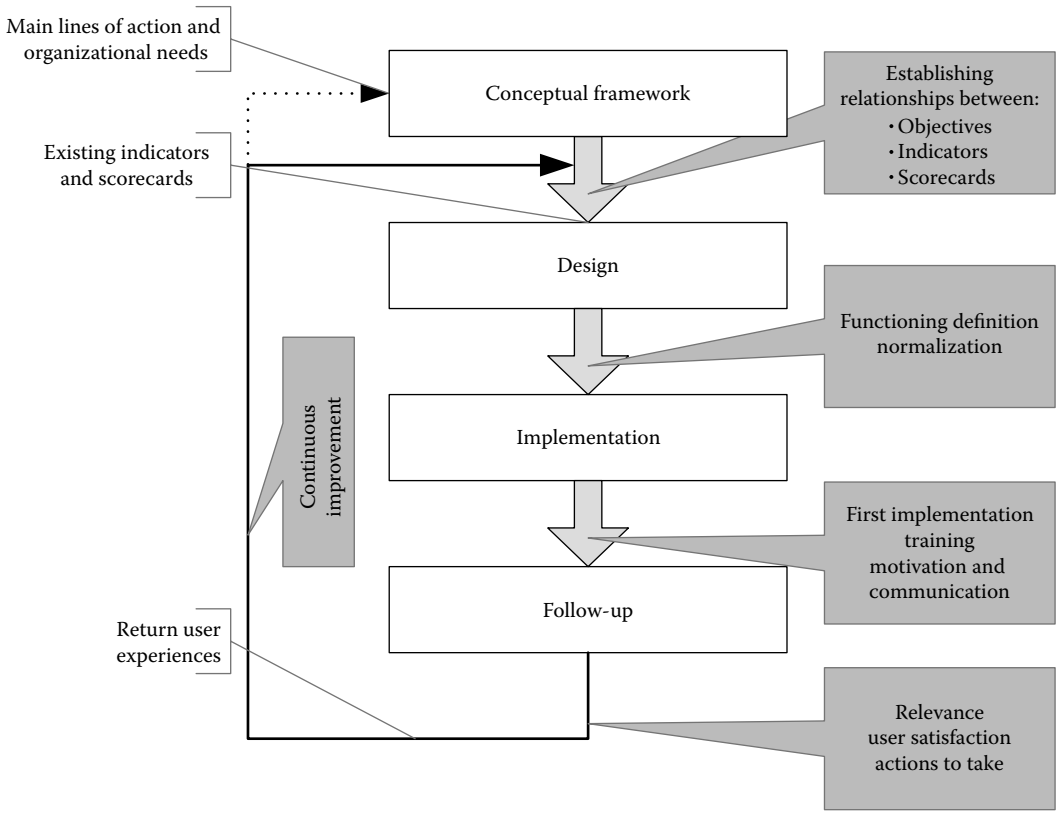


FIGURE 6.5
Life cycle of indicators and scorecards according to UNE 66175. (Adapted from UNE 66175:2003, Sistemas de gestión de la calidad. Guía para la implantación de sistemas de indicadores, AENOR, Madrid, Spain.)

To conclude, the rules suggested in the standard are valid for an individual assessment of indicators across the various periods of their lives. It is worth noting, however, that it makes only a peripheral reference to maintenance in an appendix.

6.3 The Scorecard

6.3.1 Historical Background

Moving in chronological order, we first consider "traditional methods of performance measurement." This includes methods used to measure the performance of the company from a financial perspective until the end of the 1980s. The management control systems are supported almost exclusively by accounting systems, especially financial accounting, or more generally fall under budgetary control.

Over time, new financial measures have appeared. Among the most innovative according to Meyer [213] are economic added value (EAV) and shareholder value (SHV).

Another traditional measurement of the performance is the use of indicators applied with a functional vision. Such measures include functional scorecards formed using templates managed by the responsible department.

Traditional methods of measurement performance have been widely criticized by a multitude of authors, for example, Alfaro et al. [5], leading to the creation of "balanced systems of performance measurement" in the late 1980s and early 1990s. This concept is understood as a homogeneous set of financial and nonfinancial measures, capable of tackling the complexity of the company from different views; it is derived from the strategy of the company, and its use can boost performance measurement from the strategic level to the operational level.

In the past 10 years, many researchers have attempted to establish balanced systems of performance measurement, with varying degrees of success. While the orientation of each may be on one specific aspect, most can be generalized to the whole field of balanced systems of performance measurement. For example, Adams [1] has created a list of the "duties" of the performance measures:

- Must be derived from the strategy
- Must be developed for activities and business processes
- Must be dynamic, keeping the same pace as changes in strategies, processes, and competitive environment
- Must be developed through teamwork

Others include "Classification of Balanced Performance Measures" by Keegan et al. [163], "Matrix of Results and Its Determinants" by Fitzgerald et al. [99], and "Pyramid of Performance" by Cross and Lynch [59].

Within this typology, researchers have paid special attention to balanced systems based on business processes. While many companies may collect performance data from functional activity units through its information system, they must also have measures for the company's business performance.

Healthy financial performance requires efficient processes offering better customer service; these must be measured to improve existing processes. Relevant research includes

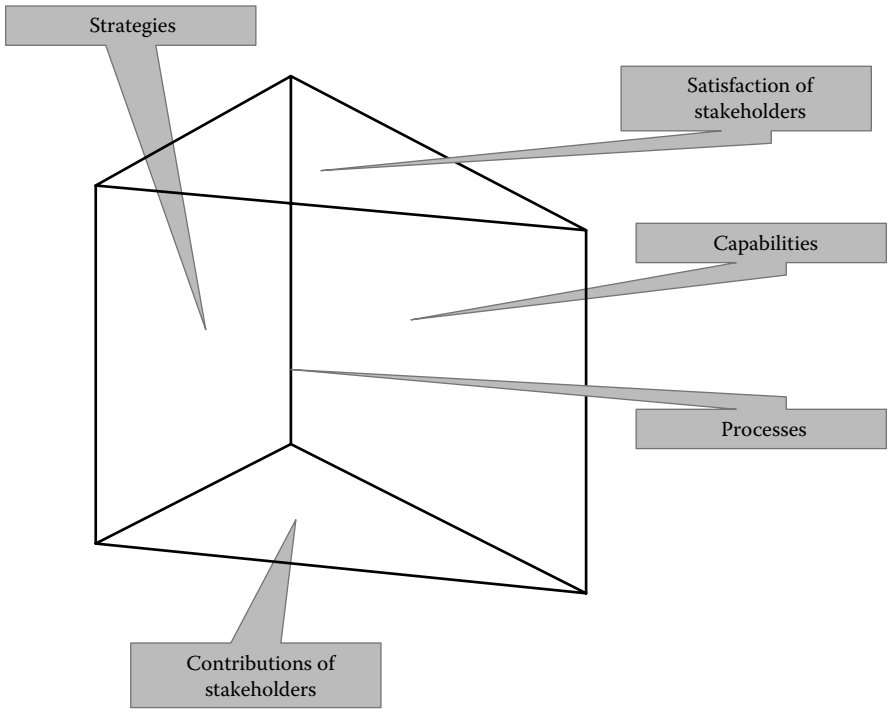


FIGURE 6.6
Performance prism.

the work on a "Matrix for Quantum Performance Measurement" by Hronec [124] and on a "Balanced Scorecard" by Kaplan and Norton [157], Bourne [30], and so on. Recent work on the "Performance Prism" by Neely and Adams [236] proposes a model with five logically interconnected perspectives (Figure 6.6).

Given the diversity of existing systems for measuring performance, it is advisable to classify them. De Toni and Tonchia [68] suggest five types of performance measurement systems. The models are characterized by three different architectural or structural connotations: vertical, balanced (Table 6.1), and horizontal (or processes). The following list briefly describes each type:

- *Strictly hierarchical models* (*vertical*): Characterized by results based on cost and other no-cost income results at different levels of aggregation; these are translated into economic or financial formats.

TABLE 6.1

Classification of Measurement Systems according to De Toni and Tonchia

Vertical architecture	Strictly hierarchical models				
Balanced architecture		Balanced scorecard models	"Frustrum" models	Models with internal and external performance	
Horizontal architecture					Models relating to the value chain

Source: Adapted from De Toni, A. and Tonchia, S., *Int. J. Oper. Prod. Manage.*, 21(1/2), 46, 2001.

- *Scorecards or dashboard models*: Have several possible (separate) results corresponding to various perspectives.
- "*Frustum*" *models*: There is a low-level measurement synthesis of aggregate indicators, but without the goal of translating no-cost results into financial ones.
- Models distinguishing between internal and external yields, with the latter being directly perceived by customers.
- Models related to the value chain. These models also consider the internal relations of customers/suppliers.

6.3.2 The Balanced Scorecard

In the January/February 1992 edition of the *Harvard Business Review*, Professor Robert S. Kaplan of Harvard University and David P. Norton, a Boston business consultant, published "The Balanced Scorecard." The article formalizes the earlier work of Professor Kaplan on the measurement of organizational performance and translates it into a BSC.

Looking at the industrial sector, they draw on management reports to summarize indicators in order to quickly identify the functioning level of an organization or department. A quick reading will give a general idea of the level of achievement of the objectives. We suggest this can be expanded to include the management of maintenance. A BSC is a suitable framework to establish indicators, determine their hierarchy, and adapt company policies to maintenance.

The scorecards used so far indicate the level reached in the attainment of objectives, usually financial, reflecting the prevailing model of management; they have remained unchanged even though the management of organizations has significantly changed its strategic vision in recent years.

To this point, even though management criteria, such as those provided by the EFQM excellence model, are considered, they are isolated and independently managed to measure technical and economic aspects of the company. Consequently, the set of indicators is neither comprehensive nor interrelated. Each set of objectives is managed by different management elements and other functional and hierarchical levels, creating the impression of primary and secondary objectives. In some departments, such as maintenance, this difference is highlighted by the clear division of operational and economic indicators, with the former of interest to the maintenance manager and the latter to senior management.

Few factors are as important to the activity of a company as the total measurement of results, but this is one of the weakest areas of modern business management. Observers say employers "are not aware" of what really happens in the company as they usually place more importance on the financial figures.

Robert Kaplan developed the BSC as a set of indicators covering all parameters that could measure the success of a company or department, designed in consensus with those responsible for its management. It acts as a monitoring tool, but has a strong motivational effect as well.

The BSC is a strategic tool; it can be used to further define the objectives that lead to an organization's survival and development. The greatest number of business failures do not result from a problem in defining business strategy but from difficulties in planning and implementing it. Attempts at TPM or RCM typically fail in the actual implementation; the choice made is usually technically sound but, unless it is monitored with an appropriate set of indicators and meets the specific goals of the organization, it rarely succeeds.

In fact, as Al-Najjar [6] says, performing RCM without economic indicators and obeying only functional indicators leads to a failure in the global vision of the department.

In business circles, the BSC is considered a quality management tool as it is compatible with any other model. All organizations are guided by their own objectives and associated indicators; BSC simply rearranges the choice of these objectives, integrating them in a balanced way to achieve organizational excellence and promoting effective and coherent actions.

Paragraph 3.8 of the UNE 66174 standard, November 2003 [351], "Guide for quality management system evaluation according to the UNE-EN ISO 9004:2000 standard," provides the following definition:

> Scorecard: Management tool that facilitates decision-making and collecting a coherent set of indicators that provide to senior management and to the responsible functions, a comprehensive view of the business or its responsibility area.

The information provided by the scorecard allows management teams, business units, resources, and processes to be aligned with organizational strategies. Concepts related to the strategic development of the company such as the "mission" and "vision" have not always been correctly or uniformly interpreted by managers because of their general wording. The BSC replaces or complements these concepts, giving them concrete meaning and translating them into comprehensive strategic indicators that include all ideal purposes set out in the mission.

Finally, the BSC provides organizations an essential aid in both the efficient measurement of results and the development of actions to improve them. This need for continuous improvement of the maintenance function and rapid adaptation of the BSC with its four perspectives make this tool ideal to build the basis of a measurement system, to motivate workers, to transmit the mission and vision of management to maintenance, and to achieve departmental alignment with higher objectives rarely considered in a part of the company dedicated to assets.

6.3.3 The Four Perspectives

To integrate all points of view found in the management of a company, the balanced scorecard adopts four key perspectives (Figure 6.7):

1. Financial perspective
2. Customer perspective
3. Internal process perspective
4. Learning and growth perspective

The financial perspective has traditionally used scorecards to monitor the company at the highest level. Generally speaking, management uses the language of numbers, more specifically, the economic language, while employees are more accustomed to the language of things. This principle relegates the management of nonfinancial indicators to lower levels, specifically to the corresponding level of production management.

The corresponding customer and learning perspectives have only recently been developed and are not usually integrated into higher management strategies. Similarly, companies often devote few resources to deal with clients. Many senior executives say

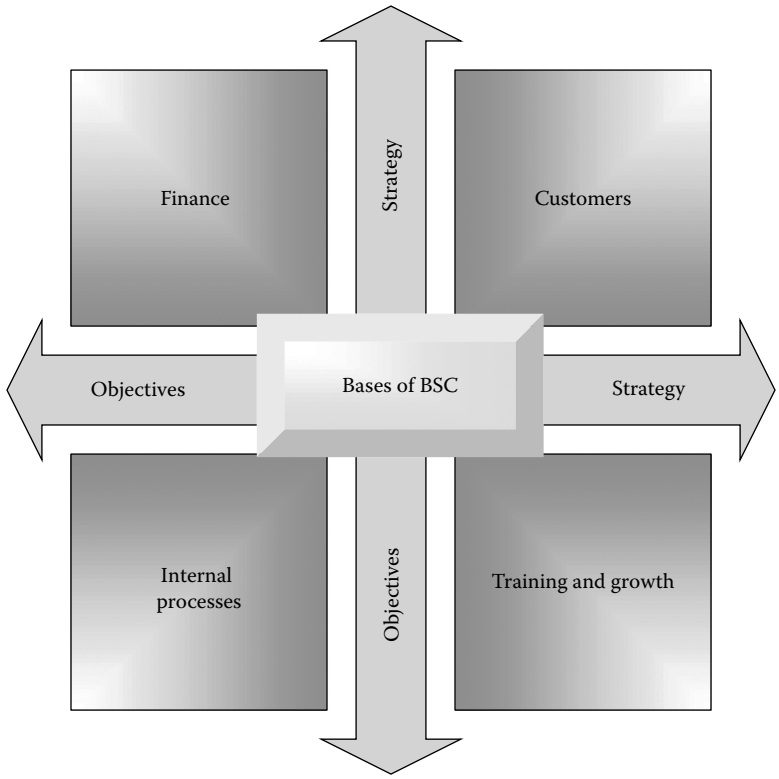


FIGURE 6.7
Interrelationship between objectives and perspectives.

they are concerned about knowledge management, but few develop tools and tactics to promote such management. The international standard ISO 9001 [360] has replaced the concept of "fulfillment of customer requirements" with "customer satisfaction," but it lacks clear references to satisfaction or employee growth.

Currently, many companies use control indicators to measure success. The results of these indicators generally reflect the consequences of much earlier decisions. The BSC, in contrast, provides strategic objectives and implements inducers to achieve them.

The four perspectives focus on the business field, but they can be modified for any type of organization or department, for example, maintenance. They must be balanced so that certain objectives of the BSC do not take precedence over others; this can lead to inaccuracies and result in counterproductive and harmful actions.

The BSC offers all employees, especially managers, accurate and adequate information about the strategy of the organization, the efficiency of production processes and service, satisfaction of employees and customers, and economic performance. Many employees, even high-level executives, have a dangerous lack of knowledge of the company's objectives; they doubt that these objectives have been determined consistently and are a result of a medium- or long-term strategy. Tsang et al. [335] warn that the need for connection between corporate strategy and performance measures should not lead to the creation of superfluous indicators, nor should their calculation consume excessive resources.

In many companies, knowledge is restricted to top managers. If an objective is communicated to the employees, the general criteria may not be concretely explained so that

objectives resemble well-meant recommendations. The measures tend to be more quantitative than qualitative, so employees may think they are doing everything they can when they are not. To remove this uncertainty, the BSC helps transform the management's good-intention statement into actions that apply to everyday work of the employee. In case of maintenance, normally the maintenance manager knows a few objectives associated with production, but nobody knows exactly what is expected of the maintenance function. The ignorance is absolute at both the supervisory and worker level.

6.3.4 Financial Perspective

Financial indicators have been used for a long time. There are economic indices on profitability, solvency, and liquidity, which can be applied to all types of companies. Two fundamental aspects can be improved, however. The first concerns the matching of indicators to the business unit, and the second is placing them within the life cycle of the company and its productive assets.

Occasionally, the same type of financial metric is applied to different business units, looking for a certain level of return on invested capital and/or assuming that they yield the same percentage of added value, without considering they may have different strategies.

In addition, the life cycle of a product will include a succession of phases, each of which may require a unique strategy.

In the introduction phase, the strategy involves expending higher resources compared to results/sales. Even though this may be a period of intense growth, the production cost of each unit is high, and sometimes the performance is negative. Investment in projects is high and maintenance of equipment produces large expenses.

When a business is in the development stage, large investments are still required, not so much in development but in logistics and promotion, but sales are higher. At this point, it is necessary to determine whether spending higher resources is intended to reduce the price or increase product promotion. The goal is to produce a sustained maintenance expenditure and technologies and methodologies that maximize system availability.

In the maturity phase, a product has conquered a market and costs have continued to decline. This, therefore, is the phase of greater profitability. Sales stabilize, and after a period determined by the nature of the competition and the possibility of specialization, it is time to start thinking about renewal. At this stage, the ability to maintain optimum levels with present assets is important, so appropriate replacement or repair policies are instituted. Changing market circumstances and possible saturation may cause a decline in sales. Sales may decrease but the benefits are maintained, and no investment is required (Figure 6.8).

Clearly, for each of these phases, the economic objectives are different not only in what constitutes the return on investment but also in cash flow, working capital, and the relationship between promotion resources and increasing sales.

Visualization of the different stages of the product determines the indicators that should define company financial objectives and suggest the correct decisions for each situation. In particular, a company can estimate the stages when it should make major investments until machinery maintenance is eliminated and machines are abandoned.

The financial perspective of maintenance lies in the definition of its function: safety for staff and facilities, respect for the environment, and availability at the lowest possible cost. Briefly stated, the financial goal of maintenance is to achieve maximum plant availability at the lowest possible cost.

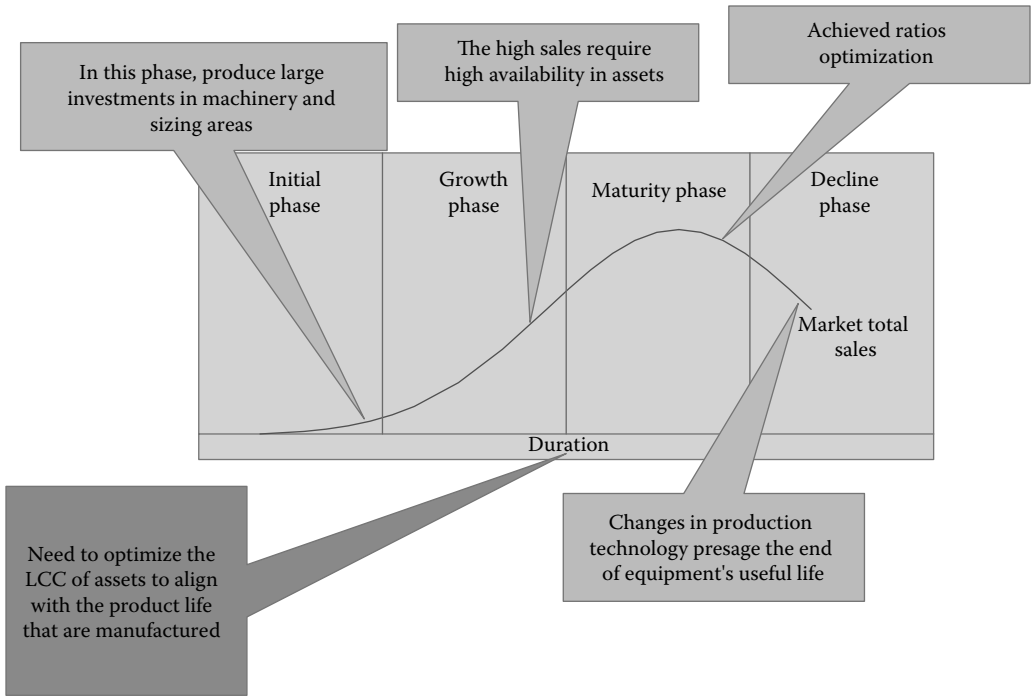


FIGURE 6.8
Product cycles.

It is common to talk about the life-cycle cost (LCC) of facilities and equipment when there is a break between the design and the operation and installation. Sherwin [294] notes a glaring flaw in the global maintenance model: performance measures and the improvements obtained from this measurement are not transferred to the design phase, so there is no complete feedback and, hence, LCC optimization is not achieved.

6.3.5 Customer Perspective

Customer satisfaction is a concept that is sufficiently developed to make it relatively easy to establish strategic objectives and appropriate indicators. The objectives should consider the following activity sequence and determinations.

Before we evaluate the achievement of customer satisfaction, we must know who the customers are, as the process of commercial product distribution involves multiple intermediaries: the distributor, the buyer or contractor, and the end user. All can be broken down into several individuals or entities. We must determine their preferences and needs and how to satisfy them. Legal and regulatory requirements, including those on competition and the environment, must be met as well.

Once we know what the customer require, we can assess whether it was possible to satisfy the proposed commercial offer, considering not only the quality and supply prices, but deadlines, packaging, delivery, advice and customer care, technical service, and documentary requirements, such as offers, delivery notes, and invoices. Even after delivery, conditions affecting satisfaction and responsibility must be satisfied, such as the

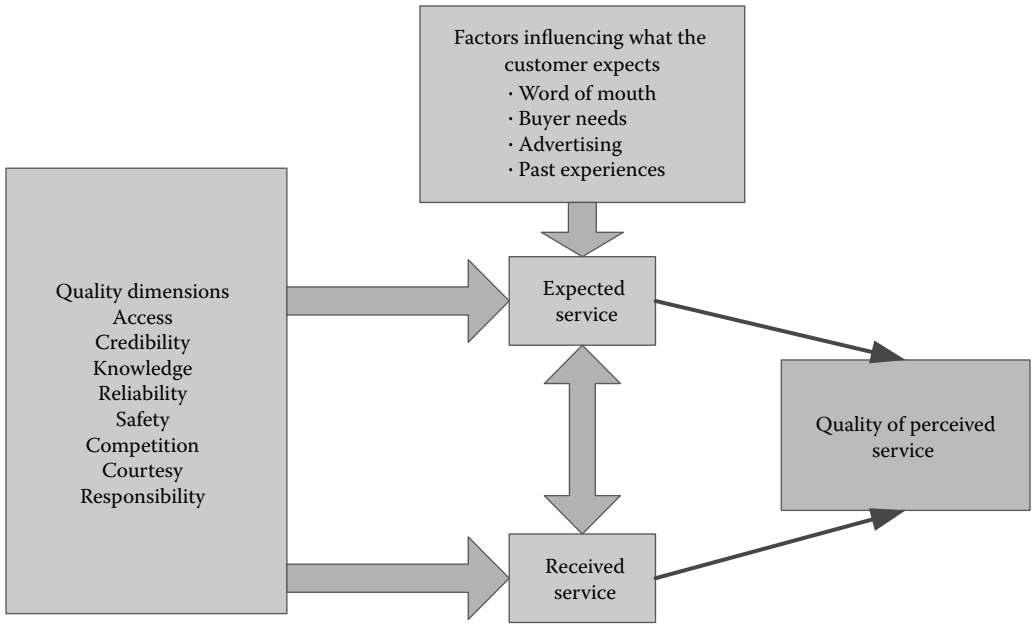


FIGURE 6.9
Factors affecting the quality of perceived service according to Kotler et al. (Adapted from Kotler, P. et al., *Principles of Marketing*, 2nd European edn., Prentice Hall Europe, London, U.K., 1999.)

duration, operating conditions, residual cost degradation, or hidden failure compensation; this lengthens the fulfillment of requirements and decisively influences the customer's decision about making a second purchase.

All the conditions described are part of quality perception, as experienced by the client, and each can result in a target, controllable by an indicator. In each case, those indicators most appropriate for inclusion must be determined if a coherent balanced scorecard is to be created (Figure 6.9).

Maintenance "customers" are the various company departments receiving its services. The production department is most affected by the service efficiency level and is the benchmark for its users. The contractors performing maintenance should also be considered "customers."

Essential points to consider are improvement in the customer satisfaction with the services provided to them, speed of services, availability of facilities, information received by maintenance, collaboration between departments, and security of facilities.

6.3.6 Internal Process Perspective

Process quality is a widely used concept but it is not always understood. For example, ISO 9001 [360] standard does not fully consider the factors influencing process quality. The quality of the process involves the quality of the product, that is, the situation giving rise to customer satisfaction. Once product quality is obtained, the remaining condition is the economy of the process, that is, the balance between effectiveness and efficiency. Once the required effectiveness is achieved, normally asset availability, the process perspective analyzes the efficiency with which such effectiveness is determined.

Therefore, process quality means the highest possible product quality and the lowest cost of the process. However, ISO 9001 [360] standard does not consider the costs.

It seems easy to explain, but the reality is complex since the concept of product quality as the cost of the process requires a comprehensive high point of view. Ben-Daya and Duffuaa [20] emphasize the need for management to understand the relationship between product quality and the maintenance performed on assets, with particular emphasis on the relationship of preventive maintenance or planned maintenance to quality and the direct impact this has on costs.

Product quality means full customer satisfaction; this requires exact compliance with the established requirements during the manufacturing process or during the provision of service. This compliance must consider the perfection of all processing operations, the provision of adequate raw materials, the choice of suitable suppliers, the proper handling of materials stored in appropriate conditions, and the use of control and operation procedures best suited for product shipment. Some authors, for example, Bester [22], have proposed models maximizing the quality of the finished product by optimizing maintenance costs.

Concepts such as research and innovation, the use of relevant technology, process repeatability and traceability of materials, and precise and calibrated control systems should not be forgotten.

When considering the cost of the processes in their entirety, the difficulty (even the impossibility) of establishing the minimum cost of operation, which logically should approach zero, must be kept in mind. Therefore, BSC indicators should be kept under constant review to take advantage of improvements in the processes of continuous improvement and technological advances. In the process cost, the major influencing parameters include rework or rejections caused by operating errors, machine breakdowns and imbalances in the plant caused by improper maintenance, transport problems, handling and unnecessary storage, loss of staff or machine time, waiting times (the difference between processing time and effective production time), and lack of order and cleanliness; other things often overlooked by managers include occupational accidents, occupational diseases, environmental pollution, and other damage to the environment.

Included in this perspective are systems the department uses to manage, organize, implement, and monitor its activity, that is, everything answering the questions: what is done, how it is done, when it is done, where it is made, what is its reliability, how much it does, and how it controls what is done.

How the various activities included in this perspective are organized will affect the balance between the effectiveness and efficiency of the maintenance function and the extent of adherence to the general objectives of the company.

6.3.7 Learning and Growth Perspective

Although, as noted previously, staff satisfaction is not specified in ISO 9001 [360] standard, the standard of excellence European Foundation for Quality Management (EFQM) devotes two of its nine criteria to staff satisfaction; one describes the actions to be taken, and the other suggests results. This fourth perspective ensures that employees are sufficiently prepared and their growth is fostered, thus developing them as people and as professionals.

Individuals who are better prepared perform better as the employees are adequately adapted to the positions, and vice versa. Ongoing instruction allows employees to assimilate

emerging technologies and changes required because of the variability of the market. A company offering opportunities for learning and growth will develop objectives related to four phases in the training sequence: identifying needs, program preparation and development of educational materials, delivery of training, and assessment of results.

When they develop indicators to assess the results, these indicators must reflect the type of education, that is, individual or collective, compulsory or voluntary. Indicators should also reflect the "care" demonstrated by the organization to employees, a concept emanating from the EFQM model and representing the conditions of belonging and connection to the organization.

Achieving adequate efficiency of customer and internal processes from a financial perspective depends largely on the employees' ability to perform their function, having the means at their disposal to do so, and their satisfaction at being integrated into the collective maintenance, internal or external, to which they belong and the work developed. This is the human factor, and it is particularly important for adequate productivity.

The satisfaction of maintenance employees is associated with three essential factors:

1. Competence
2. Technological infrastructure
3. Work climate

The company and the department must have as their main objectives the improvement of these factors to ensure employee satisfaction, employee retention, and, consequently, high productivity. The latter is essential for success in other perspectives, including the achievement of the general objectives.

6.3.8 Integrated Perspective

The structure of the BSC, depicted in Figure 6.7, indicates the procedure used to move from strategy to operation to achieve the company's objectives in each of the four perspectives mentioned. The basis of the BSC is to express the business strategy through careful selection of appropriate indicators. Companies using a BSC do not need to communicate their mission and vision because both are clearly reflected in the integrated perspective. Kaplan and Norton isolate three basic principles for the integration of the four perspectives:

1. Cause–effect relation
2. Performance inducers
3. Linkage with finances

The strategy should be based on cause–effect relations establishing consistency between what should be done and the results to be obtained; it can be expressed as the following: if a preventive maintenance system is established, it can reduce the downtime caused by installation failures. The indicator, in this case, represents the installation, but a separate sentence must make explicit the way to achieve reduced downtime by implementing a maintenance plan. This will communicate the meaning of the strategy to all employees affected by each indicator. A good scorecard should include proper selection of the results (indicator effect) and inducing actions (indicator cause), all related to the strategy of the organization.

Since companies are economic organizations whose *raison d'être* lies in survival and development, all operational improvements should be related to economic performance. The principles of total quality show that the success of companies is achieved when the satisfaction of all parties is reached: basically when they manage to satisfy employees, customers, and shareholders.

The sequence needs attention, but this should not lead to thinking that employee satisfaction and customer satisfaction are not suitable ways to achieve the satisfaction of shareholders, which is the end objective. The failure of many quality systems is occasioned by the inability to relate them to economic performance, and many improvement plans are considered objectives in themselves, not as the proper method to increase the added value of products or the organization's financial yields, eliminating waste; see Womack and Jones [377]. The ultimate purpose of all indicators of a BSC should be related to economic performance.

The decision to implement a management model based on a balanced scorecard and developing the four perspectives means aiming strategy at success in the following areas:

1. Obtaining good financial results
2. Optimizing internal processes
3. Achieving full customer satisfaction
4. Improving learning and growth of employees

A BSC can define strategy as the main lines of action that will encourage management to achieve the preset goals. A strategy suggests the style of direction, the management of resources, culture, and values; it points to methods and activities and to character and personality. A strategy should be defined by principles or corporate objectives, not necessarily quantifiable, that indicate the major business direction for the future.

Once objectives are established, an in-depth analysis is required to verify that they are consistent and there is no contradiction between them. If the objectives simultaneously stress "increased staff motivation" and "reduced costs by downsizing," there is an obvious contradiction.

A BSC in general and a BSC for maintenance, in particular, should be structured with a series of objectives to be achieved in a given time. These objectives will be derived from the general goals of the company, corresponding specifically to maintenance. Obviously, maintenance must meet the objectives that senior management wants to achieve in the same period.

The department should include additional objectives to improve their own activity; this will become part of the "pool" of knowledge and correspond to the "know how." These objectives must be realized in specific actions quantified through appropriate indicators reflecting what the department wants to achieve. In other words, these indicators are the goals the department wants to accomplish. The indicators anticipate results that can be achieved. They should be derived from data that can be measured as objectively as possible.

Clearly, these objectives, actions, and indicators will differ across companies/departments as they depend on the situation and what a particular management team considers a priority. They will be adapted to reflect the characteristics of each company/department.

The indicators are turned into control indices with a predetermined frequency to see whether the results are in line with what was intended. If so, the plan will be

continued; but if the information reveals significant misalignments, appropriate corrective action should be taken.

In summary, values are set for each indicator in a certain time and at a certain fixed frequency. Variables are defined according to the index type; they are calculated and compared with the forecast figures, to estimate the probability at the time of calculation that the predicted values can be achieved.

We previously indicated the importance the system gives to the feedback required by various people in the organization so that they can monitor how activities develop in line with strategic goals set by the company and its maintenance service. This means we need to determine who should know what and how often through these indicators.

Maintenance indicators are grouped for each of the four perspectives in the BSC, as outlined in Figure 6.10.

The proposed BSC is a tool that requires interdepartmental communication, teamwork, and the cooperation of all personnel in maintenance to one degree or another. Keep in mind that the objectives and strategies should be developed to the level considered appropriate, allowing strategies to become tactics, that is, in specific jobs. This will assist in the achievement of objectives.

Although the maintenance BSC is derived from the general management BSC, if the company does not consider BSC use a tool of organization and control, the maintenance department can use it autonomously for their own needs. In this case, the objectives, strategies, and indicators are defined by maintenance according to their needs.

There should be a balance between financial and nonfinancial objectives. The real compensation and integration of objectives should be reflected in indicators that comprise the balanced scorecard; these are listed in the following section.

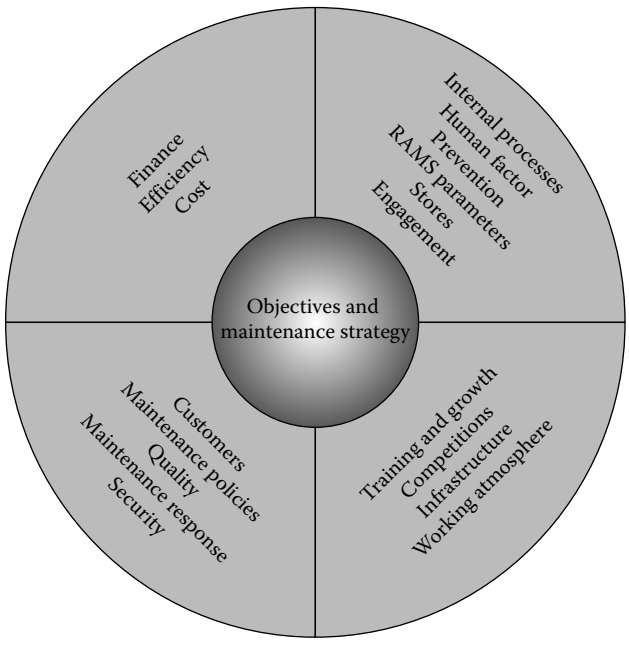


FIGURE 6.10
Maintenance BSC.

6.4 BSC Confection

6.4.1 Planning

The difference between a traditional system of management indices, such as the Tableau de bord, as defined by Cérutti and Gattino [48], and the BSC is the way indicators are selected. It is important to collect necessary and sufficient information so that the business model can be clearly defined. A lack of data or incorrect data will lead to significant failures.

The first step is a rigorous and detailed study of the internal and external circumstances of the organization to set the stage in the short and medium term.

The BSC, like any system or management model that needs to be effective from the beginning, should have the support of top management, in this case based on the conviction that it is neither technical nor economic in its orientation but, rather, a corporate and business affair. If management is not fully convinced of the chances of success, it is not likely to spend a penny on implementation. Once convinced of its value, management has to decide which operational units will use the BSC. As mentioned, a BSC can be applied exclusively for maintenance even when using a BSC is not the general policy of the company, but the absence of its global use runs an obvious risk: the department may not finish the experiment because of the lack of firm management commitment. Partial implementation can reveal a lack of confidence in the method or little interest in modifying traditional management methods (Figure 6.11).

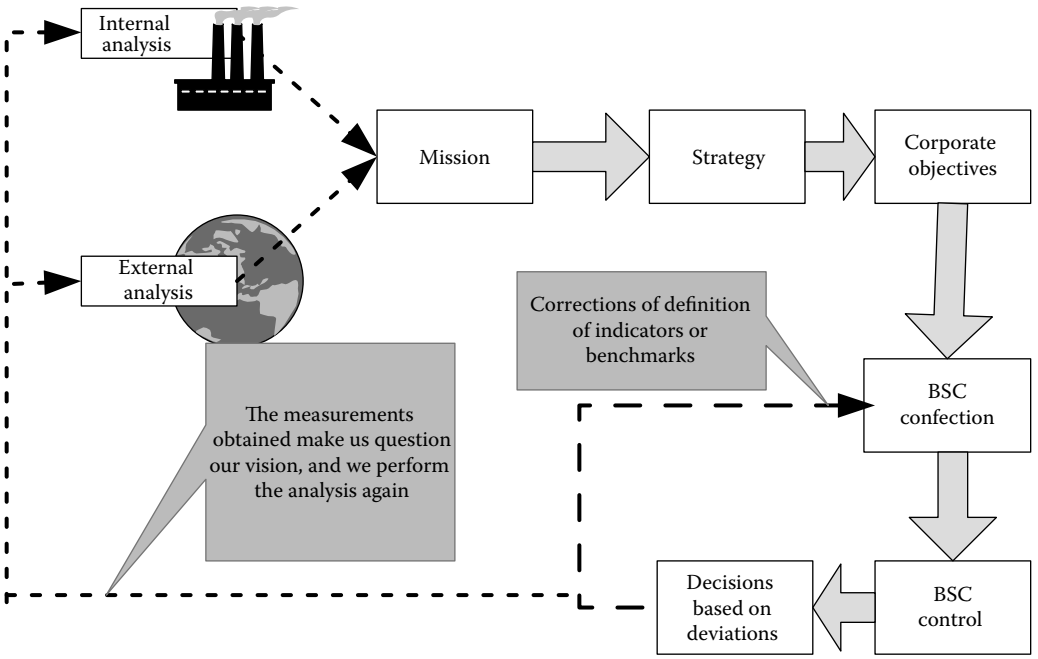


FIGURE 6.11
BSC development sequence.

6.4.2 Information Gathering

It will not be necessary to make any extra effort to gather sufficient information because a large part will be available in the company archives. Annual reports, operational data, work orders, information about the cost of resources, and other information deemed interesting will be available.

Remember that in this method, we are trying to express the strategy in a coherent set of indicators, grouped into four management perspectives, so data corresponding to these perspectives are prioritized. Therefore, indices on benefits and added value to customers, their classification and their needs, operational data from processes and services, and references to staff skills and knowledge management will be part of the information gathering.

For internal analysis, we must incorporate facts on ongoing or future projects, processes, the capacity for improvement, participatory systems, if any, considerations relating staff with past business objectives, staff motivation, leadership skills, the repercussion of activities, trade unions, and so on.

6.4.3 Definition of Strategy

The strategy should ensure the survival and development of the organization. Lately, it has become fashionable to make mission, vision, and value statements to develop policy, but these do not always guarantee the conditions mentioned earlier (Figure 6.12).

Once the BSC has been defined as a management tool that translates company strategy into a coherent set of indicators, management should establish the principles of economic success, not forgetting any side effects that produce beneficial results for stakeholders.

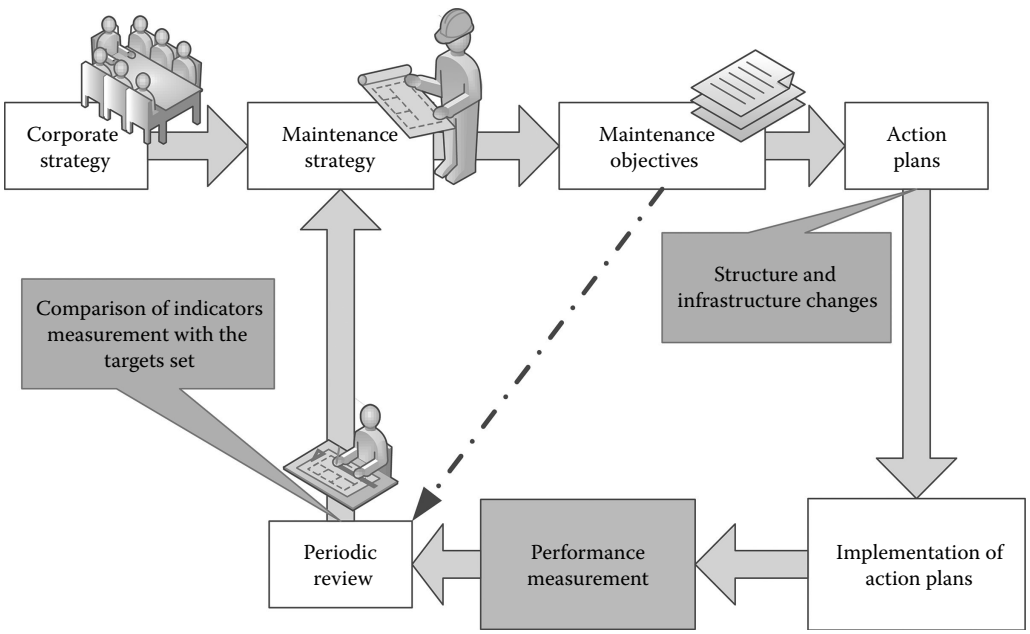


FIGURE 6.12
Implementation of maintenance indicators.

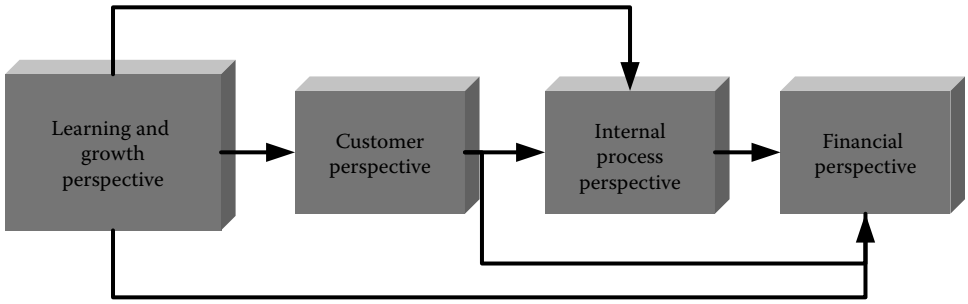


FIGURE 6.13
Linking relationships between the four perspectives.

A scheme of linkages between the four perspectives, shown in Figure 6.13, develops the cause–effect principle described previously and amounts to the real engine of the business model.

The growth of employees is considered an objective of the first perspective; it generates considerable staff satisfaction and contributes significantly to economic results. As this example suggests, all perspectives, not just financial, should form part of the strategy of the company. Nonfinancial indicators are often called "leading indicators" because they are ahead of profitability; that is, if they show good results, it is expected that good economic results will follow.

The framework can be static or dynamic. Risk analysis contrasts the current capabilities of the company with opportunities for future returns. The results of risk analysis may suggest the need for better training.

Figure 6.14 shows the dependency of the four perspectives on maintenance. The human factor has an immediate impact and is at the bottom of the pyramid, while the service provided to the customer is at the top. Between the client and human factor is the pursuit of efficiency not perceived by the customer.

6.4.4 Indicator Determination

Since the indicators are grouped into different perspectives of management, we should start by selecting the number of indicators and identifying them. In this process, corporate objectives are broken down into objectives measured by the indicators.

It may be wise to transform corporate objectives into important indicators for each perspective. The indicators must consider cause–effect relationships and action inducers. A BSC comprising an excessive number of indicators can confuse the strategy and dilute the effort. It is advisable not to exceed six indicators.

Figure 6.15 integrates maintenance with production as part of the internal process that affects the client. The maintenance team must understand its place in the corporate BSC.

The final selection of indicators for the scorecard relates to stakeholders. The statistical treatment of multiple individual and group assessments can help reach consensus on indicators eventually chosen by the organization.

The assessment could take the format in Figure 6.16.

The selection of indicators and their placement in the proposed model can be summarized by breaking down corporate objectives into objectives associated with each of the four perspectives. These objectives can be divided into a number of strategies; the

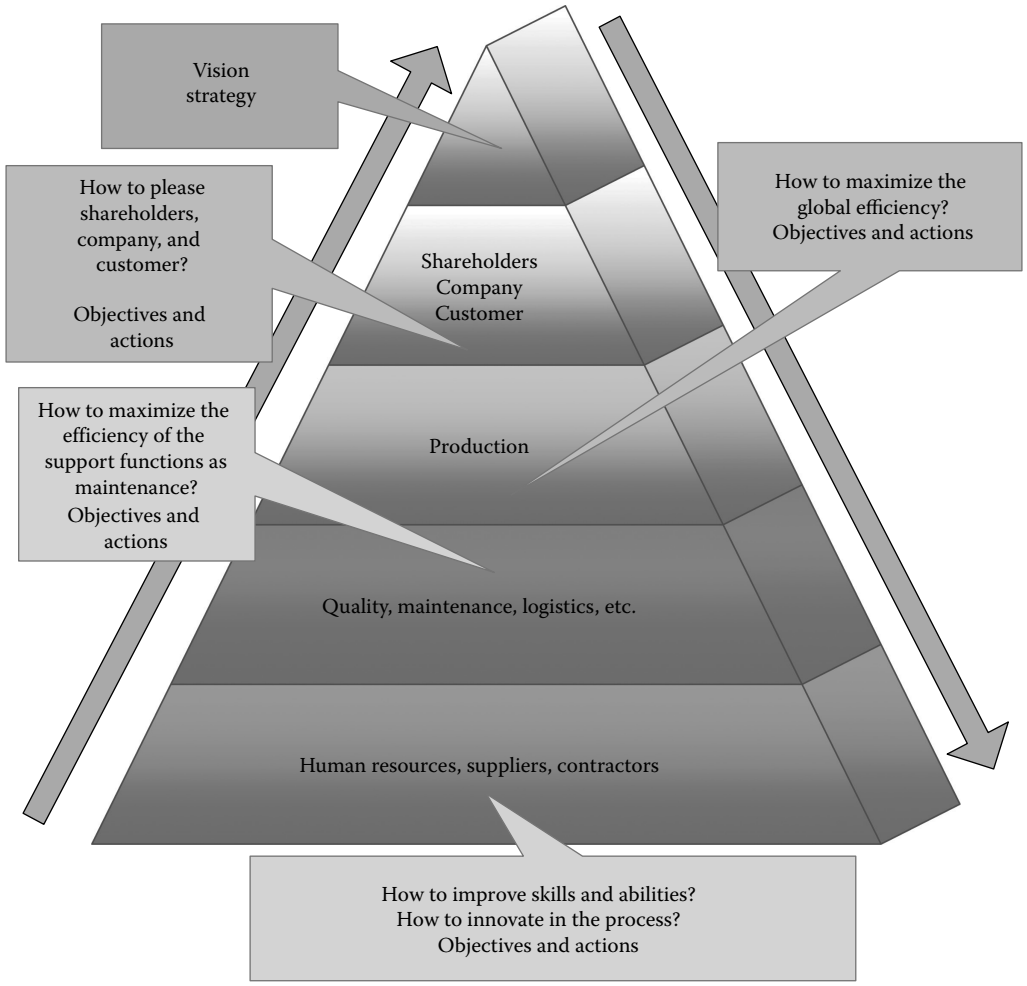


FIGURE 6.14
Hierarchical dependency of the perspectives influencing maintenance.

measurement of the success of these strategies depends on the selection of accurate indicators. In turn, the selection of indicators to monitor the appropriate positive or negative progression of these strategies should be linked to an accurate alignment of the strategies with the desired objective.

6.4.5 BSC Conformation

The connection of the selected indicators with corporate principles should be done with rigor so that management is convinced of their ability to be effective.

Figure 6.17 relates "What?" with "How?" by graphically linking indicators to the objectives set in each of the four perspectives. This allows us to visualize and classify the associated indices with each perspective and indicates the relationships to be established in measuring. The existing correlations show that some corporate principles are linked to various indicators; this means that certain points of the strategy are sufficiently heeded in the BSC.

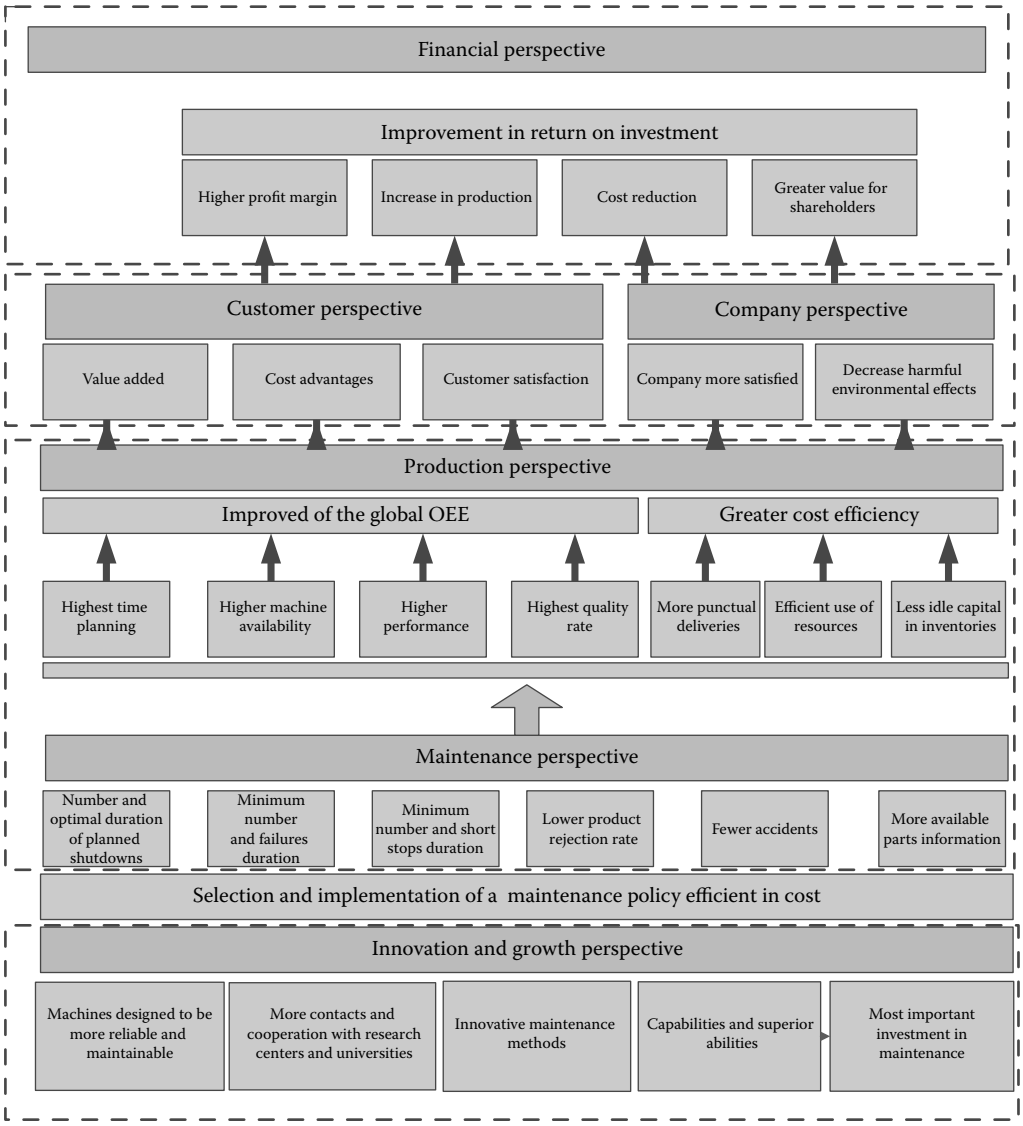


FIGURE 6.15
Location of maintenance as an internal process within the overall organization BSC.

Other objectives, however, have very low representation, indicating points of the strategy left underdeveloped in the scorecard.

Thus, the organization can check its strategy development and correct any shortcomings; in this way, the BSC may represent a set of balanced and integrated action programs to achieve excellence.

Once they are selected and evaluated, the indicators of effective strategy development can be used to relate cause and effect as well as objectives and indicators, to enhance the awareness of employees, and to control the effects the use of indices can have on the implementation of the strategy.

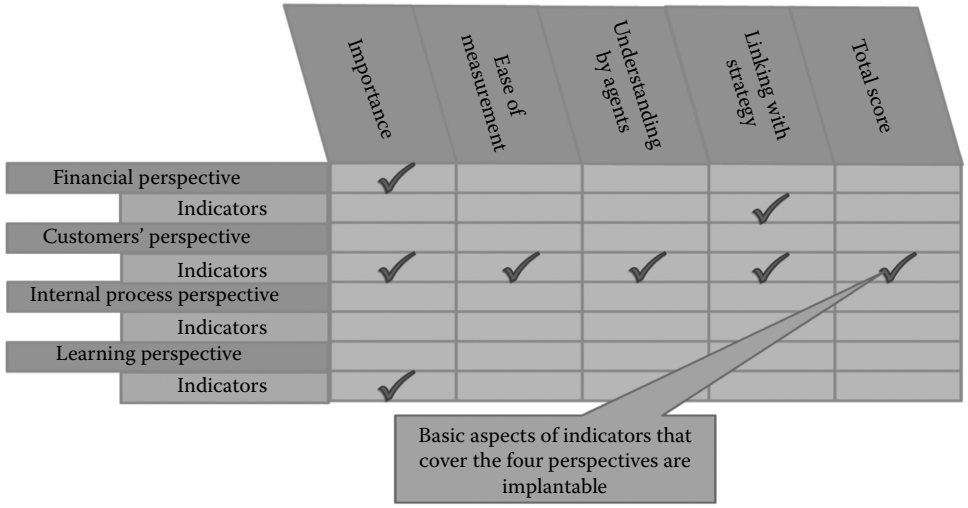


FIGURE 6.16
Indicator assessment table, according to the BSC perspective.

More than function as a simple tool to select indicators, the BSC supposes an authentic management system. It requires a detailed description of the following:

- Methods of measuring indicators
- Responsibility of the measurement
- Time limits
- Performance responsibility
- Allocation of necessary resources
- Links with personal incentives

The strategy must accommodate the global scope of the organization's performances; accordingly, the indicators should govern the activity of all staff. Since it is not always possible to cover all of the guidelines directing the activities of all employees, cascading charts should be designed for the various areas to be measured, in this particular case, the maintenance function.

It is advisable to create a record card for each indicator reflecting the perspective, those responsible, a detailed description of the objective and its method of calculation, data sources and data quality, and actions to be developed to complete the index in the most efficient conditions.

6.4.6 Communication

It is often said that once the BSC is announced, the orders are already given. In other words, the simple communication by management that it is turning to the use of a BSC results in an action program. The BSC requires a genuine management system, with the deployment of specific objectives, control of and responsibilities for action, and adequate resource allocation. Mitchell [219] reinforces the idea of proper communication of the scorecard and indicators for potential users to ensure its success; poor communication

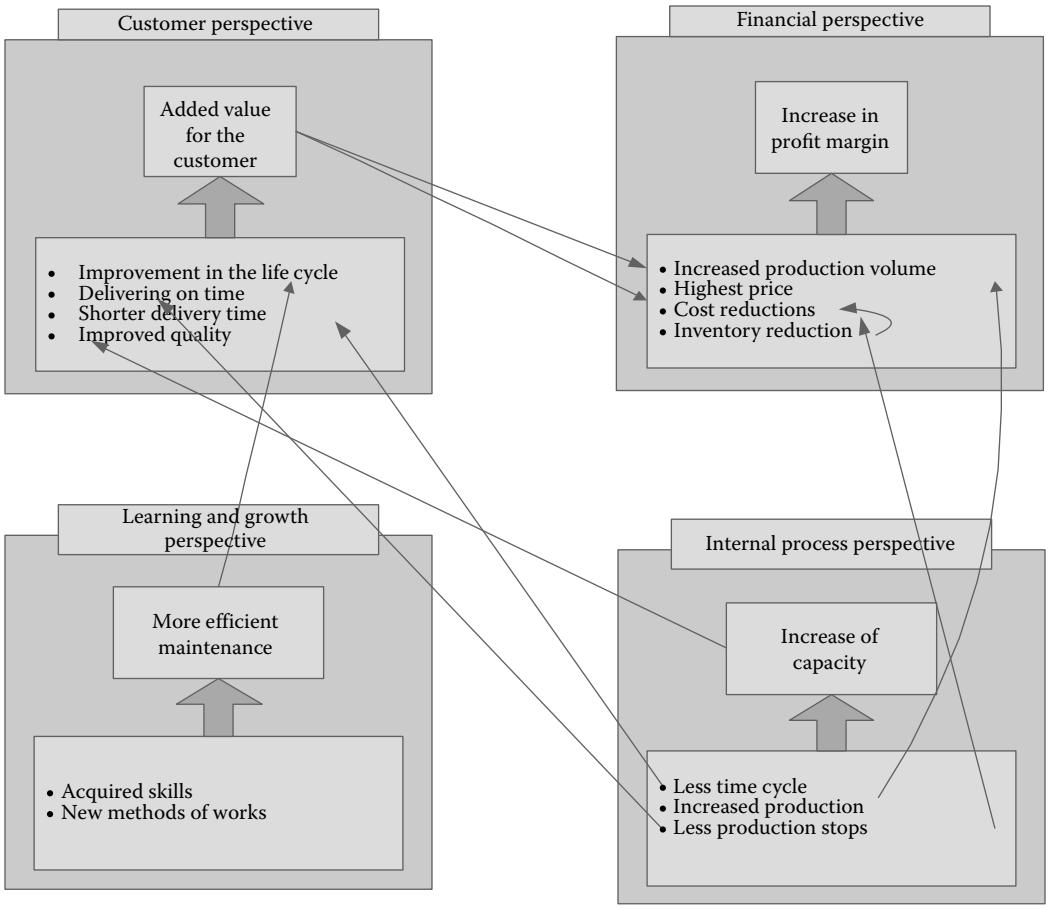


FIGURE 6.17
Use of the balanced scorecard in operations: maintenance and production.

often leads to its failure. The use of KPIs that are short, understandable, and adapted to the user often facilitates this process.

The wishes of upper management must be visible from the beginning so that staff and managers clearly understand that the BSC will be the main instrument through which the company will evaluate the market and determine the activities of groups and individuals.

In the maintenance case, maintenance departments usually pay little attention to the presentation of objectives, which as discussed, tend to focus on short deadlines and information not intended for maintenance but for production. The information goes beyond the office of the maintenance manager, so communication as shown in Figure 6.18 is less efficient as it approaches in the most basic maintenance stratum. Maintenance is often concerned about short-term or emergency projects; it is difficult to apply maintenance to medium- and long-term targets because its resources are occupied elsewhere.

Often, managers and employees know and agree with the strategy, but each interprets it in his/her own way using his/her own criteria and interests to develop a few goals, perhaps insufficiently explained. This requires management to design and implement a valid system of initial presentation and continuous communication to achieve the department's consensus with the vision of the strategy.

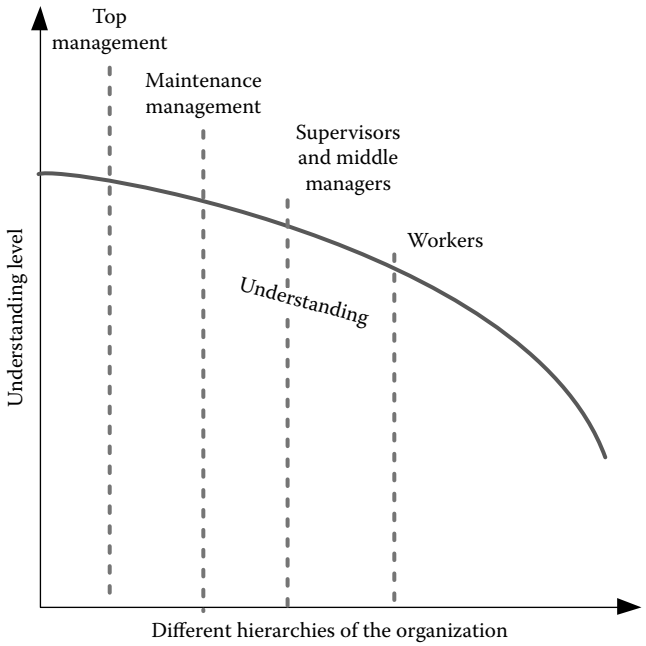


FIGURE 6.18
Errors in the communication of the maintenance strategy.

Communication must be preceded by a timely awareness; this is achieved through a marketing campaign based on internal training. The instruction of employees not only transmits knowledge but also fosters active behavior. A formative approach using an innovative tool, for example, the WCC, will help align the employees with strategic perspectives; it will develop the capacity of the individuals to improve and will articulate a set of secondary objectives.

Figure 6.19 shows the level of understanding in a proactive organization where communication channels are open in both ascending and descending directions. As Mather [208] notes, it is important to observe the maintenance indicators from a nonhistoric perspective, seeing past results as opportunities for change and potential improvements.

Fluid communication between management and maintenance strategies is required to adapt the objectives and correct deviations in the indicators. The need for organizational maturity is obvious; each indicator must be visualized as a potential improvement and viewed critically. Indicators such as the number of faults that could have been avoided with preventive inspections or delays in the implementation of work orders only are adequately treated when there is a climate of confidence, a full understanding of the objectives, and a nonpunitive use of the metric.

Referring to proactive organizations, Dwight [85] says the metrics should be communicated to the owners of the indices who have the capacity to act on them. That is, both planned and unplanned outages must be measured and evaluated by those who can directly influence changes in the trend of such indicators. Dwight stresses the need to distinguish between the communications to the owners of the indicators who are responsible for them and the communications to users whose references to the indices are for informational purposes only.

The WCC presentation has to be intensive and adapted to the language of those who receive it as employees can often contribute to development of the strategy.

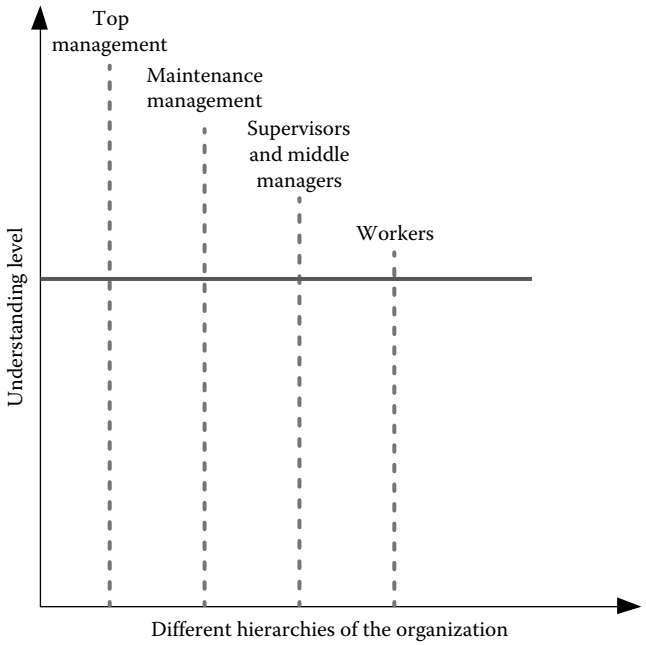


FIGURE 6.19
Communication in proactive maintenance organization.

In services such as maintenance, companies often forget that customers tend to be cared for by low-paid and often less educated employees; these employees are far removed from the managerial levels who establish the strategic principles and objectives.

6.4.7 Incentives Policy

The linking of individuals' incentives with the fulfillment of objectives and the appropriate treatment of indicators has long been the subject of discussion. Targeting people's interest in achieving particular goals can lead to harmful effects, including the isolation of individuals and departments and the general interests of the organization being forgotten.

If employees have been promised an economic incentive, when events adversely affect the ability to achieve a goal for which management is responsible or there are causes beyond the efforts made by employees, personal incentive will be lost, especially if management believes in the unachievable goal and decides to keep it. For this reason, it is necessary to describe in detail the possible implications and even aberrations that can be derived from the linkage of compliance with a particular indicator and economic rewards.

Once the possible negative implications have been considered, there is no reason not to establish rewards for the achievement of objectives, although it will be necessary to carefully select the system and its link with the strategy.

A look at Winslow's pyramid of needs leads to the conclusion that economic stimulus does not have excessive importance when the individual is not concerned about minimum needs for survival and comfort. In most cases, greater incentive is not based on pecuniary motives, but on feelings of belonging and contribution to a strategy or a project.

A BSC cannot succeed without the active participation of all actors in the definition of the strategy or, at least, a consensus on the goals to be met and the levels to reach. It is necessary to develop the beliefs people have in values; they should be recognized and augmented by the organization to ensure the success of the program.

Often, managers or executives say they lack confidence in the actions of their employees. They do not rely on them, consciously or unconsciously, to perform functions essential for the survival of the company, whether attention to customers or handling expensive computers.

If they decide to trust in the people they employ, this trust is communicated, helping to break down the walls isolating individuals and improving the psychological well-being of the employees. This, in turn, affects the economic well-being of the company.

It is necessary to determine how to do this, especially in maintenance where there is a strong human factor. Confidence in the department, ease of access to technology, and the labor climate have previously been defined as key factors of belonging. Wages, as has been pointed out, reflect only a first stage of basic needs.

The involvement of operators in the measurement system is also important. In other departments such as production, the studies of methods and times or the data obtained automatically may provide enough information. But in maintenance it depends on the proper management of work orders and all related documents.

Nor can employees be expected to contribute if they have not developed ways in which this occurs. In addition to the implementation of individual and collective participation, it is necessary to establish an atmosphere of psychological freedom. An important aspect of maintenance is the frequency of the proposed corrective or preventive improvements to equipment. The number of suggestions for improvement is often an indicator of the atmosphere of freedom to encourage these actions.

In short, an incentive policy is not necessarily economic in nature.

6.5 Document Management for Indicators Confection

6.5.1 Knowledge Management

The departments of the companies, in particular, maintenance, are undergoing a metamorphosis, namely, the application of individual professional knowledge to enhance the know-how of the entity. This does not mean disregard for individuals. The increase in collective knowledge has the goal of increasing the overall knowledge capital, but it is individuals who enrich this capital.

Many departments have document archives that are not properly harnessed or renewed. Therefore, we need tools to capitalize on the know-how of the group, taking advantage of the current possibilities of file systems, consultation, and data transmission.

The know-how of an organization is a set of interconnected knowledge of strategic value to the service of the entity itself and its customers or users that must be translated into a structure of responsibilities. This set of skills and responsibilities must be handled by appropriate management systems that allow progress in the sense of an opportunity to maximize its potential. This globalization of knowledge includes creating a system of objectives to show how to improve the effectiveness in fulfilling the mission and identifying the associated indicators that define and control the progression of this improvement.

It should be remembered that the management of maintenance has the basic functions of administrative activity: formulating objectives, planning, organization, execution, and control. Most companies have a computer system to manage maintenance, better known as CMMSs or the CMMS package; these systems facilitate the handling of the enormous amounts of information produced. In addition, some authors such as Trunk [333] and Olafsson [243] claim that it is impossible to introduce RCM or TPM methodologies in the absence of these computer systems. In fact, RCM requires the treatment of high amounts of historical and statistical data; see Moubray [226].

Trunk [333] affirms the need for CMMS if a company wants to handle the following efficiently:

- A preventive maintenance program
- Management of spare parts and stores
- Management of work orders (WOs), tracking, and planning
- Relations with contractors and suppliers

The proper implementation of these systems ensures an end to the loss of knowledge historically linked to the maintenance function, which resides mainly in the wealth of experience of the technicians associated with that function. The implementation of such systems varies. It includes isolated applications with connection interface to the various applications of accounting, payroll, and so on. It can also be part of a comprehensive management software or enterprise resource planning (ERP), a technically simple solution to integrate different applications.

6.5.2 Maintenance Implementation

As in other administrative functions, the execution of maintenance requires developing objectives and goals, designing an activity plan, scheduling tasks to designate responsibility, obtaining the resources to comply with standards, matching the maintenance action to the evaluation and control of the results, and comparing them with what has been planned in order to take appropriate measures for future actions, if necessary.

In maintenance, we need to match the need for intervention with the appropriate level of quality. The organization must offer information in a timely manner, enabling us to plan and schedule maintenance activities. We need access to human and material resources, and we must be able to manage the flow of information produced by the various activities, to assess, monitor, and, where possible, improve performance.

6.5.3 Work Order

The WO is the key instrument of the maintenance activity. It is also the central element in the flow of information generated to and from the maintenance system. Depending on its purpose, the WO can assume different names and formats. In some cases, it is a request for intervention to perform corrective action; in other cases, it is for scheduled preventive maintenance or inspection. It may request preparatory activities for capital maintenance (overhauls). It can assume the role of shop order or an order for parts for the workshop or serve as a vehicle for the implementation of safety standards and industrial hygiene. The generation and recording of information associated with a WO run parallel to the stages of order processing: development, execution, and closure.

The WO can be a request for (Figure 6.20)

- Corrective maintenance generated by the production area because of the failure of any equipment
- Corrective maintenance generated by the maintenance area as a result of fault detection during inspections, testing, verification, analysis of materials, and so on
- Planned preventative maintenance and planned work duties necessary for maintenance

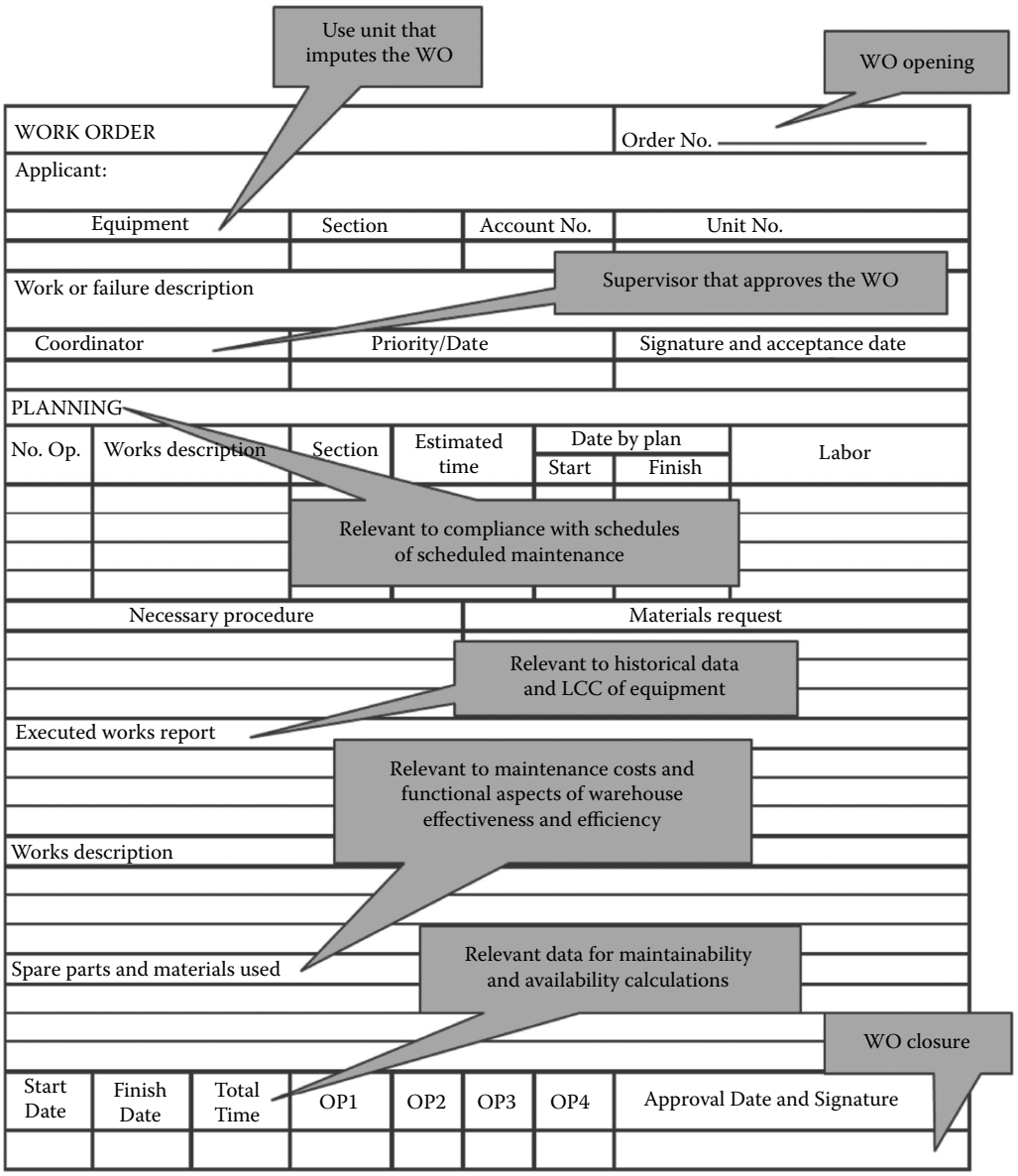


FIGURE 6.20
Work order.

- Installation and commissioning of new equipment, modification of existing equipment, or installation generated by engineering
- Implementation of standards generated by the department of safety and industrial hygiene

On the basis of data collected in the WO, we get not only technical information to follow the performance of the equipment and its components (trouble) but also economic information that allows us to take control of the maintenance costs (man-hours, material used, parts and spare parts consumed, etc.). Such information will be extremely useful to maintenance management; it can be used to request additional resources or to report performance and costs to superiors. Given its functions, the department of planning and maintenance control is the most implicated in ensuring the integrity of the information and updating it on a regular basis; its proper handling is related to the success of the maintenance activity.

Such information includes the following: the historical records of the teams, the records of the maintenance operations performed, the reports of the work teams and supervisors, and the technical documentation of the plant and machinery, along with associated general information. This is an invaluable data bank; its rational use helps in optimizing maintenance management (Figure 6.21).

It is important to preserve the information and its modifications and updates in an organized manner. A recommended action might be to establish a record or dossier of equipment for each machine or each place in the plant, depending on its importance to the production process and subject to periodic or continuous control. This dossier or team dossier is composed of two distinct parts: one contains all the technical documentation and the other keeps the information and documents generated in the maintenance area.

This second part of the dossier has three sections: the first is dedicated to planning maintenance; the second lists the execution of maintenance activities; and the third has general information supporting maintenance operations.

The first volume of the equipment dossier, namely the technical documentation, contains copies of the procurement documents, technical specifications, general plans, quality certificates, nominal parameters of operation, and graphical information in general.

The first section of the second volume (planning maintenance) has information on maintenance cycles, quantity and qualifications of staff, standard time of the execution of each activity, information derived from condition monitoring of equipment and parts, and a log chart (Figure 6.22).

The second section of the second volume contains everything relating to the maintenance executed: technical reports of maintenance, WOs, equipment calibration, and miscellaneous forms required for implementation (authorizations, free tracks, etc.).

Section three of the second volume picks up lists for spare parts and materials, letters on lubrication (points, methods, type of lubricant, quantity, change frequency), lists of tools, instructions, and graphics to arm and disarm, mounting and dismounting, lists of applicable procedures, and weight characteristics and volume.

A proper classification or cataloguing of the equipment dossiers supported by a rational system of codification will allow us to shorten the time needed to locate and retrieve the information required for maintenance operations and facilitate the analysis of faults and behavior of the equipment, operation times and repair times, the use of human and material resources, and the costs associated with the maintenance activity.

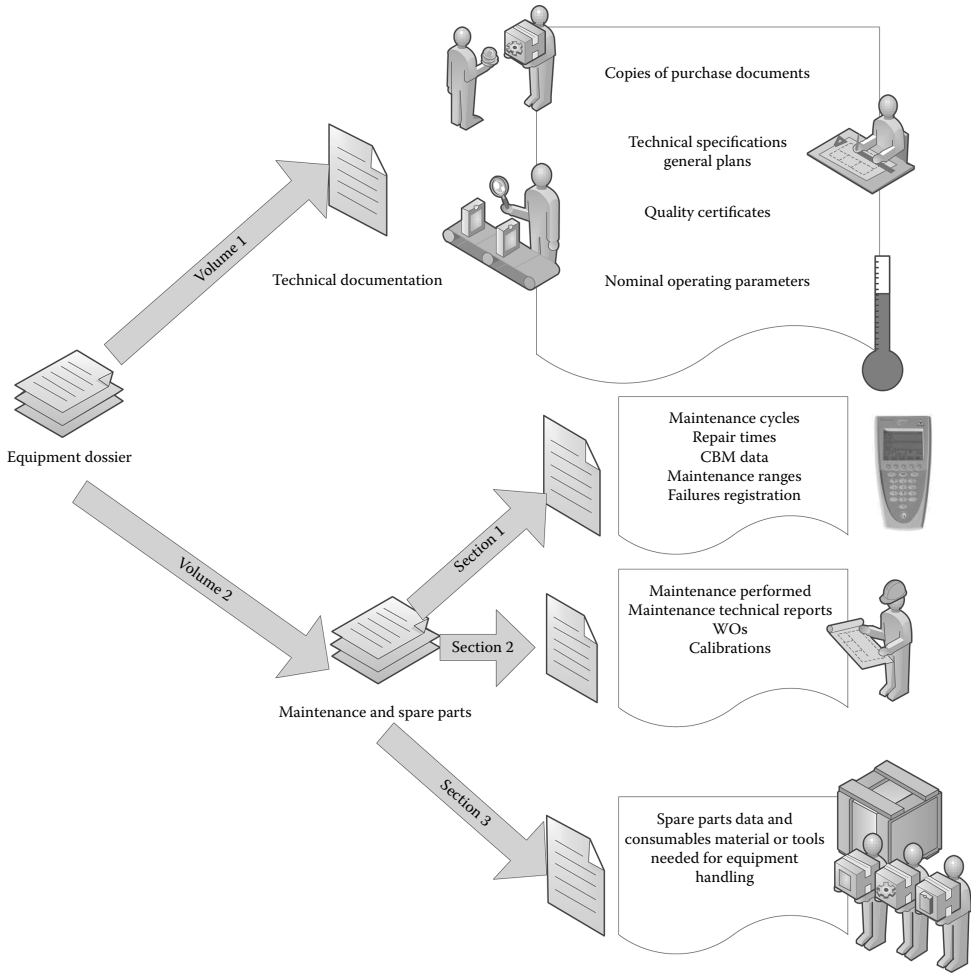


FIGURE 6.21
Documentation structure of maintained assets.

6.5.4 Information and Dossier

Note that the maintenance system receives and generates a significant mass of information. This information must be recorded, organized, and properly maintained to be used by maintenance specifically and the company more generally. One of the most relevant aspects, with regard to the organization, relates to the recovery of data to meet the requirements for maintenance decision-making in different areas. This recovery of the information is crucial: Labib [181] says the design and selection of the indicators must take into account the accessibility of the required information (Figure 6.23).

6.5.5 Equipment Classifications and Codes

A decision is more successful when it is supported by high-quality information, and the quality of the information depends on its relevance and coherence, as well as the ability to obtain it in good time. A good organization of the information by using classification codes allows its recovery in a shorter time than with any other method.

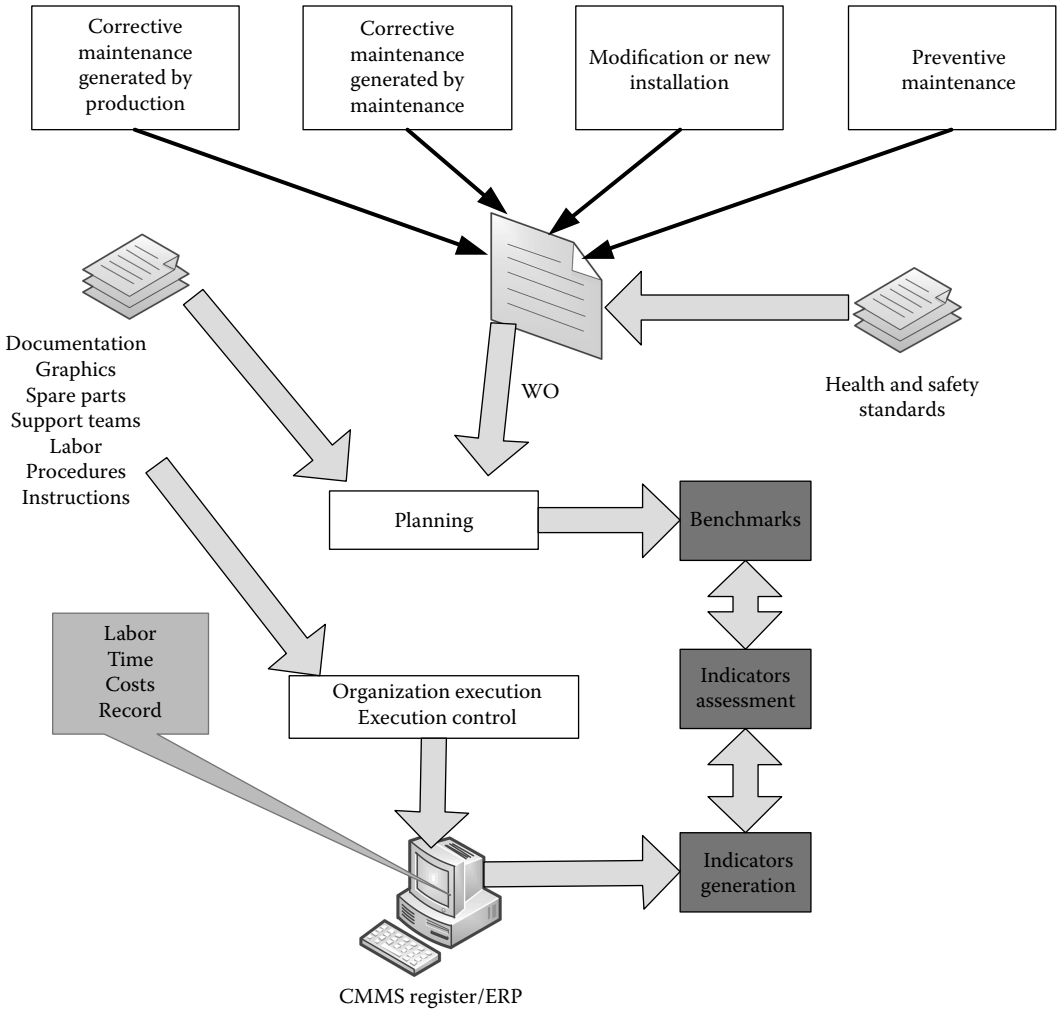


FIGURE 6.22
Flow diagram of a work order.

Although this is an important aspect for any system, it is a crucial factor when the maintenance system relies on automation.

In all organizations, codes are widely used to obtain a uniform structure of identification. For a coding system to be effective, certain conditions must be met.

The basic requirements are as follows:

- Identify the elements of the plant, including all the equipment and technological systems, as well as their individual parts, depending on the interests of users.
- Rank the teams, lines, and systems according to the areas of corresponding maintenance (mechanical, electrical, auto, chemical, civil, instrumentation and control, etc.).
- The simplest element in the code must be associated with the equipment, line, or system to which it belongs and with a specific area of maintenance.

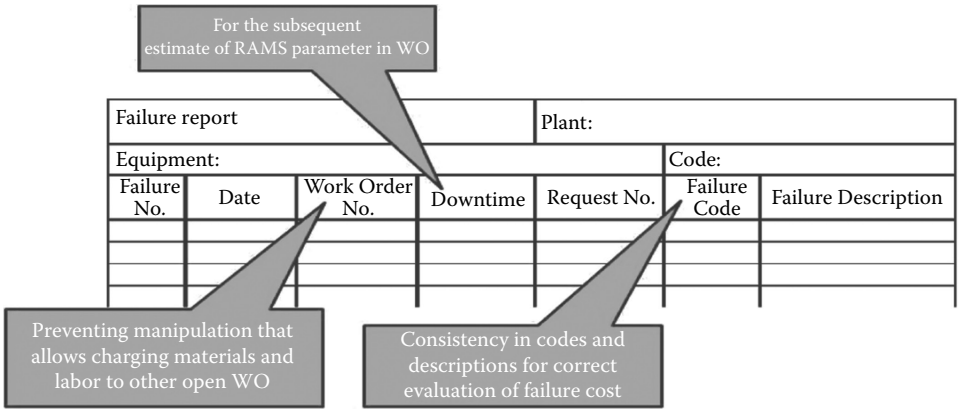


FIGURE 6.23
Listing from CMMS. Result of searches by fields.

In industrial enterprises, it is common to find classification systems structured on the basis of identification codes that reflect, among other things, the position of the equipment and components within the technological schema according to the order determining the process flow of the system. As seen in Figure 6.24, the code is unique to that type of item, and no other code can occupy the same position in the technological schema. This ensures that the component is uniquely identified.

The characters used to identify a technological system can be derived from the first two letters or initials of the system name. The letter or group of letters that identify the type of equipment may refer to an internal classification or one at the international level.

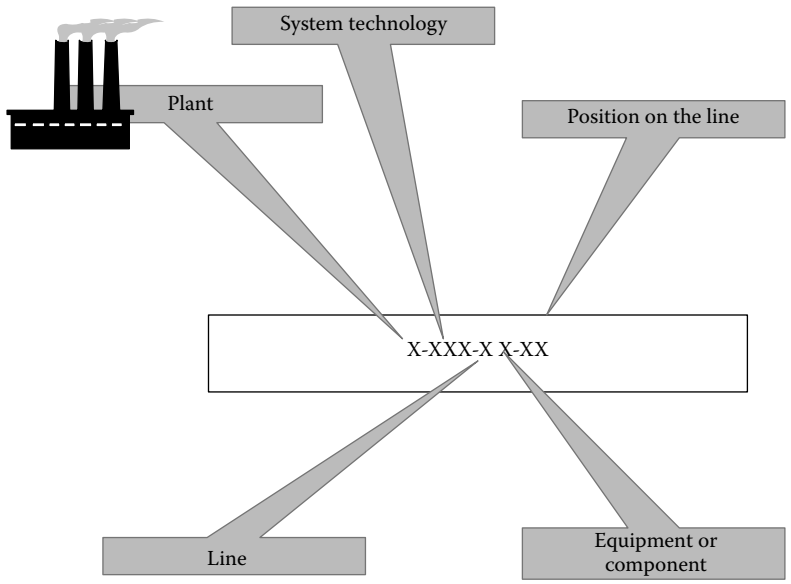


FIGURE 6.24
Equipment coding.

The type of code described has wide use in equipment identification for mounting; it also helps staff become familiar with the technological schemes during assembly and commissioning of the installation. However, despite its many advantages, this type of code does not fully meet the interests of the maintenance area, as maintenance is more concerned with the characteristics of the equipment and components and their physical location.

For a code to be satisfactory from the point of view of maintenance, its structure must ensure the following:

- All the equipment or components corresponding to the same model are grouped together under the same identification.
- The model is associated with technical documentation and regulations (drawings, instructions, repair processes, expenses standards, repair cycle, list of parts, etc.).
- Technical history can be acquired when necessary.

Taking these aspects into account, the maintenance code might have the following structure (Figure 6.25).

The first six digits are the group code associated with the technical documentation and identification of spare parts by type of equipment. The last four digits are complementary

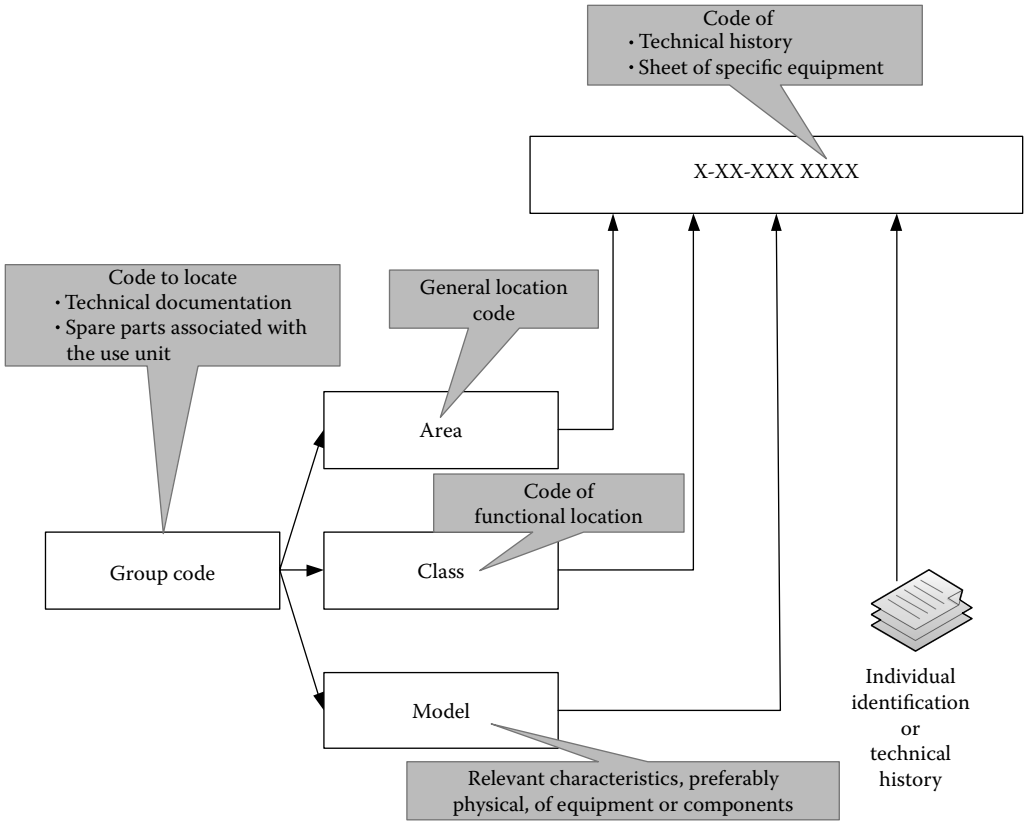


FIGURE 6.25
Proposed codes.

to the individual identification or univocal and are associated with the history or technical details of each piece of equipment or component.

Area codes may be the same as mentioned in the example of the location code. The code of the class may be appropriate, or a numeric code may be assigned. The model code may be numeric or alphanumeric but will highlight the most important features of the equipment or component, for example, type, diameter, material, function, pressure, temperature, or any other parameter.

In any case, the planning area will establish the most appropriate codes and look for reasonable ways of grouping and retrieving the information.

6.5.6 Manuals, Guidelines, and Procedures

Maintenance management includes administrative and operating activities that generate a significant amount of information. Adequate and effective communication must be established between the different organizational levels. This includes everything concerning the various forms and requirements for preparing, executing, and controlling the managerial work, as well as monitoring and operating equipment.

The most widely used means of communication in the field of maintenance include the following:

- *Instruction manual*: Describes the tasks, considering what should be done, how, when, and why. The manual is primarily used for staff training or upgrading.
- *Procedures manual*: Describes in detail methods to perform the tasks; it usually contains information flow diagrams, illustrations of formats and forms, and instructions for use.
- *Organization manual*: Duties for each position are determined; the responsibility and authority of individuals occupying these positions are defined.
- *Administrative manual*: Contains the company's provisions to ensure that everyone acts in accordance with existing rules and regulations.

6.5.7 Maintenance Manual

Maintenance activities are governed by a maintenance manual, which may incorporate one or more of the manuals mentioned earlier. The maintenance manual includes company rules that apply to maintenance. It can include normalization methods for maintenance and/or repair of equipment and devices. It also contains maintenance managing concepts and characteristics and objectives of the organization. Company size is not the fundamental criterion for determining the need to use a maintenance manual. The size of the company will influence the size of the manual and its contents, but never determine the need for its use as a means of communication. A worker cannot do his/her job properly if it is not explained well, or if the worker does not understand what to do, how, when, and why. The importance of the work within the organization must also be clear.

The maintenance manual should cover administrative issues and technical aspects separately; it includes the following basics:

- *Objectives*: What the manual sets out to achieve
- *Scope*: Activities covered by the manual

- *Responsibilities and organization*: Which unit or individuals are responsible for maintaining which facilities or equipment, who should respond to the rest of the organization, and interrelationships between maintenance units and between other entities of the company
- *Definitions*: A glossary or list of words and typical terminology
- *References*: Precise indication of documents to which reference is made
- *Function*: Concrete object of the manual (repair, inspection, testing, etc.) and ranges, instructions, procedures, standards, and so on

6.5.8 Procedures, Instructions, and Maintenance Ranges

Maintenance ranges are used for scheduled jobs to be executed periodically. The maintenance ranges incorporate activities to be performed, their frequency, the procedures, as well as the dates the planned activity began and ended. This document must accompany the maintenance record.

The procedures describe in detail the actions to be taken in the required activities. The existence of procedures is justified by the complexity of the operations, the cost of the equipment, the need to achieve high levels of availability, and the potential danger posed by failure or damage.

The preparation, review, and approval of procedures must be assigned to competent and qualified staff to ensure a better understanding of the technical and regulatory requirements of the relevant activities. The content of a statement or procedure should include at least the following:

- *Title*: Description of the element, equipment, or system concerned
- *Objective*: Purpose of the document
- *Scope*: Limits of the application of the procedure
- *References*: Document's name and code
- *Definitions*: Glossary of terms to facilitate understanding
- *Annexes*: Complementary attachments (charts, diagrams, etc.)
- *Responsibility*: Entities or persons responsible for ensuring compliance with the provisions of the procedure on implementation, verification, and approval of work; includes those responsible for review, approval, enactment, and updating
- *Body*: The method, process or system covered by the procedure; includes precautions and safety measures, work sequence, acceptance or rejection criteria, element's description and processes, inspection types, observation points, environmental conditions, equipment, instruments, necessary tools and materials, personnel qualification, identification and treatment of records information, and so on

Procedures may have check or verification sheets that must accompany the report of work performed for the purposes of review and evaluation. Procedures and instructions must be properly identified by a coding system to facilitate their location. The code may constitute two characters identifying the manual to which the procedure belongs; alternatively, it may be a group number combining the related procedures in a particular section and a self-identification procedure number.

6.6 Classical Models of Maintenance Performance Indicators

The classical perspective seeks to know the status of a plant by measuring certain processes, such as the performance of physical and human resources, among other things. For this, the company uses indicators calculated for certain periods of time and compared with previous periods. This perspective differs from the BSC in the lack of correlation with business objectives.

The objectives of performance indicators in maintenance include providing relevant information on the status of the equipment or machine, the level of preventive or corrective maintenance within the plant, incurred costs, and the performance level of maintenance personnel.

Once defined, the indicators help detect and correct problems to prevent poor quality products or shutdowns, thereby reducing the waste of time, cost, and effort. Some authors divide the indicators by level, depending on what is important to measure and the expected results.

Not all indicators must be known and managed by all workers, however. This calls for custom scorecards, depending on the relevant aspects of each user and the impact of on the overall objectives of the company.

6.6.1 World-Class Indicators

World-class indicators (or world-class indices) are the same in all countries. Of the six world-class indices, four are related to the analysis of equipment management (RAMS) and two are related to cost management (cost model), according to the following relationships.

6.6.1.1 Mean Time between Failures (MTBF)

This is the relationship between the operating time of items over a certain period and the total number of failures detected in those items in the observed period. This index should be used for items that are repaired after failure.

6.6.1.2 Mean Time to Repair (MTTR)

This is the relationship between the total corrective intervention time in a set of items with failure and the total number of failures detected in those items in an observed period. This index should be used for items in which the repair time is significant in relation to operating time.

6.6.1.3 Mean Time to Fail (MTTF)

This is the relationship between the total operating time of a set of nonrepairable items and the total number of failures detected in those items in the observed period. This index should be used for items that are replaced after a failure occurrence.

It is important to note the conceptual difference between MTTF and MTBF. The first index is calculated for items that are not repairable or repaired after the occurrence of a failure; that is, when failed, they are replaced by new item and, consequently, repair time is zero. The second index (MTBF) is calculated for items repaired after the occurrence of the fault.

Therefore, the indices are mutually exclusive, that is, the calculation of one excludes the calculation of the other one.

The calculation of MTBF should be associated with the calculation of MTTR. Because these indices have an average result, accuracy is associated with the number of items observed and the observation period.

6.6.1.4 Equipment Availability

This is the difference between the total number of hours (calendar hours) and the number of hours for maintenance (preventive maintenance, corrective maintenance, and other services) for each observed item.

The availability of an item represents the percentage of time it is available to carry out its activity. The availability index is called "equipment performance" and can be calculated as the ratio of the total operation time of each item and the sum of this time with the total maintenance time in the considered period.

6.6.1.5 Billing Maintenance Cost

This is the relationship between the total maintenance cost and billing for maintenance during a certain period. This index is easy to calculate because the values of both the numerator and the denominator are normally processed by the accounting department.

6.6.1.6 Maintenance Cost for Replacement

This is the relationship between the total cumulative cost of maintaining a certain piece of equipment and the purchase price of the same equipment (replacement value). This index should be calculated for the most important items of the company (those affecting billing, product quality or services, safety, or environment).

6.6.2 Classic Indicators of Widespread Use

Many indicators have been generated by experienced maintenance managers as a result of corporate benchmarking. They have been diffused in specialized magazines and in CMMS applications, and have been incorporated into indices in certain sectors. Of particular interest is the creation of indicators in the energy and chemical industries.

Wireman [375] classifies indicators and ranks them according to the purpose for which they are designed and their user. He offers a wide range of indicators in five hierarchies. While many are desirable for any maintenance manager, the type of information to be collected requires that they be treated with care.

According to Wireman [375], the levels of indicators are as follows:

- *Corporate indicators*: Measure what is important for senior management; these indicators mark the direction of the company.
- *Financial performance indicators*: Ensure a department is reaching financial targets set in an annual plan.
- *Efficiency and effectiveness indicators*: Measure how well process objectives in different areas are managed and whether objectives are met.

- *Tactical performance indicators*: Highlight the weaknesses of an organization in key points of each area.
- *Functional performance indicators*: Show the performance of specific maintenance functions.

These indicators are shown in Figure 6.26.

These indicators are oriented from top to bottom. If indicators are not connected, the entire organizational effort is wasted. Knowing the failures or problems at each level should allow quick adjustment to reduce losses caused by misuse of physical and human resources, among others. An error corrected at any level will modify the lower level indicators, provided there such interconnection.

Wireman makes a valuable contribution to the compilation of indicators, but the classifications presuppose a break between management interests and the maintenance department. The approach proposed here is to transfer and insert all corporate indicators into each of the indicators at the lower levels using a BSC perspective, thereby helping everyone in the organization to know what is expected of them and adapt the objectives to their hierarchical level. It breaks with the classical division of financial indicators and blue neck indicators or technical indicators.

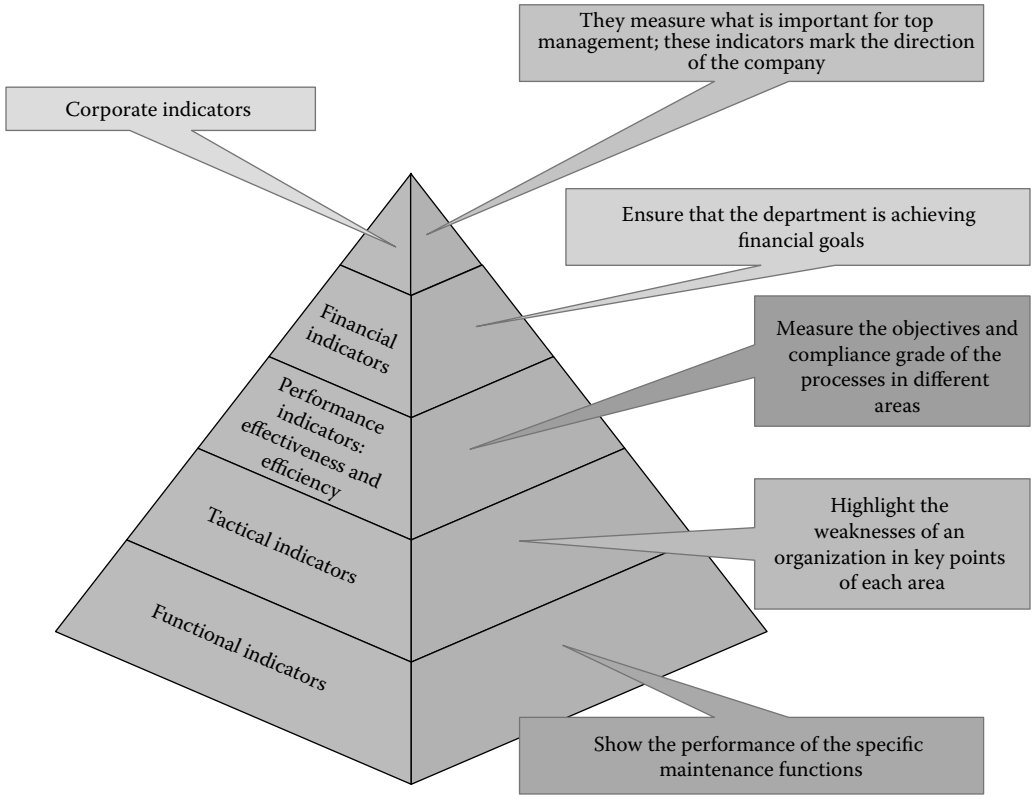


FIGURE 6.26
Hierarchy of maintenance indicators according to Wireman. (Adapted from Wireman, T., *Developing Performance Indicators for Managing Maintenance*, 1st edn., Industrial Press, New York, 1998.)

The list of indicators in the next section has been collected by various authors, maintenance managers, and consultants, including Wireman, Svantesson, and Tavares. Some have been developed out of sheer necessity; others involve the contribution of consultants. The spread of preventive maintenance in the 1970s and 1980s generated a set of calculations, but these are not applicable in more recent areas such as RCM. These indices do not normally appear in any standard; in some rare exceptions they have been included. The only standard that collects maintenance indicators, UNE 15341 [356], does not include the indicators listed in the following. The European Federation of National Maintenance Societies (EFNMS) and The American Society of Maintenance and Reliability Professionals (SMRP) are attempting to harmonize indices and agree on indicators and references used for decades with no standard regulations.

In the following section, the structure and nomenclature of indicators respond to the letter "I" as an indicator symbol; a series of following characters indicates the maintenance area which has been developed the index. For example, IPM will refer to classic indicators of preventive maintenance. When there is more than one in an area, which will be usual, a number is added to consecutively distinguish them.

6.6.2.1 Preventive Maintenance

These indicators are PMI*n*, that is, PMI acronym followed by the number referencing the indicator inside the set of preventive maintenance.

$$\text{PMI1} = \frac{\text{Unavailability time due to failures}}{\text{Total unavailability time}}$$

$$\text{PMI2} = \frac{\text{Man-hours spent on emergency works}}{\text{Total worked man-hours}}$$

$$\text{PMI3} = \frac{\text{Direct cost due to repairs of failures}}{\text{Total maintenance direct costs}}$$

$$\text{PMI4} = \frac{\text{Preventive maintenance tasks performed}}{\text{Preventive maintenance tasks scheduled}}$$

$$\text{PMI5} = \frac{\text{Tasks estimated costs PM}}{\text{Tasks-Real costs (for) PM}}$$

$$\text{PMI6} = \frac{\text{Number of failures that should have been avoided}}{\text{Total number of failures}}$$

$$\text{PMI7} = \frac{\text{Total number of work orders generated in MP inspections}}{\text{Total number of work orders generated}}$$

$$\text{PMI8} = \frac{\text{Time operating demanded} - \text{Equipment downtime}}{\text{Time operating demanded}}$$

$$\text{PMI9} = \frac{\text{Number of PM delayed tasks}}{\text{Number of PM pending tasks}}$$

$$\text{PMI10} = \frac{\text{Maintenance overtime}}{\text{Total worked hours}}$$

Some of the classic indicators based on experience have been assumed by the present regulations; for example, the PMI10 indicator of overtime is among the indicators referenced by UNE 15341 [356], but this referencing is not common.

Cooke [57] recommends the use of comparisons of corrective and preventive maintenance to evaluate the goodness of programs such as RCM that reduce inefficient preventative maintenance; he proposes the indicators described next:

$$\text{PMI11} = \frac{\text{Preventive maintenance total costs}}{\text{Preventive maintenance total costs} + \text{Corrective maintenance total costs}}$$

$$\text{PMI12} = \frac{\text{Preventive maintenance unavailability time}}{\text{Preventive unavailability time} + \text{Corrective unavailability time}}$$

6.6.2.2 Inventory and Acquisition

These indicators concern the management of purchasing and supply of spare parts; those referring to known maintenance warehouse management are denoted by the warehouse management index (WMI*n*).

$$\text{WMI1} = \frac{\text{Line articles in the inactive stock}}{\text{Total line articles in stock}}$$

$$\text{WMI2} = \frac{\text{Annual cost of warehouse use}}{\text{Total inventory estimation}}$$

$$\text{WMI3} = \frac{\text{Total controlled spare parts in warehouse}}{\text{Total available inventory (controlled} + \text{uncontrolled)}}$$

$$\text{WMI4} = \frac{\text{Total number of spare parts fulfilled by order}}{\text{Total number of spare parts requested}}$$

$$\text{WMI5} = \frac{\text{Total number of spare parts not fulfilled by order}}{\text{Total number of spare parts requested}}$$

$$\text{WMI6} = \frac{\text{Total number of urgent purchase orders}}{\text{Total number of purchase orders}}$$

$$\text{WMI7} = \frac{\text{Total number of one article purchase orders}}{\text{Total number of purchase orders}}$$

$$\text{WMI8} = \frac{\text{Maintenance work orders awaiting spare parts}}{\text{Total number of work orders}}$$

$$\text{WMI9} = \frac{\text{Material costs charged to credit card}}{\text{Total costs of maintenance material}}$$

$$\text{WMI10} = \text{Internal costs to process a purchase order}$$

6.6.2.3 Work Order System

Indicators for the proper implementation of the WOs, that is, effectiveness and efficiency, are denoted as WOI*n*.

$$\text{WOI1} = \frac{\text{Maintenance labor costs over WOs}}{\text{Total costs of maintenance labor}}$$

$$\text{WOI2} = \frac{\text{Maintenance material costs over WOs}}{\text{Total costs of maintenance material}}$$

$$\text{WOI3} = \frac{\text{Subcontractors costs over WOs}}{\text{Total costs of maintenance contractors}}$$

$$\text{WOI4} = \frac{\text{Maintenance inactivity registered in WOs}}{\text{Total maintenance inactivity}}$$

$$\text{WOI5} = \frac{\text{Maintenance labor costs charged to permanent work order}}{\text{Total maintenance labor costs}}$$

$$\text{WOI6} = \frac{\text{Costs of maintenance materials charged to permanent work order}}{\text{Total costs of maintenance material}}$$

$$\text{WOI7} = \frac{\text{Costs of an especific equipment charged to a permanent work order}}{\text{Total costs of an specific equipment}}$$

$$\text{WOI81} = \frac{\text{Emergency orders}}{\text{Total number of work orders}}$$

$$\text{WOI82} = \frac{\text{Preventive orders}}{\text{Total number of work orders}}$$

$$\text{WOI83} = \frac{\text{Corrective orders}}{\text{Total number of work orders}}$$

$$\text{WOI9} = \frac{\text{Planned work orders}}{\text{Total number of received work orders}}$$

$$\text{WOI10} = \frac{\text{Maintenance labor costs charged to planned WOs}}{\text{Total maintenance labor costs}}$$

$$\text{WOI11} = \frac{\text{Maintenance material costs charged to planned WOs}}{\text{Total maintenance material costs}}$$

$$\text{WOI12} = \frac{\text{Scheduled maintenance hours}}{\text{Total number of maintenance worked hours}}$$

$$\text{WOI13} = \frac{\text{Maintenance overtime}}{\text{Total number of maintenance worked hours}}$$

$$\text{WOI14} = \frac{\text{Total number of hours estimated in scheduled work orders}}{\text{Total hours charged to scheduled WOs}}$$

$$\text{WOI15} = \frac{\text{Number of work orders with more than 20\% of estimated labor}}{\text{Total number of maintenance work orders}}$$

$$\text{WOI16} = \frac{\text{Number of work orders with more than 20\% of estimated materials}}{\text{Total number of maintenance work orders}}$$

$$\text{WOI17} = \frac{\text{Number of delayed work orders}}{\text{Total number of maintenance work orders}}$$

6.6.2.4 Computerized Maintenance Management System

Indicators for CMMS systems depend on the circumstances; they are associated with the correct system implementation and full integration with other information systems in the company, as seen in Figure 6.27. They monitor duplications and find information gaps in certain repositories or voluntary or involuntary omission in the transmission of information. CMMS software integrates finance, payroll, production control, SCADA, and so on. When CMMS is implemented in the maintenance module, some of the most widespread applications such as financial aspects and human resources are already installed.

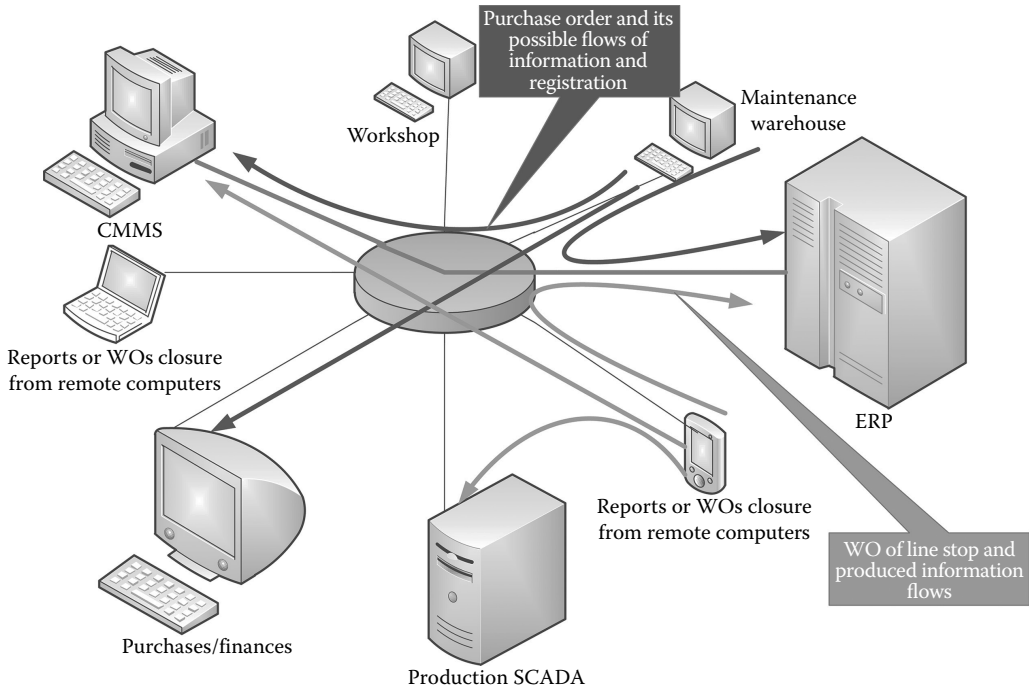


FIGURE 6.27
Software integration in maintenance. Need for accurate indicators.

All these indicators are called CMMSI*n*. The validity of CMMS indicators is limited over time; they cease to be useful when certain levels are reached in the successful implementation of information management.

$$\text{CMMSI1} = \frac{\text{Total labor costs in the CMMS}}{\text{Total maintenance labor costs in ERP}}$$

$$\text{CMMSI2} = \frac{\text{Total material costs in the CMMS}}{\text{Total material costs in ERP}}$$

$$\text{CMMSI3} = \frac{\text{Total subcontractors costs in the CMMS}}{\text{Total subcontractors costs in ERP}}$$

$$\text{CMMSI4} = \frac{\text{Total number of machines in the CMMS}}{\text{Total number of machines registered in the plant}}$$

$$\text{CMMSI5} = \frac{\text{Total number of spare parts in the CMMS}}{\text{Total number of spare parts in the plant}}$$

$$\text{CMMSI6} = \frac{\text{Total number of preventive maintenance tasks}}{3 \times (\text{Total number of machines registered in the plant})}$$

Consider an average of three preventive tasks per machine per year.

$$\text{CMMS7} = \frac{\text{Total maintenance cost of a piece of equipment in the CMMS}}{\text{Total maintenance costs in ERP}}$$

$$\text{CMMSI8} = \frac{\text{Total number of full time maintenance employees}}{\text{Number of supervisors}}$$

$$\text{CMMSI91} = \frac{\text{Total number of full time maintenance employees}}{\text{Number of planners}}$$

$$\text{CMMS92} = \frac{\text{Total number of full time maintenance employees}}{\text{Number of trainers}}$$

$$\text{CMMS10} = \frac{\text{Total number of maintenance technicians}}{\text{Number of administrative support staff}}$$

6.6.2.5 Technical and Interpersonal Training

Indicators referring to technical and interpersonal training are denoted by ITI*n*, responding to the IT acronym. This set of indicators has the most direct component of the human factor of the entire scorecard.

$$\text{ITI1} = \frac{\text{Total training budget}}{\text{Total number of employees}}$$

Note: Indicators ITI21 and ITI22 in the following example correspond to two matrices of the same indicator; that is, they have a strong correlation.

$$\text{ITI21} = \frac{\text{Total training hours}}{\text{Total number of employees}}$$

$$\text{ITI22} = \frac{\text{Total interpersonal training hours}}{\text{Total number of employees}}$$

$$\text{ITI3} = \text{Workers reading level}$$

$$\text{ITI4} = \text{Level of skills from sectorals and national tests}$$

$$\text{ITI5} = \text{Correspondence level between training provided and abilities acquired}$$

$$\text{ITI6} = \frac{\text{Total number of trainers}}{\text{Total number of maintenance employees}}$$

$$\text{ITI7} = \frac{\text{Inactivity time operating mistakes due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI8} = \frac{\text{Inactivity time maintenance mistakes due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI9} = \frac{\text{Time lost due to lack of knowledge}}{\text{Total worked time}}$$

$$\text{ITI10} = \frac{\text{Repeated maintenance time due to lack of knowledge}}{\text{Total worked time}}$$

$$\text{ITI11} = \frac{\text{Annual training budget}}{\text{Annual workers payroll budget}}$$

In the case of satisfaction with the tools and uniforms provided by the organization, the indicators are denoted by T&UI*n*:

$$\text{T\&UI1} = \frac{\text{Satisfied maintenance operators with personal equipment}}{\text{Total number of operators}}$$

$$\text{T\&UI2} = \frac{\text{Satisfied maintenance officers with technical equipment which have}}{\text{Total number of maintenance officers}}$$

$$\text{T\&UI3} = \frac{\text{Performed investments in maintenance equipment}}{\text{Planned investments in maintenance equipment}}$$

6.6.2.6 Operational Involvement

The production workers involved in the maintenance, care, or improvement of machinery have the indicators shown in the next set: OII*n*.

$$\text{OII1} = \frac{\text{Preventive maintenance hours by production operators}}{\text{Total preventive hours}}$$

$$\text{OII21} = \frac{\text{Equipment inactivity related to maintenance year_}n}{\text{Equipment inactivity related to maintenance year_}n-1}$$

OII2 = Values of the production operators involvement in maintenance

$$\text{OII22} = \frac{\text{Equipment capability related to maintenance year_}n}{\text{Equipment capability related to maintenance year_}n-1}$$

$$\text{OII23} = \frac{\text{Preventive maintenance hours by operator's year_}n}{\text{Preventive maintenance hours by operator's year_}n-1}$$

$$\text{OII31} = \frac{\text{Hours of equipment improvement per production operator}}{\text{Total number of worked hours by operators}}$$

$$\text{OII32} = \frac{\text{Hours of equipment improvement per maintenance operator}}{\text{Total number of worked hours by operators}}$$

6.6.2.7 Predictive Maintenance

The indicators relating to the implementation of a predictive maintenance program are denoted as CBMI, corresponding to "condition-based monitoring (CBM)."

$$\text{CBMI11} = \frac{\text{Total predictive maintenance hours}}{\text{Total maintenance hours}}$$

$$\text{CBMI12} = \frac{\text{Predictive maintenance costs}}{\text{Total maintenance costs}}$$

$$\text{CBMI2} = \text{Avoided costs due to use of predictive maintenance}$$

$$\text{CBMI3} = \frac{\text{Current maintenance costs}}{\text{Maintenance costs prior to CBM program}}$$

CBMI4 calculates the MTBF as the success indicator of the predictive program.

$$\text{CBMI4} = \frac{\text{Total hours considered}}{\text{Number of failures of an equipment}}$$

6.6.2.8 Reliability-Centered Maintenance and Financial-Statistic Optimization

The indicators relating to the RCM, that is, to the proper implementation of RCM, are denoted by RCMI.

$$\text{RCMI1} = \frac{\text{Number of repetitive failures}}{\text{Total number of equipment failures}}$$

$$\text{RCMI2} = \frac{\text{Number of equipment failures where they perform cause analysis}}{\text{Total number of equipment failures}}$$

$$\text{RCMI3} = \frac{\text{Number of reviewed preventive tasks in critical equipment}}{\text{Total number of preventive tasks in critical equipment}}$$

$$\text{RCMI4} = \frac{\text{Number of reviewed predictive tasks in critical equipment}}{\text{Total number of predictive tasks in critical equipment}}$$

$$\text{RCMI5} = \text{Avoided costs due to use of RCM}$$

$$\text{IRCM6} = \text{Reduction of non-compliance and accidents due to use of RCM}$$

RBSC7 calculates the MTBF success indicator of an RCM program:

$$\text{RCMI7} = \frac{\text{Total hours considered}}{\text{Number of failures of an equipment}}$$

$$\text{RCMI8} = \frac{\text{Number of reviewed spare parts in critical equipment}}{\text{Total number of spare parts in critical equipment}}$$

The indicators corresponding to financial optimization, the result of RCM analysis, are FINOPI.

$$\text{FINOPI1} = \frac{\text{Number of reviewed tasks by financial efficiency in critical equipment}}{\text{Total number of maintenance tasks in critical equipment}}$$

$$\text{FINOPI2} = \frac{\text{Number of major spare parts reviewed by financial efficiency in critical equipment}}{\text{Total number of spare parts in critical equipment}}$$

$$\text{FINOPI3} = \frac{\text{Number of reviewed policies of routine spare parts in critical equipment}}{\text{Total number of routine spare parts in critical equipment}}$$

$$\text{FINOPI4} = \text{Savings achieved by financial studies}$$

6.6.2.9 Total Productive Maintenance: Overall Equipment Effectiveness (OEE)

TPM is often confused with autonomous maintenance, that is, small tasks, such as lubrication or cleaning assets. Some indicators such as the three components of OEE do not need acronyms as they are OEEI1, OEEI2, and OEEI3. The other indicators linked to productive maintenance are classified as TPMI*n*.

$$\text{OEEI1} = \text{Availability} = \frac{\text{Total activity time}}{\text{Programmed time}}$$

$$\text{OEEI2} = \text{Performance efficiency} = \frac{\text{Actual production for the programmed time}}{\text{Planned production for the programmed time}}$$

$$\text{OEEI3} = \text{Quality rate} = \frac{\text{Total production} - \text{Defects}}{\text{Total production}}$$

$$\text{OEE} = \text{OEEI1} \times \text{OEEI2} \times \text{OEEI3}$$

$$\text{TPMI2} = \frac{\text{Critical equipment included in design improvement studies}}{\text{Total number of critical equipment}}$$

$$\text{TPMI3} = \frac{\text{Critical equipment included in 5S activities}}{\text{Total number of critical equipment}}$$

$$\text{TPMI4} = \text{Profits obtained due to OEE increase}$$

$$\text{TPMI5} = \text{Decrease in the unit production cost}$$

$$\text{TPMI6} = \frac{\text{Total absenteeism hours}}{\text{Total considered hours}}$$

Many authors, including Idhammar [127], Ivančić [135], Löppönen [195], and Wilson [373], say OEE is the most widely used indicator in TPM implementations as it has multilevel scope and wide dissemination. OEE has the ability to specify the real possibility of assets to achieve the quality demanded. It gathers information from departments such as quality, production, and maintenance. Working with OEE is possible only in highly integrated maintenance–production structures, however.

6.6.2.10 Continuous Improvement

Another issue addressed by classic indicators is continuous improvement. The nomenclature is KAII*n*, where KAI comes from "Kaizen," a term coined by Japanese industry to represent the concept of continuous improvement.

$$\text{KAII1} = \text{Savings achieved by employees' suggestions}$$

$$\text{KAII2} = \text{Savings achieved by practices obtained by benchmarking}$$

$$\text{KAII3} = \frac{\text{Critical equipment included in continuous improvement activities}}{\text{Total number of critical equipment}}$$

$$\text{KAII4} = \frac{\text{Number of suggestions given by maintenance employees}}{\text{Total number of maintenance employees}}$$

6.6.2.11 Subcontractors

The external companies involved in the production process through the provision of maintenance services are often subjected to measurement of various parameters. These indicators are CONTI*n*, with CONT referring to "subcontractors."

$$\text{CONTI1} = \frac{\text{Availability time of contracted services}}{\text{Required time}}$$

$$\text{CONTI2} = \frac{\text{Number of works requiring repetition}}{\text{Number of works performed by contractors}}$$

CONTI3 = Years of experience in the reference field

CONTI4 = Quality certifications as supplier

CONTI5 = Technological level of outsourced staff

6.6.2.12 Corporate Indicators

The company managers typically incorporate too few data on production into their scorecard. Almost none refers to maintenance. The three indicators listed next are designated as ICORP*n* to designate the corporate character of senior management. The general management on plant or factory has historically been concerned about the total production budget as well as the ability to use installed assets. Another aspect to consider is the cost of occupying a warehouse or an office.

- *CORPI1 Total production cost. All expenses required to manufacture a product*
- *CORPI2 Total occupation cost. All expenses for occupying a facility*
- *CORPI3 Assets performance. Comparison of the gain in the net value of fixed assets of the company*

6.6.2.13 Financial Indicators

The financial indicators listed in the following are the most classic ones. They are referred to as FINI*n*.

- *FINI1 Maintenance costs per unit processed, produced, or manufactured*
- *FINI2 Maintenance costs totaling process, production, or manufacturing costs*
- *FINI3 Sales maintenance costs*
- *FINI4 Maintenance costs per square meter*
- *FINI5 Maintenance costs by estimated replacement value of the plant or installation assets*
- *FINI6 Storage investment by estimated replacement value*
- *FINI7 Value of the asset at which the given maintenance carried out by maintenance worker*
- *FINI8 Subcontracting costs by total maintenance costs*

Some of these indicators have been incorporated into the recently published regulations. Maintenance costs per unit produced or maintenance costs for replacement value are incorporated into all panels, standards, and recommendations published to date.

6.6.3 Proposed Indicators by UNE-EN 15341:2008

This European Standard provides maintenance performance indicators to support management in achieving excellence in maintenance and employment of technical assets

in a competitive manner. Most of these indicators apply to all buildings, spaces, industrial services, and support (buildings, infrastructure, transport, distribution, networking, etc.). These indicators should be used to

- Measure condition
- Make comparisons (internal and external references)
- Perform diagnostics (analysis of strengths and weaknesses)
- Identify objectives and define goals to be achieved
- Plan actions for improvement
- Measure changes continuously over time

This standard describes a system for managing indicators to measure the maintenance performance within the context of the factors that influence it, such as economic, technical, and organizational aspects, in order to evaluate and improve the efficiency and effectiveness to achieve excellence in asset maintenance.

UNE-EN says maintenance performance depends on both external and internal factors, such as the location, culture, transformation process and service, size, rate of use, and age. It is achieved through the implementation of corrective and preventive maintenance activities and improvement, applying labor, information, materials, organizational methodologies, tools, and operational techniques. When a factor is defined using "internal" or "external" words, the corresponding indicator also should be used for "internal" or "external" influences, respectively.

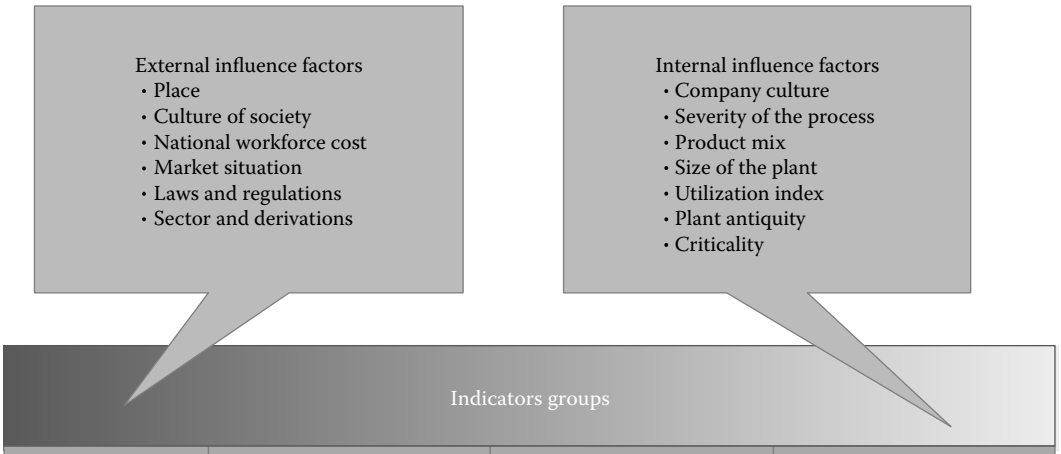
Figure 6.28 illustrates the external and internal factors that influence maintenance performance. External factors are variable conditions beyond the control of the company's management. Internal factors are specific to the group, company, factory, and facilities that are beyond the control of maintenance management but within the control of company management. When key performance maintenance indicators are used, it is important to consider these influencing factors as prerequisites to avoid misinterpretations.

Traditionally, only internal factors were considered in the maintenance field and the indicators corresponded with cost, labor hours, and little else. Dean [61] highlights the focus on balance between effectiveness and efficiency proposed by the standard, which also suggests new indicators, such as the success of RCM programs or maintenance planning capability.

To cover this mixed aspect of maintenance efficiency and effectiveness, a system of key performance indicators is structured in three groups: economic, technical, and organizational indicators. These proposed indicators can be evaluated as a relationship between factors (numerator and denominator), measurement activities, resources, or events according to a given formula. The rates proposed in this document are useful for measuring quantitative aspects or features and to make homogeneous comparisons.

These indices espoused by the standard can be used

- On a periodic basis, for example, to prepare and monitor a budget or during performance evaluation
- On a regular basis, for example, within the frame of specific audits, studies, and/or comparisons for improvement



	Level 1	Level 2	Level 3
Economic indicators	E1, E2, E3, E4, E5, E6	E7, E8, E9, E10, E11, E12, E13, E14	E15, E16, E17, E18, E19, E20, E21, E22, E23, E24
Technical indicators	T1, T2, T3, T4, T5	T6, T7	T8, T9, T10, T11, T12, T13, T14, T15, T16, T17, T18, T19, T20, T21
Organizational indicators	O1, O2, O3, O4, O5, O6, O7, O8	O9, O10	O11, O12, O13, O14, O15, O16, O17, O18, O19, O20, O21, O22, O23, O24, O25, O26

FIGURE 6.28
Factors influencing maintenance and key performance indicators as noted in UNE 15341. (Adapted from UNE-EN 15341:2008, Mantenimiento. Indicadores clave de rendimiento del mantenimiento, AENOR, Madrid, Spain.)

The time period to consider for measurement depends on company policy and management approach.

Some indicators presented in the standard are used in other approaches such as SMRP or Wireman. It is noteworthy that the standard recognizes only three indicator aspects: financial, technical, and organizational. It relegates the technical aspects to the lowest ranks of the pyramid. The standard notes the different perspectives of a maintenance scorecard but only analyzes economic indicators; it proposes organizational indicators as an aspect of human resources.

The standard leaves many aspects untreated, however. In addition, the technical, financial, and economic aspects appear insufficient to function as maintenance indicators. Similarly, the standard classifies indicators into three levels but does not specify what kind of organization must assume the levels. Nor does it mention benchmarks and objectives for each indicator, thus failing to provide the perspective necessary to implement them. Indicator implementation is inexorably linked to an objective; the success of the strategy used to achieve the objective is measured by these indices.

6.6.3.1 Economic Indicators

The corresponding nomenclature is IE followed by a sequential number from 1 to 24. This group corresponds to efficiency indicators from the cost model. Traditionally, these

indicators are considered superior to operational indicators and are intended for measurement of financial or corporate management; they are rarely used by maintenance management.

$$\text{EI1} = \frac{\text{Total maintenance costs}}{\text{Assets replacement value}}$$

$$\text{EI2} = \frac{\text{Total maintenance costs}}{\text{Added value plus external maintenance costs}}$$

$$\text{EI3} = \frac{\text{Total maintenance costs}}{\text{Quantity produced}}$$

$$\text{EI4} = \frac{\text{Total maintenance costs}}{\text{Transformation cost to production}}$$

$$\text{EI5} = \frac{\text{Total maintenance costs} + \text{Unavailability costs linked to maintenance}}{\text{Quantity produced}}$$

$$\text{EI6} = \frac{\text{Availability linked to maintenance}}{\text{Quantity produced}}$$

$$\text{EI7} = \frac{\text{Average inventory value of maintenance articles}}{\text{Assets replacement value}}$$

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI9} = \frac{\text{Total cost of external staff used in maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI10} = \frac{\text{Total contracting cost}}{\text{Total maintenance costs}}$$

$$\text{EI11} = \frac{\text{Total cost of maintenance articles}}{\text{Total maintenance costs}}$$

$$\text{EI12} = \frac{\text{Total cost of maintenance articles}}{\text{Average inventory value of maintenance articles}}$$

$$\text{EI13} = \frac{\text{Cost by indirect maintenance staff}}{\text{Total maintenance costs}}$$

$$EI14 = \frac{\text{Total maintenance costs}}{\text{Total energy used}}$$

$$EI15 = \frac{\text{Corrective maintenance cost}}{\text{Total maintenance costs}}$$

$$EI16 = \frac{\text{Preventive maintenance cost}}{\text{Total maintenance costs}}$$

$$EI17 = \frac{\text{CBM maintenance cost}}{\text{Total maintenance costs}}$$

$$EI18 = \frac{\text{Systematic maintenance cost}}{\text{Total maintenance costs}}$$

$$EI19 = \frac{\text{Improvement maintenance cost}}{\text{Total maintenance costs}}$$

$$EI20 = \frac{\text{Cost of programmed maintenance stops}}{\text{Total maintenance costs}}$$

$$IE21 = \frac{\text{Maintenance staff training cost}}{\text{Effective of maintenance staff}}$$

$$EI22 = \frac{\text{Total contracting cost of mechanical maintenance}}{\text{Total maintenance costs}}$$

$$EI23 = \frac{\text{Total contracting cost of electrical maintenance}}{\text{Total maintenance costs}}$$

$$EI24 = \frac{\text{Total contracting cost of instrumentation maintenance}}{\text{Total maintenance costs}}$$

6.6.3.2 Technical Indicators

Technical indicators respond to maintenance effectiveness and come more directly from RAMS parameters. Traditionally, these indicators are managed from the hierarchical base because they are closest to productive assets and considered less relevant for corporate direction. The designation is TI for technicians, with numbering from 1 to 21.

$$TI1 = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Maintenance unavailability time}}$$

$$TI2 = \frac{\text{Availability time achieved during the required time}}{\text{Required time}}$$

$$TI3 = \frac{\text{Number of failures due to maintenance that generates environmental damage}}{\text{Calendar time}}$$

$$TI4 = \frac{\text{Annual volume of harmful residues related to maintenance}}{\text{Calendar time}}$$

$$TI5 = \frac{\text{Number of staff injuries due to maintenance}}{\text{Working time}}$$

$$TI6 = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailable time due to failures}}$$

$$TI7 = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailability time due to planned maintenance}}$$

$$TI8 = \frac{\text{Preventive maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$TI9 = \frac{\text{Systematic maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$TI10 = \frac{\text{CBM time which causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$TI11 = \frac{\text{Number of failures which cause injuries to staff}}{\text{Total number of failures}}$$

$$TI12 = \frac{\text{Number of failures which can cause injuries to staff}}{\text{Total number of failures}}$$

$$TI13 = \frac{\text{Number of failures which cause environmental damage}}{\text{Total number of failures}}$$

$$TI14 = \frac{\text{Number of failures which can cause environmental damage}}{\text{Total number of failures}}$$

$$TI15 = \frac{\text{Total operating time}}{\text{Number of maintenance work orders which causes unavailability time}}$$

$$TI16 = \frac{\text{Total operating time}}{\text{Number of maintenance work orders}}$$

$$TI17 = \frac{\text{Total operating time}}{\text{Number of failures}}$$

$$TI18 = \frac{\text{Number of systems covered by criticality analysis}}{\text{Total number of systems}}$$

$$TI19 = \frac{\text{Total number of hours to plan systematic maintenance}}{\text{Total number of hours of internal maintenance staff}}$$

$$TI20 = \frac{\text{Planned and scheduled maintenance time causing unavailability}}{\text{Planned and scheduled maintenance time that requires unavailability}}$$

$$TI21 = \frac{\text{Total recovery time}}{\text{Number of failures}}$$

6.6.3.3 Organizational Indicators

Organizational indicators respond to efficiency in human resources; this includes an economic background and relevant aspects of the human factor involved in the process. Indicators are IO*n*, with *n* representing consecutive numbers from 1 to 26.

$$OI1 = \frac{\text{Effective of internal maintenance staff}}{\text{Total effective of internal employees}}$$

$$OI2 = \frac{\text{Effective of indirect maintenance staff}}{\text{Effective of internal maintenance staff}}$$

$$OI3 = \frac{\text{Effective of indirect maintenance staff}}{\text{Effective of direct maintenance staff}}$$

$$OI4 = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI5 = \frac{\text{Planned and scheduled maintenance man-hours}}{\text{Total number of maintenance man-hours available}}$$

$$OI6 = \frac{\text{Number of injuries of the maintenance staff}}{\text{Total effective of maintenance staff}}$$

$$OI7 = \frac{\text{Man-hours lost by injuries of maintenance staff}}{\text{Total man-hours worked by maintenance staff}}$$

$$OI8 = \frac{\text{Man-hours used in continuous improvement}}{\text{Total man-hours of maintenance staff}}$$

$$OI9 = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of production operators}}$$

$$OI10 = \frac{\text{Direct maintenance staff working in shifts}}{\text{Total effectives of direct maintenance staff}}$$

$$OI11 = \frac{\text{Time spent on emergency corrective maintenance}}{\text{Unavailability total time linked to maintenance}}$$

$$OI12 = \frac{\text{Man-hours of mechanical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI13 = \frac{\text{Man-hours of electrical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI14 = \frac{\text{Man-hours of instrumentation maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI15 = \frac{\text{Effective of internal maintenance staff with various activities}}{\text{Effective of internal maintenance staff}}$$

$$OI16 = \frac{\text{Corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI17 = \frac{\text{Emergency corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI18 = \frac{\text{Preventive maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI19 = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI20 = \frac{\text{Systematic maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI21 = \frac{\text{Maintenance overtime}}{\text{Total number of internal maintenance man-hours}}$$

$$OI22 = \frac{\text{Number of work orders performed according to planification}}{\text{Number of work orders programmed}}$$

$$OI23 = \frac{\text{Number of man-hours for maintenance training internal staff}}{\text{Total maintenance man-hours}}$$

$$OI24 = \frac{\text{Effective of the maintenance internal staff using computer}}{\text{Effective of the internal direct staff}}$$

$$\text{OI25} = \frac{\text{Direct maintenance man-hours in scheduled activities}}{\text{Total planned man-hours for direct staff}}$$

$$\text{OI26} = \frac{\text{Number of spare parts supplied by warehouse according to requests}}{\text{Total number of spare parts required by maintenance}}$$

6.6.3.4 Harmonization with American Model

The emergence of this standard published in Europe in the last year and a half has led to the beginning of a project of harmonization between two organizations promoting maintenance metrics: the American SMRP and the European EFNMS. The purpose is to extend the use of indicators on both sides of the Atlantic, creating homogeneous definitions that allow a company to use benchmarking without stopping to think whether the concept might differ.

They are comparing the European standard UNE-EN 15341 [356] and the American standard SMRP Best Practice Metrics. Harmonization is based on previous papers by Svantesson [313], and the first results were published in June 2002; see EFNMS Working Group 7 [90]. They have identified the 13 indicators, as shown in Table 6.3.

The number of indicators on both sides of the Atlantic has been growing. Kahn and Gulati [146] and Olver and Kahn [251] list 70 indicators proposed by SMRP; UNE-EN 15341 [356] has 71.

The harmonization started out by defining the terms used to describe each indicator in the European maintenance terminology standards EN: 13306 [93] "Maintenance Terminology" and IEC 60050-191 [129] "Dependability and Quality of Service." This prior harmonization of terms recently led to the publication of a glossary by SMRP Best Practices Committee [301].

All these indicators can be used by any manufacturing company; some can even be used by service companies. To develop performance indicators, according to Wireman, the following are important:

1. Make sure strategic objectives are clear, focusing on and considering the organization as a whole
2. Link business processes to essential objectives
3. Focus on critical success factors for each part of the process, recognizing their respective variables
4. Track performance trends and highlight progress and potential problems
5. Identify possible solutions to problems

To date, attempts to involve strategic objectives in the processes have not worked well because of the elitism of the hierarchy of indicators. In traditional models, financial and corporate indicators are still reserved for higher levels of the company, with functional and technical performance indicators relegated to the lower levels. This divergence is avoided with the proposed model; some of the functional or technical indicators rise to higher layers, and financial performance indicators move down to the middle strata; a BSC policy is set at all levels, and all hierarchies of the organization are aligned (Tables 6.2 and 6.3). The indicator-to-indicator comparison has led to a classification of three types:

1. *Identical indicators*: These are the same and have the same definitions, allowing direct benchmarking.

TABLE 6.2

Harmonized Indicators in June 2002

Original EFNMS WG 7 Indicators	Measure Unit	UNE 15341
I:01 Maintenance cost as % of plant replacement cost	%	E1
I:02 Spares investment as % of plant replacement cost	%	E7
I:03 Subcontractors' cost as % of the maintenance budget	%	E10
I:04 Preventive maintenance cost as % of the maintenance budget	%	E16
I:05 Preventive maintenance man-hours as % of total maintenance man-hours	%	O18
I:06 Maintenance costs as % of billing budget	%	
I:07 Maintenance man-hours for training as % of total maintenance man-hours	%	O23
I:08 Corrective maintenance man-hours for emergencies as % of total maintenance man-hours	%	O17
I:09 Planned and scheduled maintenance man-hours as % of total maintenance man-hours	%	O5
I:10 Time required for operation as % of available time	%	
I.11 Time taken for operation as % of the time required	%	T1/T2
I.12 Time taken for operation/number of corrective maintenance interventions for emergencies	hours	T16
I:13 Time taken for corrective maintenance interventions for emergencies/ number of corrective maintenance interventions for emergencies	hours	T21

2. *Similar indicators*: These provide similar information but do not exactly match.
3. *Same performance*: Performance is calculated differently but the result may be comparable.

In the late 2007, the SMRP published the results of the first harmonization of 16 indicators with the intention of eventually harmonizing all 70; see SMRP Press Release [302].

This eliminates a process in which customer and supplier only need to know who is claiming their services, and parameters of quality are rated by the latter, creating islands of information. The processes lack a global overview of the objectives and scorecards. This process with client and supplier can be seen in Figure 6.29.

Jurán [143] notes that the internal customer and supplier-chain customer are isolated from the organization's global knowledge.

6.7 Hierarchy of Indicators

6.7.1 Indicators in Multilevel Organizations

According to Svantesson [312], a KPI must be adapted to the organizational hierarchy it will use. Svantesson's suggestion can be seen in Figure 6.30; he proposes three hierarchical levels for the use of three different measures:

- Main KPI or Company KPI
- Basic KPI or Production KPIs
- Key performance parameters (KPP) for support functions and support to production, as in maintenance

TABLE 6.3

SMRP-EFNMS [90] Indicators Harmonized to January 2007

SMRP	Description	EN 15341	Harmonization Results	Comments
1.4	Maintenance inventory for replacement value	E7	Identical	Both indicators exclude spare's depreciation cost.
1.5	Maintenance cost for replacement value	E1	Identical	The 15341 includes depreciation of property maintenance equipment in annual costs.
3.5.1	MTBF	T17	Identical	
3.5.2	MTTR	T21	Identical	The 15341 uses the restore term, while SMRP uses the concept of repair.
4.2.1	Training costs	E21	Identical	
4.2.2	Training hours	O23	Similar	The 15341 calculates as a percentage of staff hours, while SMRP calculates hours per year.
5.1.1	Corrective maintenance cost	E15	Identical	The 15341 includes depreciation of property maintenance equipment in annual costs.
5.1.2	Corrective hours	O16	Identical	
5.4.1	Emergency corrective hours	O17	Same performance	The 15341 measures only the hours spent on actions that require immediate intervention.
5.4.2	Preventive man-hours	O18	Identical	
5.4.4	Accomplishment of planned WOs	O22	Identical	
5.5.6	Staff working in shifts	O10	Identical	
5.5.8	Overtime	O21	Similar	The 15341 estimates direct and indirect staff; SMRP estimates only direct. Permanent contractors are not considered.
5.5.33	Breaches of stock	O26	Idéntico	The 15341 estimates success rate and SMRP the failure.
5.5.71	Maintenance contractors' costs	E10	Identical	The 15341 includes depreciation of equipment owned by the company.
5.7.1	Continuous improvement hours	O8	Identical	

Svantesson presents a descending hierarchy, in which global KPIs start to break down and adapt to lower levels. However, we suggest two significant improvements to the author's model. First, the information from maintenance or other support areas should ascend to the highest levels. Second, the maintenance KPP is relegated to the head of maintenance but is difficult to explain, so the third level is divided into levels of leadership, middle managers, and officers, and its KPPs are adapted.

Finally, the concept of KPI and KPP is subtle but links the production function to corporate objectives.

There are many definitions for the concept of parameter as well, starting with the following fairly general one: "A parameter is a variable that in a family of elements is used to identify each by its numerical value." From the business organization point of view, the concept of parameter can be understood as follows: "A parameter is an element or factor that characterizes and identifies a susceptible aspect of measurement for the purpose of

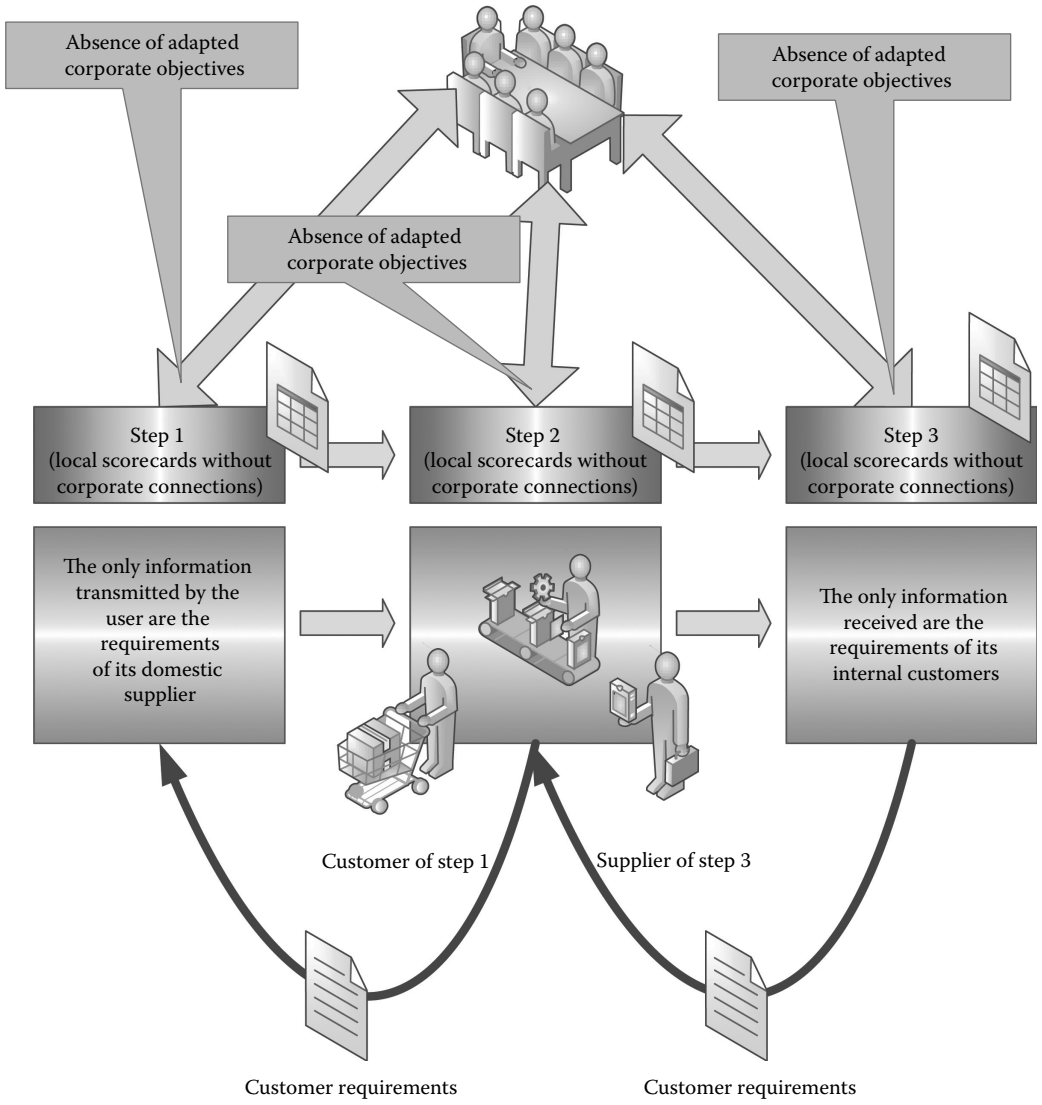


FIGURE 6.29
Scorecards using a classical internal customer perspective.

evaluating or establish a control over that aspect"; see Alfaro [4]. This definition assumes that all parameters indicate some qualitative or quantitative characteristic, measured through a value that will serve to monitor and control it.

There are also several definitions of indicator. Chatin et al. [51] say: "An indicator represents the behavior of the levers of action, of the results and their evolutions. It is characterized by a single definition that allows a common language, a source and a calculation frequency." Parameter and indicator, for all practical purposes, have the same meaning, thereby allowing them to be used interchangeably for the same purpose. It is, therefore, unnecessary for maintenance to use the word "parameter" instead of "indicator" when they are semantically equivalent and both serve the global objectives of the company.

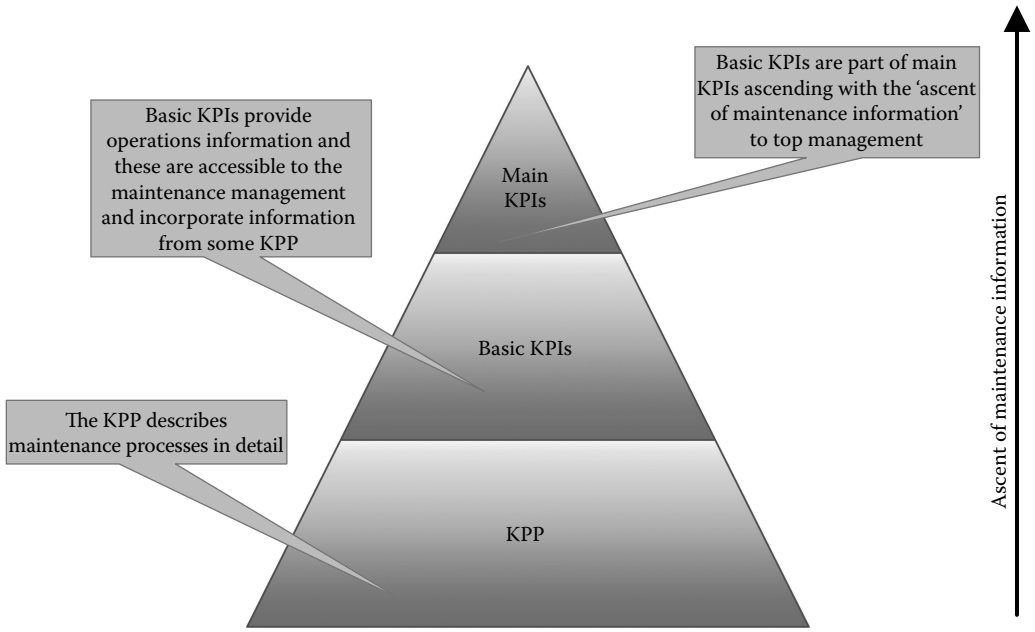


FIGURE 6.30
Hierarchy of KPIs and KPPs according to Svantesson. (Adapted from Svantesson, T., Course materials handed out at the UTEK conference "Aktuellt inomm underhåll", UTEK, Stockholm, Sweden, 2001.)

Maintenance indicators must end the traditional view of maintenance as an inferior or secondary process; see Löfsten [192]. At the least, it performs a supporting function or provides logistic support.

6.7.2 Maintenance Organizational Structure and Indicators Proposed through BSC

We have proposed a hierarchy of indicators in five levels observed from the four perspectives of the balanced scorecard and organized according to five different hierarchical levels. The most modern organizations in processes, manufacturing, and even service provision have adopted organization charts for the hierarchy of indicators (Figure 6.31):

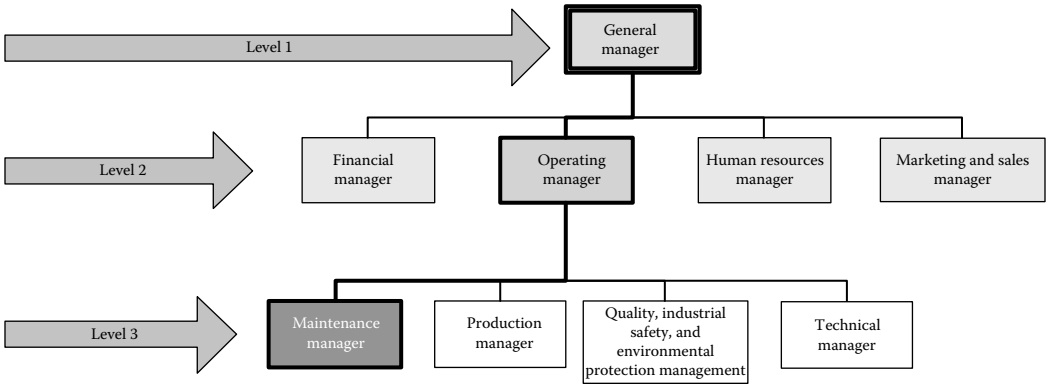


FIGURE 6.31
Organization chart of management levels.

The corporate organizational chart begins with Level 1, management or general management; this level will determine prime directives, including for operations, considered Level 2, which, in turn, contains production and maintenance, considered Level 3. In other words, it defines a range of three levels from the head of maintenance to the CEO with an operations manager in the middle. This implies the existence of relevant indicators for maintenance on each of the levels. In this case, human resources can be located at Level 2; the department will supply information for some indicators but, in turn, must monitor others, for example, in maintenance and in other areas of the company.

The maintenance department has three hierarchical levels, as seen in organizational chart in Figure 6.32.

- *Operations manager*: Is responsible for providing services required by the plant, such as preventive and corrective maintenance, in a timely and efficient manner. Depending on the plant size, there may be supervisors under the operations manager; the supervisors manage maintenance operations in the respective units. Supervisors and operation managers are in charge of workers who are assigned to a particular area or sent where they are needed.
- *Planning manager*: Plans and enforces all maintenance plans that are strategically developed for key areas of the company. Planning is based on WOs, the equipment history, and available resources.
- *Control and management manager*: Reviews the indicators presented in the previous section and monitors their improvement, especially if negative figures are found; assists the maintenance manager in the interpretation and observation of the scorecard and the promotion of timely corrective measures.
- *Administrative manager*: Is responsible for managing all aspects of the maintenance budget and personnel involved in maintenance; also manages tools, spare parts warehouse, and purchasing.
- *Hygiene and safety manager*: Prevent accidents to people, the environment, and the physical structure.

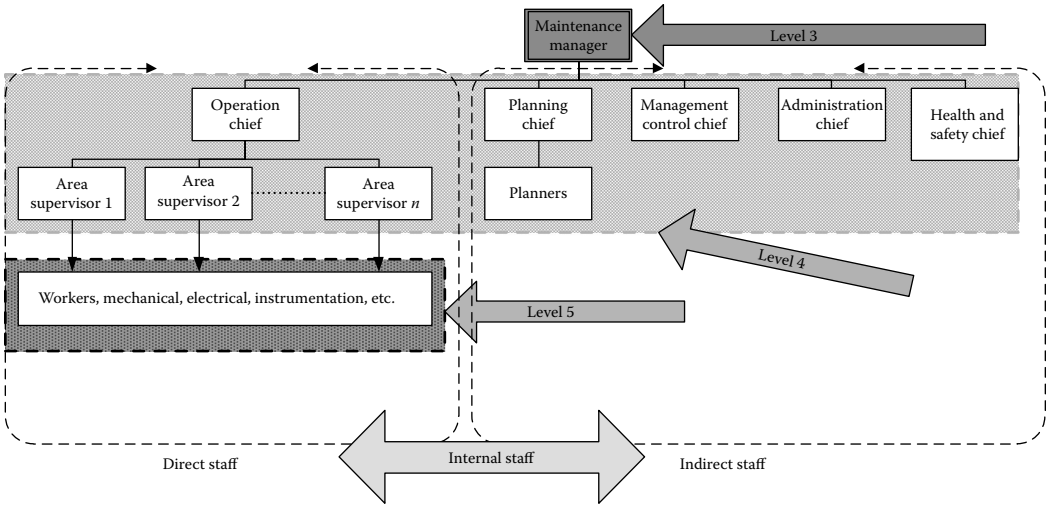


FIGURE 6.32
Organizational chart of maintenance function.

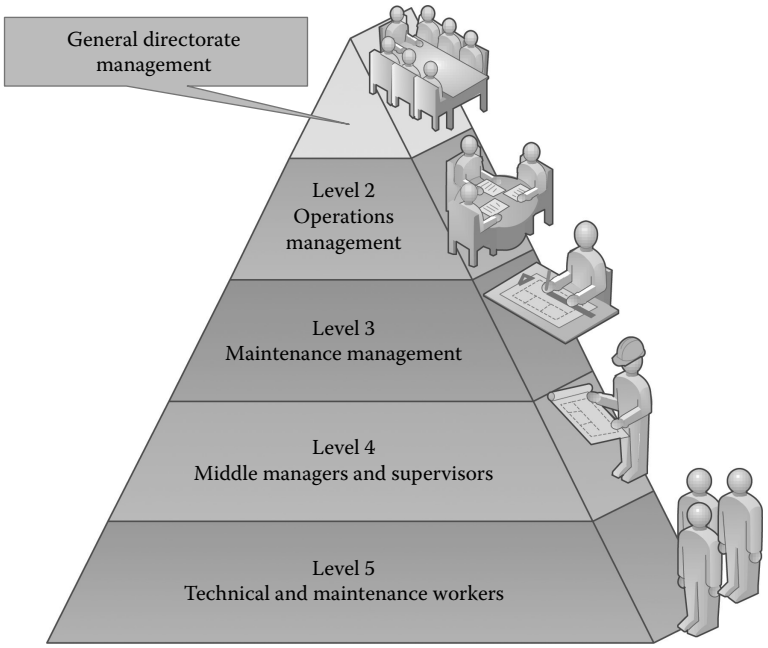


FIGURE 6.33
Organizational levels in the hierarchy of indicators.

The last four are considered indirect maintenance staff and are linked to CMMS management as are most administrative and support staff.

All these levels represent functional figures and do not need to be a single person; depending on the size of the organization, there may be several. The position of operations manager is justified when there are several area supervisors, that is, of the shop workers or personnel working at the machines.

The maintenance function generates information flows in five different levels, as seen in Figure 6.33, going from the operator who performs the most basic preventive WOs to a hierarchical level equivalent to the manager or CEO. Each tier needs appropriate indicators based on the information required for its daily work.

The five hierarchical levels are the following:

- *Level 5*: This level includes operators, maintenance technicians, and engineers working at the machine, ensuring technical and functional integrity.
- *Level 4*: This level represents a middle manager of maintenance or a supervisor responsible for the upkeep and maintenance of a particular machine with a series of mechanical and electrical workers performing the maintenance. The indicators proposed at this level directly affect a subsystem formed by a machine or multiple machines as well as administration or indirect maintenance activity.
- *Level 3*: This level is considered the head of maintenance. It includes production and quality managers as well as the engineering department manager and the technical department manager, if there is one.
- *Level 2*: This level represents operations management, encompassing all the responsibilities of the handling and transformation of raw materials, as well as

the conservation and maintenance of productive assets. CFOs, HR, or marketing may require indicators of maintenance at this level.

- *Level 1*: This represents the corporate-level or general management. It is the organization's highest level.

After defining the levels in the hierarchy that generate indicators, we must apply the four BSC perspectives (Figure 6.34).

The hierarchy of indicators is proposed simultaneously with the perspectives, noting the level that makes more use of each indicator. An indicator is not necessarily exclusive to a particular level, but the information it provides is more or less important to the various objectives at the different levels. The indicators can be known to everyone, but only a few levels are able to use and modify them.

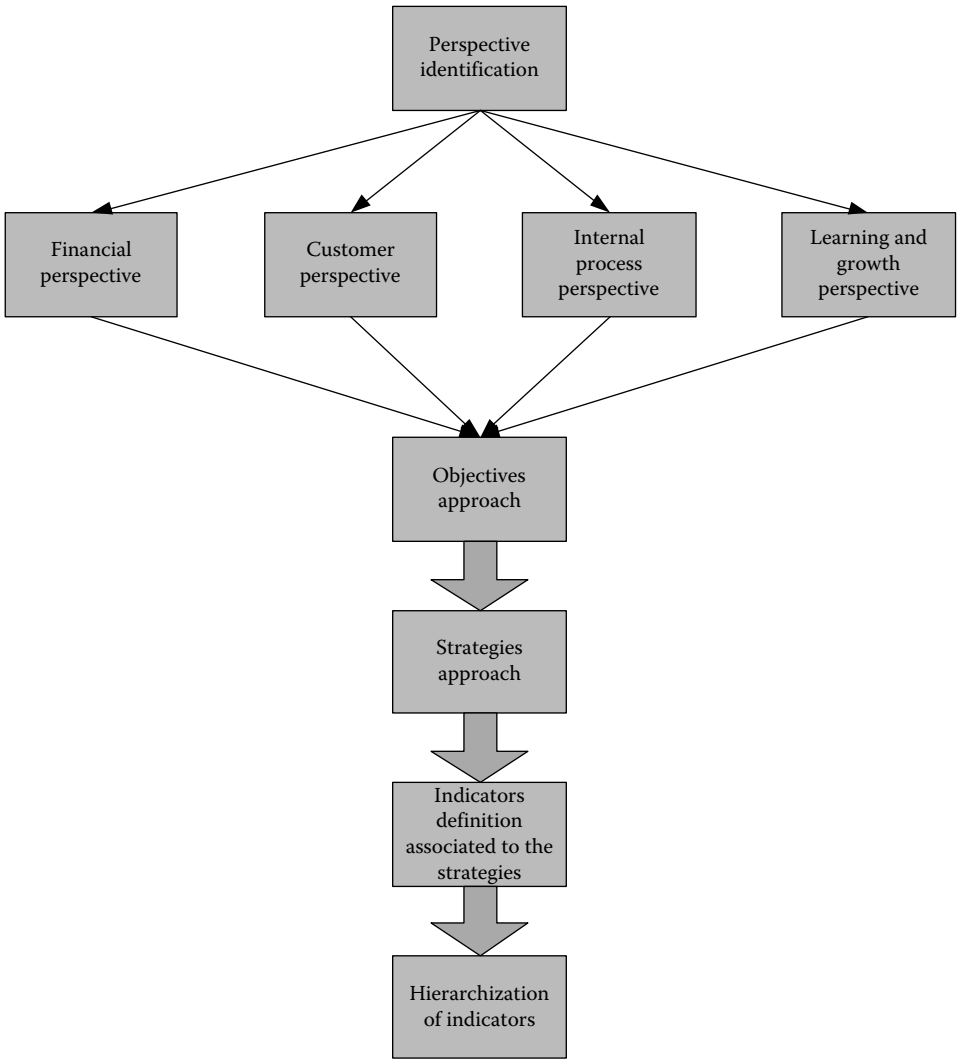


FIGURE 6.34
Selection of indicators.

6.7.3 Financial Perspective

The financial perspective is based on two main objectives in the maintenance function, namely efficiency and effectiveness, which must be balanced. That balance is shown in Figure 6.35 and can be achieved by the following:

- Increased availability
- Decreased associated costs

Once the objectives are defined, the strategy associated with each is determined, as explained in the following sections.

6.7.3.1 Objective: Availability Improvement

Maximum availability is obtained with a cost level tending to infinity. Therefore, there is no need to talk about availability alone. Rather, we need to consider availability related to cost. We do not consider maximum availability, but optimal availability. To improve this, costs must rise.

The cost not only refers to the overall cost of maintenance. Comprehensive maintenance cost reflects the economic efficiency of maintaining a machine. The absolute comprehensive cost of a machine is meaningless unless accompanied by the value of the machine. Therefore, we use the ratio of the integral maintenance cost divided by the value of investment. The indicator to control for a given period I is

$$\frac{\text{Total maintenance costs}}{\text{Assets replacement value}}$$

This indicator is configured as a "key factor" to be observed by several levels.

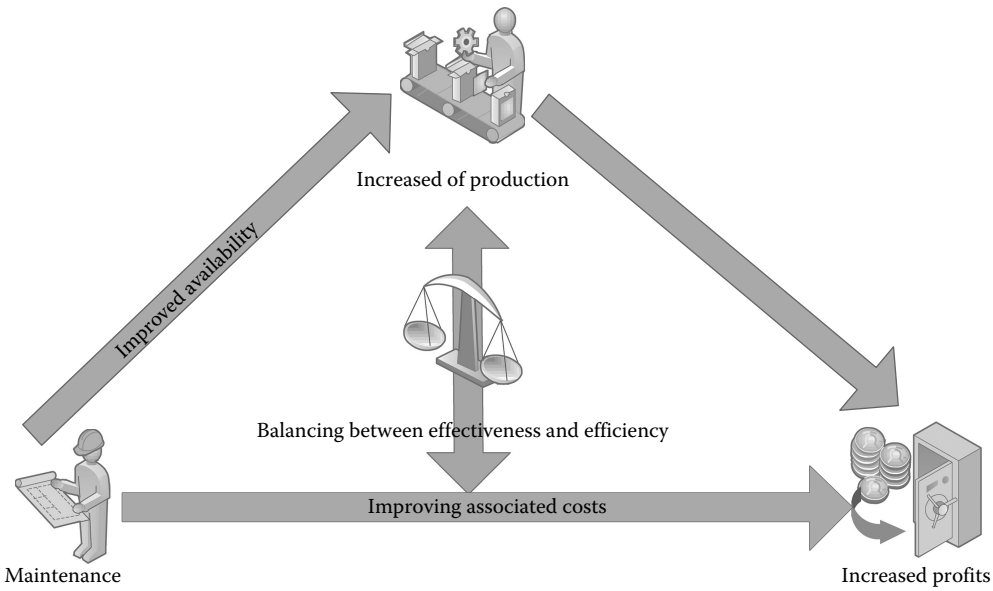


FIGURE 6.35
Balancing effectiveness and efficiency in the financial perspective.

Strategies

Dynamize the maintenance response

This section studies the influence of the performance of maintenance over the availability of systems and the factors that may influence its improvement. It is crucial to the concept of availability associated with maintenance to see what type of maintenance causes unavailability. For example, indicators must show the difference between unavailability due to maintenance for failures and planned maintenance.

Level 1

At the corporate level, it is not relevant if machines are stopped because of failures, repairs, and so on. This level seeks greater availability to increase the productive capacity of the organization.

$$\text{TI6} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailable time due to failures}}$$

Level 2

At the operations management level, it is relevant to know the unavailability due to maintenance and to cross check failures to quantify the logistical support of the maintenance function to the production function. Similarly, the number of interventions with respect to the total operating time provides the production manager with the average size of the temporary availability between interventions in the system.

$$\text{TI1} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Maintenance unavailability time}}$$

$$\text{TI16} = \frac{\text{Total operating time}}{\text{Number of maintenance work orders}}$$

Level 3

The head of maintenance can change availability or unavailability, modifying the relationship of planned maintenance. The average time for intervention reported in WOs is relevant if the head of maintenance wants to reduce the mean value and increase the relative availability.

$$\text{TI7} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailability time due to planned maintenance}}$$

$$\text{WOI_DELAY} = \frac{\text{Total time for interventions}}{\text{Number of executed WOs}}$$

Improving the effectiveness of the forecast

Improving the forecast of availability is a fundamental task in developing a plan of indicators because production will depend on availability. A large proportion of the company strategy pivots on productive capacity. To estimate parameters, all elements of the system that cause unavailability should be known. In this case, unavailability is caused by preventive, BCM, and systematic maintenance. Indicators such as the number of corrective

or emergency WOs and the percentage of corrective compared to preventive maintenance should provide the required information. Indicators will display the changes required to optimize availability not necessarily reducing emergency interventions to zero because excessive preventive maintenance consumes many resources and all recent methodologies advise against indiscriminate preventive maintenance.

Level 2
Operations managers seeking to plan production also need to know the average time of unavailability because of WOs. The application of noninvasive methods such as CBM or preventive maintenance that do not need to stop the machine should increase this parameter.

$$\text{TI15} = \frac{\text{Total operating time}}{\text{Number of maintenance work orders which cause unavailability time}}$$

Level 3
The proportion of time for corrective and preventive maintenance that generates unavailability is relevant.

$$\text{TI8} = \frac{\text{Preventive maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{TI9} = \frac{\text{Systematic maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{TI10} = \frac{\text{CBM time which causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

Level 3
Level 4
Level 5
The following indicators are relevant to three hierarchical levels. First, indicators are calculated for the entire plant's WO classification types; these reflect current maintenance policy. Second, some indicators are limited to certain areas and are useful for supervisors and middle management responsible for a set of machines. The relevant statistics are extracted from these machines. Such indicators are typical when different units and areas require different maintenance policies. Finally, relevant data are required for maintenance function planners, also considered middle management. Workers and technicians at the machine level must improvise in emergencies, possibly causing poor quality of their work. Certain indicators will be monitored by this level.

$$\text{WOI81} = \frac{\text{Emergency orders}}{\text{Total number of work orders}}$$

$$\text{WOI82} = \frac{\text{Preventive orders}}{\text{Total number of work orders}}$$

$$\text{WOI83} = \frac{\text{Corrective orders}}{\text{Total number of work orders}}$$

$$\text{WOI9} = \frac{\text{Planned work orders}}{\text{Total number of received work orders}}$$

Improve warehouse efficiency

The maintenance warehouse plays an important role in the time between a WO's opening and closing, basically by the speed of service in providing parts, spare parts, and eventually tools for intervention. It is important, therefore, to know how much to stock so that work orders are not held up waiting for parts. The warehouse is responsible if there is a lack of stock; the capital invested in spare parts must be properly prioritized with respect to the value of the assets and the constraints on the size and infrastructure of the warehouse.

Level 4

The maintenance warehouse is responsible for and in charge of the logistical supply of spare parts, tools, and consumables and is usually considered supervisory or middle management. Indicators are related to compliance with requests, especially open WOs waiting for spare parts.

$$\text{OI26} = \frac{\text{Number of spare parts supplied by warehouse according to requests}}{\text{Total number of spare parts required for maintenance}}$$

$$\text{WMI4} = \frac{\text{Total number of spare parts fulfilled by order}}{\text{Total number of spare parts requested}}$$

$$\text{WMI5} = \frac{\text{Total number of spare parts not fulfilled by order}}{\text{Total number of spare parts requested}}$$

$$\text{WMI8} = \frac{\text{Maintenance work orders awaiting spare parts}}{\text{Total number of work orders}}$$

Improved staff technical training

Employee training has a direct impact on activities in maintenance, and, of course, their skills and knowledge influence how quickly a problem is remedied, along with the durability of the solution. We can track downtime caused by a lack of training or knowledge in both production and maintenance workers. These indicators are necessarily treated as confidential and only used to promote training to restore lost availability levels.

Level 4
Level 5

The maintenance errors attributable to training deficiencies are difficult to quantify by senior management. This prevents an objective assessment of this parameter. More problematically, it is considered punitive if wrongly exercised. The maintenance officer and his immediate supervisor might reduce certain tasks or possibly add additional equipment to improve the current situation, but actions are not intended to be punishment for a lack of knowledge. To give an example, it is typical to replace dial indicators

with lasers to align rotating machinery, but this requires specific training. Without such training, continuous testing and error of the comparators and lost time per machine may result.

$$\text{ITI7} = \frac{\text{Inactivity time operational errors due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI8} = \frac{\text{Inactivity time maintenance errors due to lack of training}}{\text{Total inactivity time}}$$

Better prepare the work

The planners' work is facilitated when the data are large enough to give an overview of the average time for intervention, the number of delayed WOs, or very high percentages of labor or costs. The parameter evolution described later gives a quick idea of progression in the ability to forecast and prevent unavailability. Depending on the maintenance policy adopted, the indicators will adopt one shape or another. But in any case, delays, overtime, or higher diversion rates are synonyms for poor execution of planned WOs.

Level 3

Level 4

General deviations in material and workmanship are relevant to the maintenance manager to know the accuracy of the plans of their middle managers. These indicators can be shared between maintenance managers and planners, and, if they are strictly followed, they guarantee good planning. Overtime is a relevant index for predictions.

$$\text{WOI15} = \frac{\text{Number of work orders with more than 20\% of estimated labor}}{\text{Total number of maintenance work orders}}$$

$$\text{WOI16} = \frac{\text{Number of work orders with more than 20\% of estimated materials}}{\text{Total number of maintenance work orders}}$$

$$\text{WOI13} = \frac{\text{Maintenance overtime}}{\text{Total number of maintenance worked hours}}$$

Level 4

The following indicators are relevant only for planners and supervisors in their specific areas. They are mainly related to the estimation of WO hours proposed by planners and corrected in future forecasts with the returned reports of the operators. Also relevant is the number of overdue WOs; this shows an erroneous assessment of maintenance resources or maintenance capacity.

$$\text{WOI14} = \frac{\text{Total number of hours estimated in scheduled work orders}}{\text{Total hours charged to scheduled WOs}}$$

$$\text{WOI12} = \frac{\text{Scheduled maintenance hours}}{\text{Total number of maintenance worked hours}}$$

$$\text{WOI17} = \frac{\text{Number of delayed work orders}}{\text{Total number of maintenance work orders}}$$

Check the effectiveness of the strategies applied

Strategies implemented in maintenance produce effects on indicators if these indicators have been properly selected. For teams using these strategies, it is interesting to consider inactivity in the production demand period. For TPM, a key indicator will be production workers' performance of basic preventive tasks, reflected in the *OII*23 indicator. OEE is included, despite being a corporate indicator that covers production. OEE indicators are complex to calculate. The benefits obtained from the use of OEE are difficult to quantify when more policies are simultaneously in play and benefits cannot be directly attributed to any of them. With RCM, the same thing happens in the response time of the system; that is, it may take months to see significant changes in some of the indicators.

Level 1

Investment in maintenance technologies or new methodologies must have more or less visible results over a period of time. These indicators will be relevant to senior management and will incorporate compliance with operational availability, OEE indicators as a compendium of production effectiveness, quality and maintenance and, by extension, optimization of maintenance to adjust the unit cost of the product in relation to maintenance. Finally, the overall rating of a corporate commitment, such as benchmarking, requires all the financial data and the ability to evaluate the use of such practices

$$\text{OEEI1} = \text{Availability} = \frac{\text{Total activity time}}{\text{Programmed time}}$$

$$\text{OEE} = \text{OEEI1} \times \text{OEEI2} \times \text{OEEI3}$$

$$\text{TPMI5} = \text{Decrease in the unit production cost}$$

$$\text{KAII2} = \text{Savings achieved by practices obtained by benchmarking}$$

Level 2

The operations management level is interested in knowing the progression of preventive work for production workers as well as compliance with and the quality of production levels. Operations management requires a variation of OEE and is observed by senior management. It is important to realize that, at this level, improvements in capacity level or production quality require maintenance policies, subsequently impacting the general management costs.

$$\text{OII23} = \frac{\text{Preventive maintenance hours by operator's year_}n}{\text{Preventive maintenance hours by operator's year_}n-1}$$

$$\text{OEEI2} = \text{Performance efficiency} = \frac{\text{Actual production for the programmed time}}{\text{Planned production for the programmed time}}$$

$$\text{OEEI3} = \text{Quality rate} = \frac{\text{Total production} - \text{Defects}}{\text{Total production}}$$

TPMI4 = Profits obtained due to OEE increase

RCMI5 = Avoided costs due to use of RCM

Level 3
For the maintenance manager, the use of new methodologies will result in better service to customers and cost reductions in some budget items, mainly attributable to failure costs.

CBMI2 = Avoided costs due to use of predictive maintenance

$$\text{CBMI3} = \frac{\text{Current maintenance costs}}{\text{Maintenance costs prior to CBM program}}$$

Level 4
For the middle management level responsible for a machinery area, it is easy to calculate the progression of availability or machinery capabilities by looking at similar situations in past periods. Simple comparisons of production or inaction between equally intensive productive periods represent the positive or negative evolution of newly implemented methodology.

$$\text{OII22} = \frac{\text{Equipment capability related to maintenance year_}n}{\text{Equipment capability related to maintenance year_}n-1}$$

$$\text{OII21} = \frac{\text{Equipment inactivity related to maintenance year_}n}{\text{Equipment inactivity related to maintenance year_}n-1}$$

6.7.3.2 Objective: Cost Improvement

Similarly, maintenance costs and availability should be correlated to meet production or operation requirements. That is, the objective is to search for the required availability level at the lowest possible cost. This index must be observed in a time trend. Thus, for a period *i*, it will be

$$\frac{\text{Maintenance costs}}{\text{Availability required by operations}}$$

Finally, the units of maintenance cost per obtained availability hour should be reduced.

Strategies

Consensus on maintenance costs
By introducing the cost model into the maintenance function, it becomes clear that the majority of the costs attributable to this department are intangible and hidden; this leads to different interpretations.

Therefore, the heads of maintenance must know the rules of the game: that is, how they are going to analyze their costs and under what parameters. The four indicators mark the

relationship of maintenance costs of the final product manufactured to the availability achieved or the replacement value of the machinery.

These are corporate numbers used at the highest levels to define major changes in manufacturing policies and, by extension, in maintenance. The parameters represent total costs; they can be modified to affect the macro indicators mentioned earlier.

$$\text{EI6} = \frac{\text{Availability linked to maintenance}}{\text{Quantity produced}}$$

$$\text{EI1} = \frac{\text{Total maintenance costs}}{\text{Assets replacement value}}$$

$$\text{EI3} = \frac{\text{Total maintenance costs}}{\text{Quantity produced}}$$

$$\text{EI4} = \frac{\text{Total maintenance costs}}{\text{Transformation cost to production}}$$

Level 1

The maintenance figures given to the highest level are reduced, but provide relevant information for decision-making. The maintenance budget with respect to the replacement value of the assets is an essential element in the decision to renew equipment or relocate plants. Similarly, the relationship of maintenance to the product manufactured or the cost of this manufacturing create scenarios for maintenance.

$$\text{EI1} = \frac{\text{Total maintenance costs}}{\text{Assets replacement value}}$$

$$\text{EI3} = \frac{\text{Total maintenance costs}}{\text{Quantity produced}}$$

$$\text{EI4} = \frac{\text{Total maintenance costs}}{\text{Transformation cost to production}}$$

Level 2

For operations, the relevant ratios relate to the availability for production to adequately quantify what quantity can be made in the available time.

$$\text{EI6} = \frac{\text{Availability linked to maintenance}}{\text{Quantity produced}}$$

$$\text{EI5} = \frac{\text{Total maintenance costs} + \text{Unavailability costs linked to maintenance}}{\text{Quantity produced}}$$

Level 3
Determining the percentage of different types of maintenance in the total budget data is handled by the maintenance director. The director can decide to move funds from one item to another, looking for improvement in the availability achieved for the customer.

$$\text{EI15} = \frac{\text{Corrective maintenance cost}}{\text{Total maintenance costs}}$$

Level 3
Level 4
Indicators at the level of planned maintenance are the responsibility of the maintenance manager but must also be observed by planners because they are reflected in the economic forecasts and the schedules of CBM and systematic maintenance.

In certain areas, it is interesting to break down this concept, even the EI15 of corrective maintenance, because the different parts of machinery often entail different maintenance policies. For example, rotating machinery can have a high proportion of costs in MBC; in another type of machinery, this is barely perceptible. Therefore, the distribution of maintenance costs, apart from the overall computation, may be done according to manufacturing areas or units of use.

$$\text{EI16} = \frac{\text{Preventive maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI17} = \frac{\text{CBM maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI18} = \frac{\text{Systematic maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI19} = \frac{\text{Improvement maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI20} = \frac{\text{Cost of programmed maintenance stops}}{\text{Total maintenance costs}}$$

Plans to reduce energy consumption
The parameter of energy consumption has a dual connotation in the maintenance field. On the one hand, the overall amount of maintenance is a function of the energy consumed in the plant. On the other hand, power expenditure continues during stoppages; it is a fixed cost. A reduction in total maintenance cost by increasing reliability may result in a reduction in the total energy used; a decrease in maintenance costs by a budget cut may increase energy costs.

Level 2
There is a complex relationship between maintenance and energy consumption. It is subject to observation by the operations manager (responsible for production, energy, maintenance, etc.). Therefore, checking the relationship between the maintenance costs and energy consumed will lead to lower costs and lower energy consumption.

$$\text{EI14} = \frac{\text{Total maintenance costs}}{\text{Total energy used}}$$

6.7.4 Client Perspective

As mentioned, clients play a role in the maintenance function, mostly through their perception of the function of production. Clients want safety and good service, including prompt delivery of services and the confidence that advanced techniques are being used. The objectives associated with the maintenance function are as follows:

- Improvement of maintenance policies
- Improvement of quality
- Maintenance improvements
- Safety improvements
- Improvement of associated costs

Once the objectives are defined, the strategies associated with them can be created.

6.7.4.1 Objective: Improving the Maintenance Policies

Strategies

Improve customers' knowledge of maintenance policies

The main client who provides logistic support or maintenance service is production. The maintenance–production relationship is often summarized as "I build, you repair" or "your role is secondary" because "I am the one who manufactures what we sell and what you pay for." Surveys may be useful here. They will indicate the knowledge level of the client. They can also address the effects of availability and unavailability. However, in reality, these surveys tend to be negative, largely because of the disputes between the two functions.

For 30 years, people have been trying to fuse production and maintenance. The indicators appearing in the financial perspective as successes of the TPM program could well appear here as hours for preventive maintenance and improvements to equipment performed by production operators to foster a sense of ownership, pride of belonging, and knowledge of what they do.

Level 2

Operations management will reflect a knowledge of maintenance through involvement in routine tasks and suggestions for machinery. These indicators should obviously start from TPM policies, self-maintenance, participatory management, and promotion of versatility, with complicity between production and maintenance. The application of such methodologies and indicators should follow a previous training period. If operators are not aware, it will be totally ineffective.

$$\text{OII1} = \frac{\text{Preventive maintenance hours by production operators}}{\text{Total preventive hours}}$$

$$\text{OII31} = \frac{\text{Hours of equipment improvement per production operator}}{\text{Total number of worked hours by operators}}$$

Level 3

Surveys often give negative results for surrounding areas' knowledge of the maintenance department. Production is always considered superior to maintenance, except

in the rare case when the asset has a much higher value with respect to the product manufactured and its faults are tremendously expensive. The only degree of consensus includes regularly negotiating the production and maintenance function on the basis of the production plan and the scheduled stops for preventive maintenance, corrective maintenance, and so on. If there is no conflict, it is possible to speak of consensus.

CLII1 = Maintenance knowledge surveys

CLII2 = Consensus degree between production and maintenance

Increase the percentage of scheduled jobs

The client sees the programming as a sign of quality and good service. Interestingly, this is not always the case in maintenance; for example, RCM advocates applying preventive maintenance that is wasteful. But the customer perceives good service as the completion of the planned schedule.

Level 4

Through CMMS, planners have the opportunity to compare the data of their planning with the results of the WOs. The correction of deviations indicates the changed use of resources and a redesign of the planning.

$$\text{OI22} = \frac{\text{Number of work orders performed according to planification}}{\text{Number of work orders programmed}}$$

6.7.4.2 Objective: Quality Improvement

Strategies

Reduce the number of jobs that must be repeated

When a stop occurs in maintenance, customers are critical. In production, such stops should be limited. If maintenance must repeat an earlier action because of defective materials, and so on, the blame falls on maintenance and the perceived service deteriorates. Small but frequent interventions in a short period can lead the client to think that maintenance is not finishing repairs or they do not know the machines in depth.

Level 3
Level 4

For the maintenance manager, the number of interventions indicated in different WOs is a valuable indicator of the quality of the work done by the team. Excessive WOs carried out by the same team for similar causes in a short space of time will suggest that this is not being maintained in an optimal form. Obviously, there is a problem of possible manipulation through the concealment of the true causes of open multiple WOs. Strict administrative control will detect this type of manipulation. This parameter is helpful at the level of use units or specific machinery and is a useful tool for supervisors' areas that monitor interventions in a series of specific machines and do the calculations of this parameter on the basis of these machines.

$$\text{REPI1} = \frac{\text{Total time for interventions}}{\text{Number of interventions}}$$

Level 4
Level 5
At the supervisors' and officers' level, we can quantify the time of repeated tasks without determining the reason for such repetition, allowing the supervisor to take timely action.

$$\text{ITI10} = \frac{\text{Repeated maintenance time due to lack of knowledge}}{\text{Total worked time}}$$

Increase the reliability and maintainability of the equipment
The financial perspective demands the availability of assets, that is, the amount of time they can produce. Availability depends on reliability and maintenance. The enhancement of these two parameters in unison is a qualitative aspect, perceived by the customer as a better treatment of assets, that is, allowing availability while lengthening asset life with adequate maintenance.

Improved reliability depends on reducing breakdowns and improving maintainability by shortening the time of intervention. Improving both means having fewer and shorter interventions. The indicators in this level are two clearly differentiated types. Distribution functions are associated with maintainability and reliability revealed in the historical data; these data can stimulate future behavior by suggesting appropriate improvements. Such complex calculations are justified only in sectors with a few critical elements, such as chemical, nuclear, or aeronautics industries. Other systems can use the parameters proposed by MTBF and MTTR, as well as the failure rate of the equipment or system, to allow future planning.

Finally, we include indicators of some methodologies aimed at increasing the reliability and maintainability of the equipment, for example, 5S, cycles of improvement, or modifications to the design to increase reliability and improve maintainability. These are common practices when knowledge of an asset is broad enough for improvements, making overhauls more profitable than buying a new asset.

Level 3
Policies for improving the equipment come from the head of maintenance. The equipment considered critical should be known: of the critical equipment, those subjected to technological or methodological improvements to increase its useful life and reduce maintenance costs should also be known.

$$\text{TPMI2} = \frac{\text{Critical equipment included in design improvement studies}}{\text{Total number of critical equipment}}$$

$$\text{TPMI3} = \frac{\text{Critical equipment included in 5S activities}}{\text{Total number of critical equipment}}$$

$$\text{KAII3} = \frac{\text{Critical equipment included in continuous improvement activities}}{\text{Total number of critical equipment}}$$

Level 4
Middle management must control the parameters of the RAMS teams who are responsible for knowing at least the basic elements. However, a lack of training in RAMS means such methodologies are underutilized in the industry. That said, the manufacturers in certain sectors facilitate the correct development of the life cycle of their machines. The calculation

of reliability and maintainability is extremely useful to planners because they can adjust the policies of both planned and unplanned maintenance. World-class parameters such as MTBF and MTTR provide essential data. The graphic representation of the number of failures per unit time on a graph is a bathtub curve, useful in making decisions.

$$\text{RAMSI1} = R(t) \text{ Reliability of equipment or system}$$

$$\text{RAMSI2} = M(t) \text{ Maintainability of equipment or system}$$

$$\text{RAMSI3} = \text{MTBF of equipment or system}$$

$$\text{RAMSI4} = \text{MTTR of equipment or system}$$

$$\text{RAMSI5} = \lambda(t) \text{ Risk rate of equipment or system}$$

6.7.4.3 Objective: Improving the Maintenance Response

Strategies

Streamline the maintenance response before an urgent demand

The client's demands of the service provider can be extremely contradictory because of human factors, especially changing perceptions of reality. As mentioned, when the customer believes there is an emergency, the situation should be dealt with quickly, especially if it relates to production. There is a hierarchy of priority levels depending on the severity of the failure. There are parameters of delay in the response associated with each hierarchical level. In the previous chapter, we presented three parameters:

1. *MWT*: Mean waiting time, the sum of MODT and MLDT
2. *MODT*: Mean operational unavailability
3. *MLDT*: Mean logistical response time

Level 2

The promptness of service is essential to the appreciation of quality. Thus, parameters of quality of the service provided by maintenance to production are the selectivity and the priorities of the emergency department.

$$\text{WOI_DELAY1} = \frac{\sum \text{Awaiting time of preventive WOs}}{\text{Total number of preventive WOs}}$$

$$\text{WOI_DELAY2} = \frac{\sum \text{Awaiting time of improvement WOs}}{\text{Total number of improvement WOs}}$$

$$\text{WOI_DELAY3} = \frac{\sum \text{Awaiting time of urgent corrective WOs}}{\text{Total number of urgent corrective WOs}}$$

$$\text{WOI_DELAY4} = \frac{\sum \text{Awaiting time of not urgent corrective WOs}}{\text{Total number of not urgent corrective WOs}}$$

In this case, the reaction capacity of production before the fault (MODT) is expressed by the response to the demand by production (MLDT). MODT tends to be almost zero because SCADA systems are interconnected with the CMMS systems or there is a CBM of permanent monitoring. We get a virtually instant response. Therefore, we can conclude that MLDT coincides almost entirely with MWT or timeout. The indicators proposed for this strategy, therefore, are associated with the timeouts relating to each type of client notices.

Reach consensus on an appropriate emergency codification

The response to the demands of the customer is a "key factor" in the quality of service provided and its perception. The problem lies in the severity of the interventions demanded by customers (Figure 6.36).

Obviously, the client knows more about the problem and has a first impression of the gravity of the situation based on the immediate consequences. The client will expect the service to act accordingly, depending on the severity or urgency perceived. This is possible only if there is an appropriate emergency codification between the client and the service provider that allows rapid identification and cataloging of the seriousness of the problem.

Level 2
Level 3
Level 4

The establishment of levels of urgency must be the result of consensus between three hierarchical levels. Operations must express the need for urgency; planners must look at the type of orders associated with urgent situations; and the head of maintenance must find the average level of the previous two.

EMERGI1 = Number of emergency levels associated with reminders

$$\text{EMERGI2} = \frac{\text{WOs number with urgency level associated}}{\text{WOs number attended}}$$

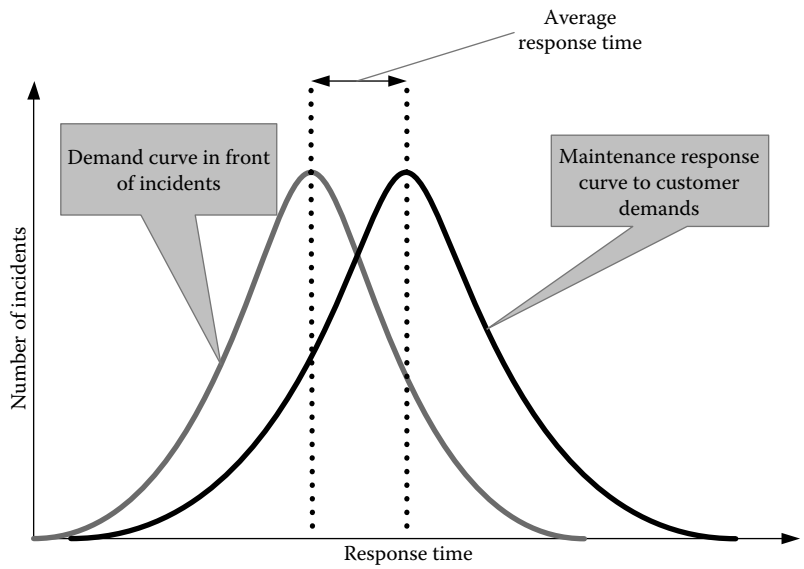


FIGURE 6.36
Gaps between the curve of the emergency department and job requests to maintenance.

A way of encoding OTS to prioritize the allocation of work by maintenance planners proposed by Kuratomi and Alvarez [179] is as follows:

- *Red*: Necessary stop due to severe machine condition
- *Green*: Improvement or amending maintenance
- *Blue*: Preventive maintenance

Kuratomi fails to consider the possibility of a failure or emergency order in which there is no compulsory stop of the productive cycle because it will activate a redundancy or simply because the fault slows production but does not stop it. An additional color is suggested to reflect this state of the system; see Figure 6.37.

The color coding and the state corresponding to the emergency represented in Figure 6.37 responds to the following description:

- *Red*: Necessary stop due to severe machine condition
- *Yellow*: Sensitive loss of capacity or production quality
- *Green*: Improvement or amending maintenance
- *Blue*: Preventive maintenance

To adapt the plan for real possibilities of preventive maintenance

For a few years, preventive maintenance was used as a substitution policy whereby any reduction in unscheduled downtime was considered a success. Common sense and the introduction of new methodologies have reversed this practice and rationalized the use of preventive maintenance for cases recommended by the manufacturer or cases considered essential after an analysis of equipment.

This new policy has gained strength because, if a department is occupied in higher priority tasks, it cannot perform all the scheduled preventative maintenance. The customer will react negatively if a series of planned tasks are perceived as blatantly disregarded. A positive image requires an appropriate degree of compliance.

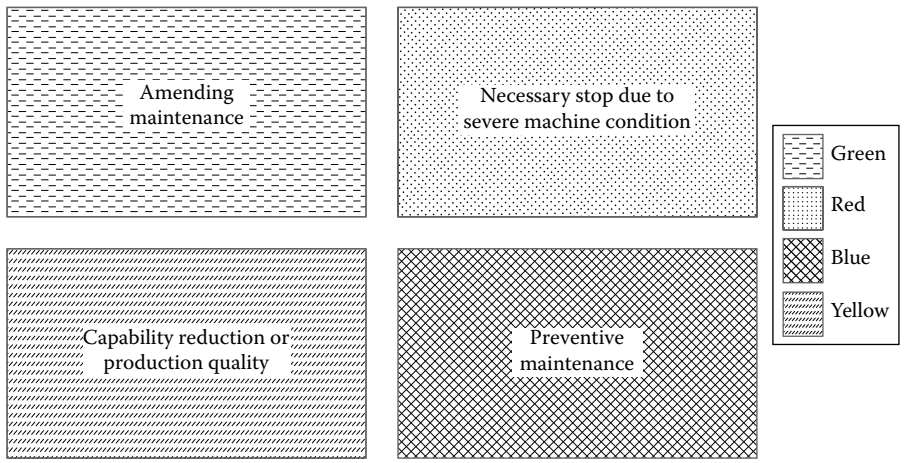


FIGURE 6.37
Coding emergencies associated with WOs.

Level 4
The degree of compliance with preventive maintenance and delayed WOs are relevant to planners who schedule this type of action according to the physical materials available to them. If materials are inadequate to meet minimum requirements in spite of the rationalization of the PM, such incidence should be reported to the maintenance manager.

$$\text{PMI9} = \frac{\text{Number of PM delayed tasks}}{\text{Number of PM pending tasks}}$$

$$\text{PMWOI} = \frac{\text{Number of preventive WOs performed according to planification}}{\text{Number of preventive scheduled WOs}}$$

Planning nonurgent corrective maintenance
Corrective maintenance requires an agile response. It can have different degrees of urgency; some actions must be executed immediately, while others may be postponed until spare parts arrive. It may also be possible to postpone the stoppage of production if the fault has reduced but not stopped productive capacity. The client may prefer a reduction in productive capacity to aggressive intervention. Therefore, the use of resources allocated to planned corrective maintenance must be monitored. We must not try to reduce the percentage of unavailability linked to urgent corrective maintenance.

Level 3
Unavailability linked to urgency is relevant to the maintenance manager. This value suggests that the situation is not under control.

$$\text{OI11} = \frac{\text{Spent time on emergency corrective maintenance}}{\text{Total unavailability time linked to maintenance}}$$

Level 4
Once the maintenance manager knows the unavailability, the interventions that have been waiting for corrective maintenance can be planned; the resources relevant to the corrective measures requiring immediate intervention can be reserved. It will be useful to reduce urgent corrective maintenance to a minimum and replace it with planned corrective maintenance because of the costs and to ensure the adequate preparation of people and materials for the intervention.

$$\text{OI17} = \frac{\text{Emergency corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI16} = \frac{\text{Corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

6.7.4.4 Objective: Safety Improvement

Strategies
Follow the requests of the safety committee
As mentioned previously, the risk encountered by maintenance personnel is elevated by the nature of the activity and the need to work in awkward postures or risky situations,

frequently by disabling the guards installed in machines to protect the production operators. In certain industries, especially the chemical and energy sectors, machines handle products harmful to health and the environment; faults lead to leaks, and performing maintenance is risky.

Level 1
The need for companies to be respectful of the environment and provide employees with a safe working environment means that the related technical aspects have hierarchical relevance to the highest levels of the company. The sanctions and costs associated with accidents or damage mean that companies are committing themselves to health and the environment.

Level 2
For the operations manager, maintenance interventions can cause certain injuries to the staff in production and maintenance, for example, small environmental damages such as gas leakages, acoustic contamination, or residues such as oils, fuels, and so on. This requires careful attention to the safety indicators chart.

$$\text{TI11} = \frac{\text{Number of failures which cause injuries to staff}}{\text{Total number of failures}}$$

$$\text{TI13} = \frac{\text{Number of failures which cause environmental damage}}{\text{Total number of failures}}$$

$$TI5 = \frac{\text{Number of staff injuries caused for maintenance}}{\text{Working time}}$$

$$\text{TI4} = \frac{\text{Annual volume of harmful residues related to maintenance}}{\text{Calendar time}}$$

Level 3
The maintenance manager should identify problems in the plant for which he has responsibility and improve their statistics. He should check any damage his department incurs to the environment, as well as the injuries to the staff while performing repairs. The degree of acceptance of instructions from the safety committee will be monitored, as will the long-term security plans allowing overhauls or uncontrolled modifications without risk to people or the environment.

$$\text{TI3} = \frac{\text{Number of failures due to maintenance that generate environmental damage}}{\text{Calendar time}}$$

$$\text{SAFI1} = \frac{\text{Requests addressed by safety committee}}{\text{Total requests}}$$

$$\text{SAFI2} = \frac{\text{Requests for long works agreed}}{\text{Total requests}}$$

$$\text{OI6} = \frac{\text{Number of maintenance staff injuries}}{\text{Total effective of maintenance staff}}$$

Study the needs of personal protection when maintaining equipment
It is imperative to proactively review the potential for accidents in the maintenance equipment to prevent danger to operators working in the field.

Level 3
The accidents suffered by maintenance personnel have a cost associated with any kind of industrial accident but the loss of skilled labor does not have a tangible cost. Therefore, the following indicator must be viewed not as a loss in the labor force but as a loss of knowledge. It will be subject to review by the director of safety and hygiene, dependent on operations at level 3, the level of the maintenance manager.

$$\text{OI7} = \frac{\text{Man-hours lost due to injury to maintenance staff}}{\text{Total man-hours worked by maintenance staff}}$$

IRCM6 = Reduction of noncompliance and accidents due to use of RCM

Level 4
Level 5
At the level of the machine or group of machines, there are technical and formal experts who can predict potential leakage or accidents. These technicians can analyze the seriousness of cuts, and so on, for personnel involved in production and maintenance. Indicators are relevant for different machine areas with their own associated risks. Once studied and monitored, these indicators will address safety and hygiene, proposing measures to prevent the occurrence of potential accidents.

$$\text{TI12} = \frac{\text{Number of failures that can cause injury to staff}}{\text{Total number of failures}}$$

$$\text{TI14} = \frac{\text{Number of failures that can cause environmental damage}}{\text{Total number of failures}}$$

6.7.5 Internal Processes Perspective

The perspective of internal processes has two main objectives in maintenance: effectiveness and efficiency. They work together to achieve a balance in the following objectives:

- Improve organization of maintenance work
- Improve reliability of maintenance
- Improve maintenance stock
- Improve outsourcing of maintenance
- Improve maintenance response
- Improve maintenance safety
- Improve associated costs

Once these objectives are defined, strategies can be associated with them.

6.7.5.1 Objective: Improvement of the Work Organization

Strategies

Relocate the staff in an appropriate way

This strategy is intended to balance the workload associated with the different maintenance personnel and the costs associated with the different centers. It is necessary to achieve an appropriate balance between electrical workers, mechanical workers, and so on, as well as the different unions. A relevant indicator in this strategy is the number of personnel who can work in a number of areas.

Level 3

Level 4

Versatility is a valuable indicator for the maintenance manager. The possibility of relocating staff precludes idle times due to a lack of a specific type of work. The hours of each type of worker and the need for each according to the WOs will give the number of mechanics, electricians, and so on, required. These data will be equally relevant to planners and supervisors of certain types of machinery as they will be able to concentrate more electrical and mechanical maintenance or CBM as required.

$$\text{OI15} = \frac{\text{Effective of internal maintenance staff with various activities}}{\text{Effective of internal maintenance staff}}$$

$$\text{OI12} = \frac{\text{Man-hours of mechanical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI13} = \frac{\text{Man-hours of electrical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI14} = \frac{\text{Man-hours of instrumentation maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI18} = \frac{\text{Preventive maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI19} = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI20} = \frac{\text{Systematic maintenance man-hours}}{\text{Total maintenance man-hours}}$$

Reduce overtime

The two indicators reflecting overtime check two aspects: first, the overtime of internal staff and the total number of hours of internal staff; second, the almost permanent presence of subcontracting for maintenance personnel and their overtime. The latter indicator is relevant as the internal staff may not be doing many extra hours.

Level 2
Level 3
The maintenance budget can be considerably increased by overtime; too much overtime in external services may show improper sizing of the maintenance function for a given site.

$$\text{PMI10} = \frac{\text{Maintenance overtime}}{\text{Total worked hours}}$$

Level 3
Level 4
The overtime worked by staff assumes an error in the planning for a given period.

$$\text{OI21} = \frac{\text{Maintenance overtime}}{\text{Total number of internal maintenance man-hours}}$$

Streamlining preventive maintenance

The wastage produced by overly generous preventive maintenance has led many organizations to overrepresent maintenance, with excessive stoppages and interruptions to implement it. The misconception that preventive maintenance avoids costly corrective maintenance has helped to spread this idea. This is corrected by CBM and RCM implementations.

Level 2
Preventive maintenance, as mentioned, has a rationale and is not indiscriminate. The proportion of corrective maintenance and the cost tell the client about the service provided. The availability of assets must be maximized while the operating cost is reduced.

$$\text{PMI11} = \frac{\text{Preventive maintenance total costs}}{\text{Preventive maintenance total costs} + \text{Corrective maintenance total costs}}$$

$$\text{PMI12} = \frac{\text{Preventive maintenance unavailability time}}{\text{Preventive unavailability time} + \text{Corrective unavailability time}}$$

Level 3
The maintenance manager will want to know the degree to which people are engaged in preventative maintenance, as well as the number of WOs emerging from preventive inspections. Ultimately, we need to be aware of the criticality of the equipment.

$$\text{OI5} = \frac{\text{Planned and scheduled maintenance man-hours}}{\text{Total number of maintenance man-hours available}}$$

$$\text{PMI7} = \frac{\text{Total number of work orders generated in MP inspections}}{\text{Total number of work orders generated}}$$

$$\text{RCMI3} = \frac{\text{Number of reviewed preventive tasks in critical equipment}}{\text{Total number of preventive tasks in critical equipment}}$$

Level 4
Planners must check the compliance of the WOs with planned preventive maintenance and note any deviations in its implementation. They must also control the average number of preventive maintenance actions on machinery. Parameters are calculable in specific machinery areas by supervisors.

$$\text{PMI4} = \frac{\text{Preventive maintenance tasks performed}}{\text{Preventive maintenance tasks scheduled}}$$

$$\text{PMI5} = \frac{\text{Tasks estimated costs PM}}{\text{Tasks-Real costs (for) PM}}$$

$$\text{CMMSI6} = \frac{\text{Total number of preventive maintenance tasks}}{3 \times (\text{Total number of machines registered in the plant})}$$

The latter equation provides an average of three preventive tasks per machine per year.

Adapt the size of the department to the real needs of the company
This set of indicators checks the number of maintenance personnel and administrative support staff. It determines the number of trainers and planners and the proportions of maintenance personnel to production personnel.

Level 1
The general direction will need to know the proportion of maintenance personnel to the total staff. This is compared to other industrial sectors using benchmarking. Similarly, the proportion of the staff in the maintenance budget is compared to the proportion of staff in the total company budget; indirect maintenance staff are also considered.

$$\text{OI1} = \frac{\text{Effective of internal maintenance staff}}{\text{Total effective of internal employees}}$$

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI13} = \frac{\text{Cost by indirect maintenance staff}}{\text{Total maintenance costs}}$$

Level 2
Reducing the indicators mentioned earlier involves collaboration between production and maintenance. It is important for the operations manager to note the hours dedicated to maintenance by the production operators compared to the total hours of manufacturing or the total hours of maintenance. A relevant indicator for production is the number of maintenance people who work in shifts; this follows the complete cycles of production and keeps track of the personnel available for urgent corrective maintenance in addition to the planned maintenance.

$$\text{OI9} = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of production operators}}$$

$$OI4 = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI10 = \frac{\text{Direct maintenance staff working in shifts}}{\text{Total effectives of direct maintenance staff}}$$

Level 3
The maintenance manager will need to check the size of his staff list and the proper distribution and hierarchy of the list. The ratios of planners, trainers, supervisors, and clerical/administrative staff will be relevant in modifications of the department. Of particular note is the ratio of indirect staff (managers, managerial staff clerks, store keepers, planners, and engineers) to the staff working on machines.

$$CMMSI8 = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of supervisors}}$$

$$CMMSI91 = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of planners}}$$

$$CMMS92 = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of trainers}}$$

$$CMMS10 = \frac{\text{Total number of maintenance technicians}}{\text{Number of administrative support staff}}$$

$$OI2 = \frac{\text{Effective of indirect maintenance staff}}{\text{Effective of internal maintenance staff}}$$

$$OI3 = \frac{\text{Effective of indirect maintenance staff}}{\text{Effective of direct maintenance staff}}$$

Assign times to maintenance work
This strategy is the main responsibility of the planners. It has the aim of making an accurate prediction of the difference between the WOs and the forecast made by the department. The strategy includes considering the costs of materials and labor, as well as the times for each WO or the technical assembly required. This will assist in preparing the budget for the following year, in the proper sizing of the department's human and material resources, and in making a more accurate prediction of availability with respect to the financial perspective of maintenance.

Level 3
Planners will be able to adjust the time requirements by observing the difference between maintenance causing unavailability and maintenance requiring unavailability. With this strategy, they can directly observe the accuracy of the forecasts and indirectly see the expertise of the officers who perform certain tasks.

$$TI20 = \frac{\text{Planned and scheduled maintenance time causing unavailability}}{\text{Planned and scheduled maintenance time that requires unavailability}}$$

Level 4
Using the WO reports, planners will be able to observe whether the planned maintenance represents a significant percentage of the maintenance work. The need to conform to the maintenance budget while attending to temporary needs requires careful monitoring of the indicators of planning.

$$\text{WOI10} = \frac{\text{Maintenance labor costs charged to planned WOs}}{\text{Total maintenance labor costs}}$$

$$\text{WOI11} = \frac{\text{Maintenance material costs charged to planned WOs}}{\text{Total maintenance material costs}}$$

$$\text{OI25} = \frac{\text{Direct maintenance man-hours in scheduled activities}}{\text{Total planned man-hours for direct staff}}$$

6.7.5.2 Objective: Improving Reliability

Strategies
To reduce failures
Reliability will increase by preventing failures. It is important to distinguish high availability with high reliabilities, being these first possible with multiple rapid maintenance operations at the same rates low reliability. One of the most obvious ways to improve reliability is to reduce the number of interventions.

Level 3
The *PMI1* indicator reports the proportion of time a machine is unavailable because of failures over the total time it is unavailable. This comparison shows reliability by noting interventions to prevent failure. The head of maintenance is concerned about the status of the assets, not their productive exploitation, occasionally making these indices of availability contradictory if they are linked to production and, therefore, to the customer. Generally speaking, the maintenance manager wants to apply more planned maintenance as technicians know that machines reassembled after failures have a loss of reliability and maintainability that significantly reduces their useful life.

$$\text{PMI1} = \frac{\text{Unavailability time due to failures}}{\text{Total unavailability time}}$$

Level 4
Planners concerned with reliability will be linked to all the indicators relating to emergency work and the magnitude of these jobs; the observation of the parameter of total hours in emergency work will provide global information on the reliability of the assets; the number of interventions will suggest any lack of planning and a possible reduction in plant reliability.

$$\text{PMI2} = \frac{\text{Man-hours spent on emergency works}}{\text{Total worked man-hours}}$$

Level 5
Repetitive and preventable faults are two parameters of concern to maintenance managers. This type of indicator is associated with certain units and lacks meaning in

the whole plant or in higher ranks of the organizational hierarchy. They are indicators of reliability but must be administered and analyzed by the managers themselves.

$$\text{PMI6} = \frac{\text{Number of failures that should have been avoided}}{\text{Total number of failures}}$$

$$\text{RCMI1} = \frac{\text{Number of repetitive failures}}{\text{Total number of equipment failures}}$$

To learn about the reliability of the equipment and its evolution

RAMS parameters are the operational base for the scorecard; the costs and the relationship between the human beings involved in maintenance are built on these parameters. The selection of parameters and their measurement require document management, including the records of WOs and the SCADA systems of production.

Once the parameters are estimated and quantified, if data are sufficient, we will be able to model the behavior of the selected components, determine the probability distributions that fit their vital behavior, and make predictions of the parameters. Obviously, these tests cannot be applied to all machinery for economic reasons; therefore, a relevant indicator will apply to specific teams. The MTBF and MTTR parameters are known as world class; therefore, they are commonly used.

Level 1

The RAMS parameter that is considered the key is availability; this is the actual time for the production of the assets.

$$\text{TI2} = \frac{\text{Availability time achieved during the required time}}{\text{Required time}}$$

Level 2

Level 3

Level 4

Calculating MTBF and MTTR by exploiting the statistical data in the CMMS yields relevant information on three levels. At the level of operations, the MTBF and MTTR of the entire system are global indicators of variations, suggesting the need for improvements or technological changes.

These indicators are equally relevant to the maintenance manager as they are useful for specific units or specific areas of the plant. These parameters are associated temporarily with certain equipment and methodologies, as RCMI4 or CBMI7; intended visualize the success of the programs through the reduction of the parameters. However, it is difficult to impute a reduction to a specific methodology when plants have multiple factors that may cause variations.

$$\text{TI21} = \frac{\text{Total recovery time}}{\text{Number of failures}}$$

$$\text{TI17} = \frac{\text{Total operating time}}{\text{Number of failures}}$$

$$\text{CBMI4} = \frac{\text{Total hours considered}}{\text{Number of failures of an equipment}}$$

$$\text{RCMI7} = \frac{\text{Total hours considered}}{\text{Number of failures of an equipment}}$$

Level 3
An important parameter is the identification of equipment deemed critical; fault analysis is used to statistically model the functional behavior of such systems.

$$\text{TI18} = \frac{\text{Number of systems covered by criticality analysis}}{\text{Total number of systems}}$$

$$\text{RCMI2} = \frac{\text{Number of equipment failures where they perform cause analysis}}{\text{Total number of equipment failures}}$$

6.7.5.3 Objective: Improvement of the Stock in Maintenance Warehouse

Strategies
Redefine the items needed
The improvement in the stock covers two key areas: the first is determining the number of spare parts that must be stored to give the availability agreed upon with the customer (i.e., the production function). We can analyze what percentage of slow-moving or inactive parts are in the store if these parts are properly registered in CMMS. We may otherwise be unaware of their existence. We must also assess the proportion of the stock to the total value of the assets and the total maintenance budget. Some spare parts such as bearings of a certain size are extremely expensive, and their replacement cost is prohibitive. In addition, the value of spare parts does not decreases over time, but is subject to absolute decreases with the emergence of new technology or the replacement or overhaul of a machine. In the latter two cases, the value of these spare parts drops to zero. Finally, we must control the storage of spare parts on the basis of criticality. Critical equipment refers to those whose parts are more sensitive to the value. Parts for noncritical equipment should not take up material resources such as space.

Level 1
Level 2
The indicators are important to the management level as they facilitate decision-making to replace assets, adopt new technologies, or subcontract certain activities. Some parts have a high value but, as noted, they can have a sudden obsolescence.
FINI6 Storage investment by estimated replacement value

$$\text{EI7} = \frac{\text{Average inventory value of maintenance articles}}{\text{Assets replacement value}}$$

Level 3
For the maintenance manager, knowing the percentage of the cost of spare parts to the total maintenance cost is very important. Many benchmarking studies provide approximate statistics; most divide the direct maintenance costs into 70% labor and 30% spare parts or material.

$$\text{EI11} = \frac{\text{Total cost of maintenance articles}}{\text{Total maintenance costs}}$$

$$\text{WMI2} = \frac{\text{Annual cost of warehouse use}}{\text{Total inventory estimation}}$$

$$\text{EI12} = \frac{\text{Total cost of maintenance articles}}{\text{Average inventory value of maintenance articles}}$$

Level 4
The store manager is interested in the quantification of the spare parts and the duration of the contract, as well as the degree of control and the correlation between the purchases made and the records in the CMMS. This is also relevant to planners trying to determine the number of spares to store for critical equipment according to the current provisioning policy.

$$\text{WMI1} = \frac{\text{Line articles in the inactive stock}}{\text{Total line articles in stock}}$$

$$\text{WMI3} = \frac{\text{Total controlled spare parts in the warehouse}}{\text{Total available inventory (controlled + uncontrolled)}}$$

$$\text{CMMSI5} = \frac{\text{Total number of spare parts in the CMMS}}{\text{Total number of spare parts in the plant}}$$

$$\text{RCMI8} = \frac{\text{Number of reviewed spare parts in critical equipment}}{\text{Total number of spare parts in critical equipment}}$$

Redefine the sourcing policy
Once stock levels based on the need for replenishment has been defined, while also considering idle stock, the levels should be set and monitored by the policies governing the purchase and supply of these parts. In this way, we can control the spare parts purchased in emergencies by managers. The planning for purchase orders can be improved, and extra costs, especially caused by the purchase of isolated articles, will be reduced. Similarly, the costs associated with the execution of a purchase order, in terms of material and human resources and time, will be quantified. This is especially helpful if the process of documentation is long or credit cards are used, that is, when shopping without authorization in sudden emergencies.

Finally, it will be useful in the introduction of new maintenance methodologies, by displaying the number of policies or spare parts. In particular, RCM policies prevent the acquisition of spare parts for noncritical equipment ahead of those spare parts whose nonavailability can stop production.

Level 2
The purchasing department may not be part of operations, but it has strong dependence on the financial part of the organization. It must ensure that the channels of the purchase orders are fluid and there is no excessive waste of resources. It must approve

purchase orders requested by the maintenance warehouse; it must also analyze the number of urgent orders that have a higher cost due to the haste of the management, and so on, and the purchase of isolated articles. All these factors require an agile interface between purchasing and the maintenance warehouse.

$$\text{WMI10} = \text{Internal costs to process a purchase order}$$

$$\text{WMI6} = \frac{\text{Total number of urgent purchase orders}}{\text{Total number of purchase orders}}$$

$$\text{WMI7} = \frac{\text{Total number of one article purchase orders}}{\text{Total number of purchase orders}}$$

Level 3
Level 4
When we institute RCM or analyze the criticality of equipment, we should remember that the stock in the maintenance warehouse may question the appropriateness of the current policy. Such stock can range from the supply of oil or fuel to bearings or elements required for refitting. These are short-term indicators whose validity is temporary and corresponds to change over time and transition between policies. It will be especially relevant to the maintenance department if it has made purchases with credit cards; excessive use will result in greater availability but will represent a failure of the overall plan.

$$\text{FINOPI3} = \frac{\text{Number of reviewed policies of routine spare parts in critical equipment}}{\text{Total number of routine spare parts in critical equipment}}$$

$$\text{FINOPI2} = \frac{\text{Number of major spare parts reviewed by financial efficiency in critical equipment}}{\text{Total number of routine spare parts in critical equipment}}$$

$$\text{WMI9} = \frac{\text{Material costs charged to credit card}}{\text{Total costs of maintenance materials}}$$

6.7.5.4 Objective: Improving Recruitment

Strategies
Verify the suitability of the current system of subcontracting
This set of indicators assesses whether the current policy of subcontracting is adequate or should be modified. To do this, we use parameters such as the percentage of the budget aimed at subcontracting, and its breakdown compared to in-house employees. We include the billing according to hours of service for projects on a tight budget. It is useful to know whether the information on contracts in purchasing and finance coincides in hours, service, and cost with that stored in the CMMS. It is also relevant to know whether the contracts are in accordance with the hours and budget of WOs or have been called in through other channels to make interventions in the plant.

Level 1
The senior level is interested in the absolute numbers of external employees compared to the total maintenance budget. The monitoring of this figure is usually the trigger for the progressive externalization of more services.

$$\text{EI10} = \frac{\text{Total contracting cost}}{\text{Total maintenance costs}}$$

Level 2
Level 3
The operations-level management and human resources (equal hierarchical levels) and the maintenance manager want to know the cost of the total wages for subcontracted staff compared to the total maintenance budget. This is important when a contract has people performing ongoing work alongside the maintenance department and billing by hour.

$$\text{EI9} = \frac{\text{Total cost of external staff used in maintenance}}{\text{Total maintenance costs}}$$

Level 3
Level 4
The maintenance manager will have additional data on the origin of contracts showing whether they were motivated by a WO or something else. In the same way, it is useful to know the distribution of contracts on the basis of services rendered, for example, mechanical or electrical technicians, CBM, and so on, or on the basis of specific areas or machines.

$$\text{WOI3} = \frac{\text{Subcontractor costs over WOs}}{\text{Total costs of maintenance contractors}}$$

$$\text{EI22} = \frac{\text{Total contracting cost of mechanical maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI23} = \frac{\text{Total contracting cost of electrical maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI24} = \frac{\text{Total contracting cost of instrumentation maintenance}}{\text{Total maintenance costs}}$$

Level 4
Planners and maintenance managers must ensure that the information in the purchasing departments and human resources relating to contracts in historical and current maintenance is correctly submitted to CMMS.

$$\text{CMMSI3} = \frac{\text{Total subcontractors costs in the CMMS}}{\text{Total subcontractors costs in ERP}}$$

Qualify the level of services provided by contractors

The contractors' index will include all indicators related to external maintenance, that is, staff subcontracted by the hour. Maintenance is linked to targeted interventions, typically

involving technical complexity or plant overhauls. There are several ways to evaluate service. The recorded parameters are usually associated with response times, knowledge, certifications of quality, and so on. Indicators in some sectors, such as automotive certifications or compliance with the manuals of suppliers, are required in manufacturing companies, as they have to do with the security of equipment and labor. The average skills of the subcontracted employees and the technological level of the company should be clearly identified.

Level 2
The rules of procedure and the policy on quality determine who is awarded a contract. The direction of operations will take into account experience as well as the certifications and accreditations common in the relevant industry.

$$\text{CONTI3} = \text{Years of experience in the reference field}$$

$$\text{CONTI4} = \text{Quality certifications as supplier}$$

$$\text{CONTI5} = \text{Technological level of outsourced staff}$$

Level 3
Level 4
At the maintenance level, it is important to assess the quality of the work provided by considering the availability of the service compared to the required availability and the number of jobs that require reprocessing. These indicators are relevant at a global level for the maintenance manager, especially for the supervisors and planners who are the actual users of the service and have direct supervision of the quality of the finished work.

$$\text{CONTI1} = \frac{\text{Availability time of contracted services}}{\text{Required time}}$$

$$\text{CONTI2} = \frac{\text{Number of works requiring repetition}}{\text{Number of works performed by contractors}}$$

6.7.6 Learning and Growth Perspective

Learning and growth refer to the acquisition of skills and abilities, that is, the development of the human factor discussed in previous chapters. These are indicators of increased effectiveness and efficiency; therefore, they are related to customer satisfaction and financial factors. The objectives associated with this perspective are the following:

- Improving skills
- Improving service infrastructure
- Improving labor climate

Once these objectives are defined, the strategy associated with them can be determined.

6.7.6.1 Goal: Improving Skills

Strategies

Improve technical and professional skills of staff

Maintenance professionals require ongoing training because of the changing technological and methodological environment. Companies that have internal staff dedicated to these tasks can check the effect of the training actions. Indicators such as the budget for training per employee or the annual hours of training they receive will be crucial to learn the status of the training program. It is important to differentiate the training hours given by external agents from those given by internal staff to determine the effectiveness of the training.

The measurement of the effectiveness of these training actions is controversial, however. In some countries such as the United States or Scandinavia, it is common to survey employees on the level of reading in their homes or give a test comparing them to national industry sectors or comparable levels among all production plants. These measurements are not widespread; they represent the final evaluation of the training action and observe whether the day-to-day contribution is effective as a result of a course or seminar.

The three indicators in the box remarked *ITI*3, *ITI*4, and *ITI*5 are very useful but complex because they are unreliable and create animosity among the more experienced staff. To carefully observe the IFH*5*, the supervisor must monitor the quality of the work relating to the training and note the evolution since its conclusion.

Level 1

Level 2

Staff training is often a sign of the innovation in organizations. Indicators relating to training are usually the concern of the highest business authorities. They are determined by the budgets for training and the hours taught, as well as the cost of the training with respect to the total payroll.

$$\text{ITI1} = \text{EI21} = \frac{\text{Total training budget}}{\text{Total number of employees}}$$

$$\text{ITI21} = \frac{\text{Total training hours}}{\text{Total number of employees}}$$

$$\text{ITI11} = \frac{\text{Annual training budget}}{\text{Annual workers payroll budget}}$$

Level 2

Level 3

The maintenance manager should try to measure the skills acquired and the effectiveness of the training, even though this may be extremely difficult. The measurement of skills such as reading, writing, or problem-solving often has a negative image.

$$\text{ITI3} = \text{Workers' reading level}$$

$$\text{ITI4} = \text{Level of skills from sectorals and national tests}$$

$$\text{ITI5} = \text{Correspondence level between training provided and abilities acquired}$$

Level 3
The maintenance manager remains responsible for the maintenance shared with TPM production; a degree of training between operators can be observed without resorting to teachers or external training hours. The organization of the training actions is more relevant.

$$\text{ITI22} = \frac{\text{Total interpersonal training hours}}{\text{Total number of employees}}$$

$$\text{ITI6} = \frac{\text{Total number of trainers}}{\text{Total number of maintenance employees}}$$

$$\text{OI23} = \frac{\text{Number of man-hours for maintenance internal staff training}}{\text{Total maintenance man-hours}}$$

Promote the improvement suggestions of employees
Proposals for improvement are a valid indicator of the involvement of operators and maintenance officers in the corporate objectives. In TPM policy, this includes the production operators who often feel protective towards the equipment they handle. Indicators such as the number of suggestions submitted and the savings achieved with these suggestions are easily quantifiable by committees constituted to assess the results of the suggestions, including financial ones.

An indicator can be proposed to measure the time for improvement. This depends on the prevailing methodology. Employees could meet outside working hours to share experiences and make suggestions. Alternatively, time could be provided during the working day.

Level 2
Any suggestions or improvements of the employees and their economic impact transcend to the direction of maintenance by the savings in overall costs that can be assumes by improving some significant items of all sorts, including quality or production. A policy of suggestions is based on a quality policy in which you dedicate a set time to work for continuous improvement, which is difficult to quantify.

$$\text{KAII1} = \text{Savings achieved by employees suggestions}$$

$$\text{OI8} = \text{OII32} = \frac{\text{Man-hours used in continuous improvement}}{\text{Total man-hours of maintenance staff}}$$

Level 3
When engaged employees develop suggestions subject to measurement by the maintenance manager, this is a very relevant indicator; it shows the employees' degree of interest in their work, as well as the pride of belonging and a sense of ownership of the equipment. High rates of suggestions submitted, with positive effects, will significantly increase the credibility of and confidence in the maintenance department.

$$\text{KAII4} = \frac{\text{Number of suggestions given by maintenance employees}}{\text{Total number of maintenance employees}}$$

6.7.6.2 Objective: Improvement of the Service Infrastructure

Strategies

Technical equipment and administrative needs

Having the appropriate technical equipment and the right administrative backup are key factors in satisfaction. For example, CMMS is a source of valuable information. Operators are very much aware of the protective clothing appropriate to the conditions in which they work: chemical, electrical, thermal, and so on, and this brings a level of satisfaction. At a more technical level, satisfaction comes from administrative compliance with the needs of workers and maintenance engineers, especially in the diagnosis of faults or the implementation of new technologies.

Level 3

The maintenance manager will notice investments in technical equipment and personnel. This will be a key indicator of the confidence of the management. With the implementation of CMMS, organizations will be able to monitor the percentage of maintenance operators who manipulate a computer; certain operators may enter the data for WOs or obtain information without the help of auxiliary or indirect personnel.

$$\text{OI24} = \frac{\text{Effective of the maintenance internal staff using computer}}{\text{Effective of the internal direct staff}}$$

$$\text{T\&UI3} = \frac{\text{Performed investments in maintenance equipment}}{\text{Planned investments in maintenance equipment}}$$

Level 4

On another level, the supervisors in the field will receive first-hand information on the degree of satisfaction of their operators with the technical equipment and personnel; based on these indicators, they will be able to make requests for improvement.

$$\text{T\&UI1} = \frac{\text{Satisfied maintenance operators with personal equipment}}{\text{Total number of operators}}$$

$$\text{T\&UI2} = \frac{\text{Maintenance officers satisfied with the technical equipment available}}{\text{Total number of maintenance officers}}$$

To adapt the information to the staff and their technical and management needs

The documentation in maintenance management, as mentioned, is crucial for the proper functioning of the system and the successful implementation of the relevant methodologies. The CMMS as a repository of information is quite reliable, especially in the early stages of its implementation. It has accurate knowledge of the individual machines, spare parts, and costs in the system versus the total, whose information is distributed in a nonuniform manner in the departments of procurement, accounting, and production. The reliability of information translates into the degree of fulfillment of the WOs in maintenance planning and implementation. The simultaneous presence of several resources necessary for the execution of WOs or erroneous planning based on bad data will generate significant delays by creating conflicts in the use of these resources. These include delays due to a lack of knowledge, many of which correspond to the inability to extract information; for example, CMMS may not be applicable to all levels of the maintenance function.

Level 3

It is crucial for the maintenance manager to correlate CMMS with other systems of the plant. As mentioned earlier, a transitional period collates data, builds the foundations, and sets up communication between the different systems. All the WOs, purchases, or requests can now exist in all records of the plant. In the same way, those WOs experiencing delays because of the lack of means give warning signs of potential problems between resources and requirements.

$$\text{DELAYI3} = \frac{\text{Number of delayed WOs by lack of resources}}{\text{Number of total WOs}}$$

$$\text{CMMSI4} = \frac{\text{Total machines numbers in the CMMS}}{\text{Total machines number registered in the plant}}$$

Level 4

Planners, supervisors, and managers of the CMMS must correlate the different items and historical costs, materials and labor associated with each area, trying to compile the information scattered across multiple databases before the implementation of the specific maintenance system.

$$\text{CMMSI1} = \frac{\text{Total labor costs in the CMMS}}{\text{Total maintenance labor costs in ERP}}$$

$$\text{CMMSI2} = \frac{\text{Total material costs in the CMMS}}{\text{Total material costs in ERP}}$$

$$\text{CMMS7} = \frac{\text{Total maintenance cost of an equipment in the CMMS}}{\text{Total maintenance costs in ERP}}$$

Level 4

Level 5

Planners, supervisors, and workers are the only ones who walk by the machines. Therefore, they will be able to determine the time wasted by lack of training. A culture in which these indicators are in the hands of those using them means petitions for improvements are much more useful than when indicators are owned by the highest levels. However, data are acquired through questionnaires that arouse suspicion and are perceived as punitive.

$$\text{ITI9} = \frac{\text{Time lost due to lack of knowledge}}{\text{Total worked time}}$$

$$\text{DELAYI1} = \frac{\text{Time lost due to lack of human resources}}{\text{Total worked time}}$$

$$\text{DELAYI2} = \frac{\text{Time lost due lack of technical resources}}{\text{Total worked time}}$$

6.7.6.3 Objective: Improvement of the Labor Climate

Strategies

Deepen the satisfaction of employees

As previously mentioned, the human factor is relevant once the basic needs (economic and subsistence) are covered. This includes proper equipment and a pleasant working climate. Surveys measure the degree of employee satisfaction. These are especially important during collective bargaining, mergers, acquisitions, or restructuring. Other degrees of satisfaction relate to management's ability to hear information from the operators on improvements, training, or equipment.

Level 2
Level 3

Surveys for the maintenance personnel will be useful to the director of the department and for those who determine the labor policies of the company (human resources and finance). The conjunction of the survey of the satisfaction of all departments with the conclusions is done at Level 1.

$$\text{CLABI1} = \text{Total satisfaction surveys}$$

Level 3
Level 4
Level 5

In the maintenance area, it is especially important to monitor positive contribution to the department and the growth of employee training. Maintenance managers, supervisors, and the employees themselves will be interested in the degree of acceptance of their suggestions for technical improvement and the positive or affirmative responses to their requests for training.

$$\text{CLABI2} = \frac{\text{Submitted suggestions}}{\text{Met and granted suggestions}}$$

$$\text{CLABI3} = \frac{\text{Submitted training applications}}{\text{Granted training requests}}$$

Reduce conflict in the service

The following indicators are two aspects of the same reality: sanctions to an employee and an employee's complaint about something unpleasant. Quantifying these indices requires absolute discretion. Attempting to quantify complaints or verbal discussions of sanctions is problematic. For one thing, the company bureaucracy may frighten the operator who wants to bring a complaint. For this reason, these indicators may not show accurate data.

Level 2
Level 3

The maintenance department and its higher level are responsible for receiving complaints and dealing with them, as well as executing appropriate sanctions.

It is important that the complaints are registered and there is no concealment of data, as this procedure is interpreted as the key to continuous improvement. Sanctions should not signify reproach or revenge. Rather, the maintenance manager applies sanctions

according to the regulations issued by the company. Similarly, complaints are channeled through the company's system.

$$\text{CLABI4} = \frac{\text{Number of imposed sanctions}}{\text{Total number of employees}}$$

$$\text{CLABI5} = \frac{\text{Number of submitted complaints}}{\text{Total number of employees}}$$

Increase the level of staff retention

Staff seniority and the retention level of the company can be used as indicators in maintenance because workers often have alternatives in other areas; they are not forced to stay in a place they do not like. Absenteeism could be considered a degree of conflict, but it can be attributed to the retention level of the company.

Level 2
Level 3

Operations direction and human resources (entities on the same level) consider parameters of employee loyalty to be total years of employment and voluntary leaves. When coupled with information from the maintenance department, the HR information shows longevity in the organization. Excessive rotation and/or too many staff who lack seniority can have dramatic consequences for availability. Movements in these indicators have implications on two levels: the labor climate in the department, and the wage policy and labor climate of the company.

$$\text{HRI1} = \frac{\text{Voluntary dismissals}}{\text{Total number of employees}}$$

$$\text{HRI2} = \frac{\text{Sum of years in staff list}}{\text{Total number of employees}}$$

Level 2
Level 3
Level 4

Absenteeism is an observable indicator at different levels, starting with the individual worker. The measure is easily manipulated because many hours of absenteeism are masked by peers or supervisors or disguised as medical leave. In recent years, a series of controls and stricter monitoring of medical absenteeism (especially lengthy absences) have made these indicators more reliable. For supervisors, there are satisfaction and commitment indicators for their people; the same is true for the maintenance manager. The latter can detect any discrepancies or abnormal situations that foster such absenteeism; for example, it is often triggered by inappropriate or unhealthy working conditions.

$$\text{TPMI6} = \frac{\text{Total hours of absenteeism}}{\text{Considered total hours}}$$

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7

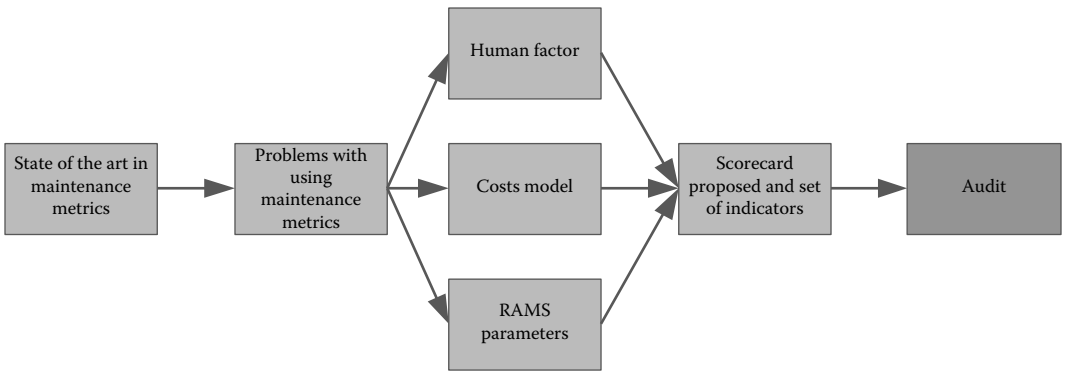
Maintenance Audit

7.1 Introduction

Auditing maintenance is a seemingly simple concept that conceals much greater complexity because of regulatory gaps and different points of view about the practice of maintenance, even within organizations.

As highlighted in the preceding chapters, there is recent and growing interest in measuring the performance of the maintenance function. But because of the differing criteria for what defines maintenance and the absence of standardized procedures, not to mention the limited literature on the issue, we are unable to apply an audit model to maintenance in manufacturing and service organizations.

Several standards relate to the assessment of the performance of maintenance systems. A classic one is COVENIM 2500-93 [58] Venezuela; it dates back 92 years and considers an assessment using a survey format. A more recent one is the adaptation of EN 15341 [94] in UNE-EN 15341 [356] in Spain, which proposes a range of over 70 indicators. The two standards are alike in that they consider opposing metrics: qualitative (surveys) and quantitative (indicators). This will be discussed later as a necessary combination for the correct measurement of the maintenance function.



This chapter presents the problems associated with the measurement of maintenance performance and the factors influencing it. It proposes a methodology using simple measurement according to predetermined indicators, along with a balanced of scorecard with four perspectives. The maintenance function will be audited according to the degree to which objectives are achieved and the level of satisfaction achieved from each perspective.

This chapter notes the difference between the concepts of consulting and auditing; these are sometimes deliberately confused by people who do not really perform audits but who want to sell consulting services and costly system implementations that are often unjustified. Unlike consulting, an audit provides a snapshot of the situation at a given moment and notes the trends of certain previously established indicators. Reporting on the current "State of Excellence" is the best starting point for any improvement process, according to Wardehoff [366]. After this, the process data suggest improvements based on the impact on the indicators.

It is important that internal and external audits do not tamper with measures by reliable staff, which translate into further reports and Heisenberg's uncertainty. Nor should they contaminate the measures. We must remember that the auditor's role is normally seen as negative. In maintenance, an audit rarely happens; therefore, it generates anxiety and possibly the temptation to manipulate those data considered negative. This could undermine the progress of the audit. For this reason, it is crucial that the auditor goes unnoticed and gets the information quietly. When auditors have to conduct surveys, these should be designed to provide a positive vision of improving the situation, not to express a punitive measurement process.

Many issues have been raised about whether or not to perform a maintenance audit, what it is intended to achieve, how it should be done, and so on. Accordingly, many of these issues have already been considered by an auditing process and related to the qualitative and quantitative process. As noted previously, both aspects determine the audit itself. A classic example of qualitative audits is mentioned by Mitra [223] and Jurán [143,144]; an example of a quantitative audit referring to energy is by Thumann [329]. These two typologies are quite different and present distinctive problems in the evaluation process.

1. *Qualitative aspects*: Mainly related to human factors and the evaluation of complex performance associated with people's duties
2. *Quantitative aspects*: Not associated with the measurements proposed but how they are performed

Tavares [322] relates these concerns to the achievement of a maintenance audit and says some difficulties are justified to reach the ultimate goal of evaluating maintenance.

We suggest two methods to evaluate the maintenance function: the balanced scorecard proposed in the previous chapter and the audit procedure explained in this chapter.

- *Audit justification*: Companies usually must perform audit in the field of maintenance: in fact, all company areas, including maintenance, are normally measured and evaluated according to their performance. The maintenance department is characterized, as discussed in previous chapters, by models of costs and secret costs. It is time to see that maintenance is simply one more function to evaluate with respect to effectiveness and efficiency [150].
- *External or internal character of the audits and their frequency*: Audits must have both external advice and the active participation of the internal staff. In the early stages, lack of practice of conducting audits may require external support to measure performance. However, audits can be performed internally as well. Internal audits can go into more depth and have fewer negative effects. It is important to mention that the lack of certification and few current regulations on maintenance audits can mean the objective or goal is not the audit itself but, rather,

is simply the consequence of acquiring expensive services or equipment. Coetzee [56] recommends conducting an annual audit with external support and measuring performance monthly to create the appropriate records for the general auditor. The periodic nature of the audit is commonly acknowledged; Vosloo [365] mentions that it is an error to do a single audit if we are looking for continued improvement.

- *Qualitative and quantitative aspects of the audit*: Qualitative and quantitative audit aspects are clearly differentiated in maintenance, but we propose a combination of both. Surveys constitute the qualitative level; the measurement of indicators represents the quantitative level. Both methods should be used together; combining them will help staff realize the reality of maintenance and will better measure the performance of the maintenance function. Clarke [52] says a maintenance assessment must consider the acquisition, operation, maintenance, and disposal of assets by visualizing performance in all aspects of the organization's business.
- *Performance after audit*: Woodhouse [380] sees maintenance audits as a tool to improve the investment in assets because they may lead to reorganization or costs savings. Organizations frequently do not realize their expected production. To correct the deficiencies in the system, obviously they must find them. But they cannot count on guesswork, and there is no magic formula. It is a mistake to make cuts without performing an audit.
- *Positive and negative aspects of internal and external audits*: A complex audit often causes objections, and it may be difficult to determine the indicators. A systematic process will speed up the process. However, we should be prepared for the results because some may be negative in terms of costs, financial efficiency, and so on. The weak points suggest improvements that can be made.
- *Minimum number of employees and staff*: There is no a minimum number of employees in the maintenance area to justify an audit. We can go from 100% internal maintenance up to 100% completely outsourced. The audit process is simply meant to measure the performance already implemented, giving the degree of maturity and observing prospects.
- *Minimum training for the auditor*: The training required to conduct a maintenance audit is not regulated; any person with knowledge of basic concepts of maintenance and management processes can audit the maintenance function. However, this can be complex depending on the maintenance evolution and maturity. Hoberg and Rudnick [122] propose that the directors and supervisors designate the internal staff who will be involved in the audit process. An external consultant or trainer can teach them how to clarify and attain their objectives. The audit team, therefore, begins the collection process and performs data analysis, but it is monitored by a facilitator. Many authors, such as Kaiser [149], Idhammar [128], and Tomlingson [331], agree with Hoberg and Rudnick [122] on the need to create a multidisciplinary team to perform the audit.
- *Implications of subcontractors in the audit process*: Audits must involve contracted companies. Subcontractors are a key part of the process because, to a greater or lesser extent, they are part of the performance of the maintenance function and contribute to it. The audit, for example, will consider effectiveness and efficiency. Results of the audit of outsourced activities will have relevance to future outsourced activities, now largely determined by a hit-or-miss process.

- *Security implications and audit environment*: In his concept of the management of assets, Woodhouse [380] emphasizes the risks faced by operators; some physical assets pose a great danger for individuals and the environment. Accordingly, they are an intrinsic aspect of the management scheme. For this reason, audits must consider the quality, safety, and environment: The work of maintenance is the most accident-prone, threatening both staff and the environment. Examples of hazards include working with barriers lowered, leakage or gases, working at heights, or being exposed to some of the chemical products associated with assembly and disassembly. In addition, handling machinery of a certain weight causes lumbar damage, shoulder tendonitis, and so on. Maintenance is also charged with preventing harm to production operators; for example, if the mechanical seal of a centrifugal pump does not hold, it will lose fluid and harm any operator who is close by. These two responsibilities, to the staff and environment, are the main security factors in the maintenance audit.
- *Participants in the audit*: The audit process should include all personnel involved in the maintenance function as required by a balanced scorecard (BSC; see previous chapter). All levels in the chain of command have a hand in maintenance; each must provide information on its function and obtain the indicators needed to perform that function. Staff from other areas such as production, purchasing, finance, or human resources should be included; they all have an impact on efficiency, especially the efficiency of maintenance. Obviously, the creation of multilevel working groups and interdepartmental teams requires some degree of corporate maturity.

7.2 Maintenance Audit

7.2.1 Internal and External Audit

The purpose of an audit on the effectiveness and efficiency of maintenance is to determine where the organization is doing well and where it might improve so that maintenance services have the required quality and opportunity. For Tomlingson [331], the audit must describe what is being done and what it should be doing, and propose mechanisms of improvement to achieve this. This instrument provides an overview of the structure, relations, procedures, and personnel in the maintenance practice. First, it is necessary, but not sufficient, to decide and implement improvements in the management of the maintenance department.

Audits can be internal or external; in the first audit, an external auditor generally supervises the work of an internal auditor, with subsequent audits conducted by internal staff, especially follow-up audits.

External audits are justified on three clearly differentiated occasions:

1. When an audit requires the guardianship of the audit team and results must be objectified, along with the ways to exploit the results.
2. When an internal audit reveals a strong imbalance in any of the parameters. In such cases, an impending crisis or one that has already occurred has not been noted in previous audits because the parameters were simply not there.

3. When we want to train staff in enhanced technological or organizational change. If this is difficult to achieve from inside the company, an external consultant, convinced of the positive effects of the cited improvement on maintenance indicators, could make a difference. An example is the inclusion of maintenance tasks performed by operators; it must be an external auditor who promotes the improvement toward that level of maturity with available objective data.

The internal audit, more routine and frequent, is an assessing function within the organization, regardless of the performance of the department. A company must have implemented a feedback system aimed at continuous improvement so that the proposed improvements deriving from an audit are implemented and have measurable impact in the following audit. The main objective of an internal audit is to advise the person in charge of making decisions about the efficiency and effectiveness in procedures and processes of production. When an internal audit is performed, the results and recommendations are the subject of subsequent considerations and decisions.

Multiple factors affect the audit of the maintenance function, as shown in Figure 7.1. During the past 20 years, maintenance has changed, perhaps more than any other discipline of the industry. Changes stem from an increase in the number and variety of physical resources that must be maintained; plants are much more complex, with new maintenance techniques and points of view changing the maintenance organization and their responsibilities. Maintenance is also responding to changing expectations. These include a rapidly growing knowledge of the extent to which the failure of a computer affects safety and the environment, a growing knowledge of the connection between maintenance and product quality, and increasing pressure to achieve high availability of the plant and keep costs in check.

In addition to the previous expectations, there has been an explosion of new concepts of maintenance and maintenance techniques. New ideas are emerging every day.

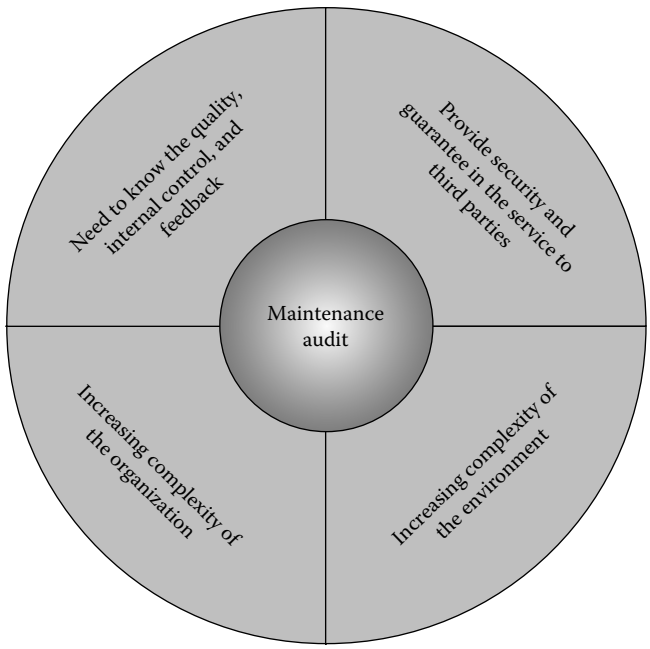


FIGURE 7.1
Fundamentals of the internal maintenance audit.

Campbell [41] cautions that before we employ new technologies and methodologies indiscriminately, we must take into account the current maintenance audit to detect the strengths and weaknesses of the current system. New developments include

- Tools to support decision-making in areas of risk, failure modes, and effect analysis and expert systems.
- New maintenance techniques, such as monitored condition; equipment designs put more emphasis on reliability and maintainability.
- A major move toward an organic understanding of participation, teamwork, and flexibility.

The internal maintenance audit evaluates the effectiveness and efficiency of the internal control system implemented by the management of maintenance. Its primary objective is to give recommendations to senior management, to strengthen existing internal controls, or to suggest new ones.

Figure 7.1 summarizes these factors and shows the four justifications of a maintenance audit, with special emphasis on what was said previously and the ignorance that has hitherto surrounded the maintenance function due to the lack of data on its costs, ignorance about the life of a machine, or simply the lack of necessary staff training. We emphasize the need for control of environmental concerns and organizational measures of performance.

7.2.2 Maintenance: Audit Model

First and foremost, a maintenance audit depends on the strategy or design specified by the organization. Second, it depends on the maintenance department. Nevertheless, a global audit is generally called for when an audit is applied for the first time.

Campbell [41] reminds us that service is one of nine parts in the management of production assets. Because of the multiplicity of the maintenance function, the content of a maintenance audit should cover many areas, ranging from the identification and description of the maintenance department to the use of specific tools. The importance of considering all aspects involved in the management of maintenance is to be the basis for suggesting alternative solutions to the problems identified during the audit. It should be noted that, once we decide to implement actions to improve maintenance aspects that do not meet expected standards, the auditing tool should include the necessary questions and indicators to measure the state of those aspects during the improvement process. In other words, the instrument is not static in time, but should follow the dynamics of the evolution toward the identified targets.

The audit should look at six aspects, as shown in Figure 7.2, covering all fields belonging to good maintenance management. The audit begins by characterizing the type of maintenance practiced in the company, which is key information for the auditor, especially if external, so that the recommended improvement actions are consistent with the structure, shape, and maintenance practices of the organization audited.

The audit should also cover aspects of routine analysis, identifying the criticality of the equipment and estimating the maintenance time. As mentioned, RAMS parameters are central to determining indicators. RAMS metrics for maintenance will be the primary objective of an effective audit. These data will be critical for assigning priorities in the execution of maintenance tasks.

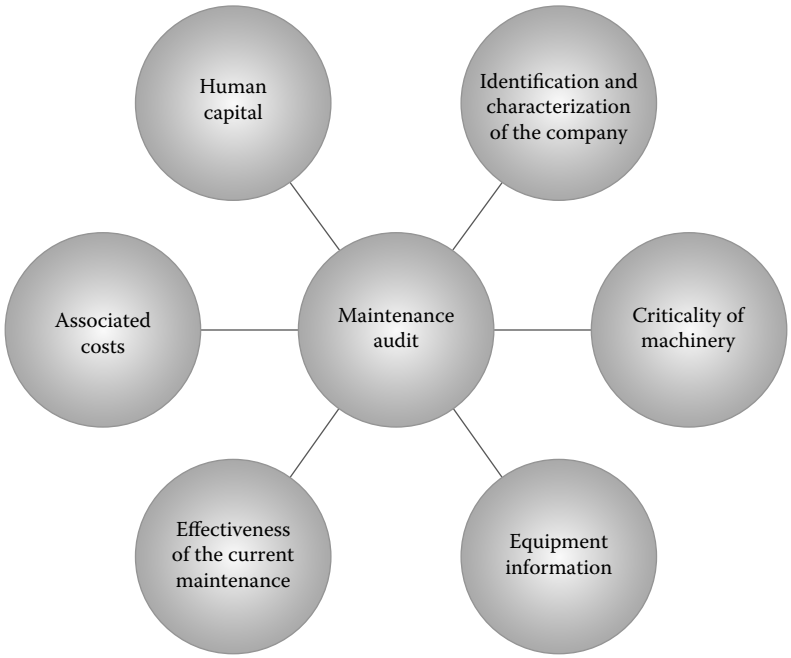


FIGURE 7.2
Maintenance audit process structure.

7.2.3 Evaluation and Presentation of Results

The audit consists of two aspects: one qualitative and the other quantitative. Indicators located in the different elements of the BSC (as proposed in the previous chapter) constitute the quantitative part, while surveys carried out at different hierarchical levels comprise the qualitative part.

Indicators are measured at points where "sensors of management" have been placed, as explained in the previous chapter. These indicators, together with the results of the surveys, are processed as shown in Figure 7.3; note that indicators and surveys provide measurements from different dimensions.

The indicator measurements are arranged according to the references associated with each one, presenting deviations from normality, the corresponding alarms, or the situation under control. Some indicators contribute measurements in conventional units such as monetary units, temporary units, or number of actions, products, and so on; others give ratios of certain magnitudes representing percentages and types of maintenance or representing indices of efficiency or inefficiency, where the desirable value is unity or zero.

Surveys are scored according to the 5-point Likert scale. Each question is given a score of 1 when the situation is bad or unfavorable; a score of 3 for regular situations or ones that may be salvageable; and a score of 5 when a situation is well implemented or meets its objective, at the time of the survey. This assessment is a strong component of the auditor's appraisal on the state of the item being evaluated.

The average value of the score for each aspect considered is presented in a graph like the one shown in Figure 7.4, accompanied by a score adapted to the different hierarchical levels on which the survey was conducted.

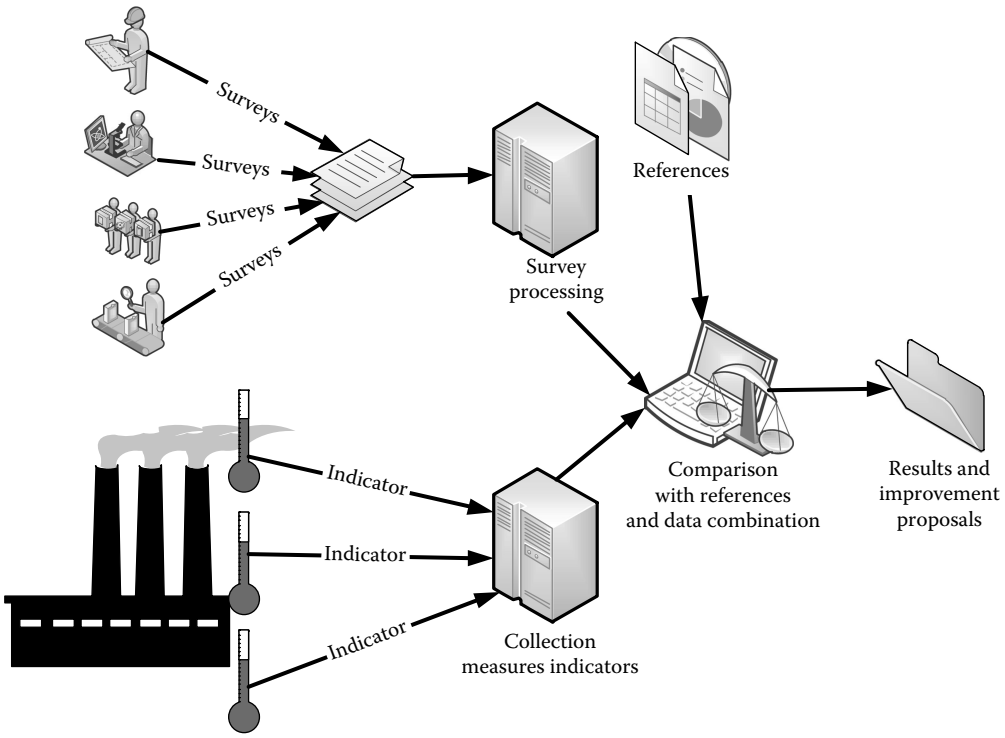


FIGURE 7.3
Qualitative and quantitative audit model.

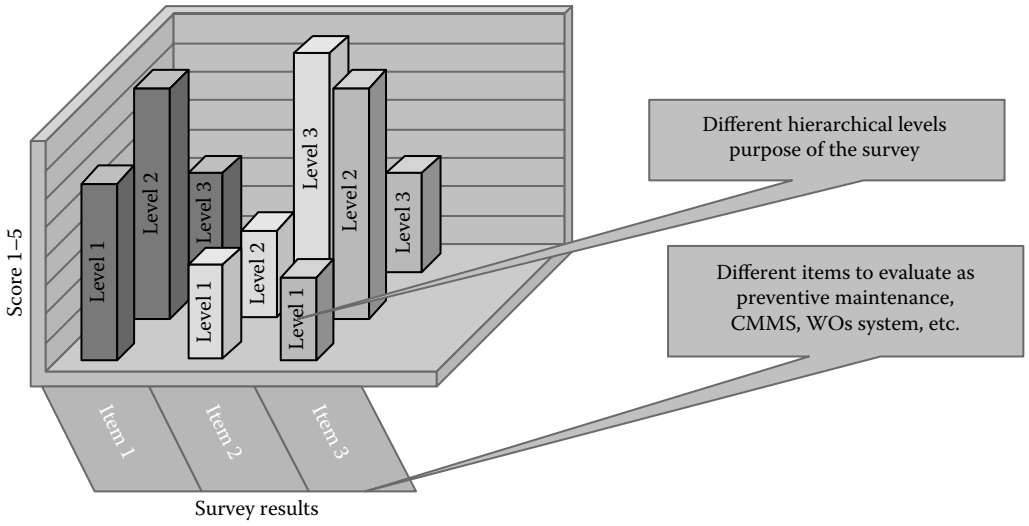


FIGURE 7.4
Graphical representations of survey items and hierarchical levels.

In this way, the auditor has a relative appreciation of all aspects and can compare them. The auditor can focus on those aspects that are poorly qualified and has a guide to begin studying the details of why this situation occurred. The criterion used to define the rating system used in surveys of maintenance is as follows:

$1.0 \leq \text{Score} \leq 1.6$: deficient aspect

$1.6 < \text{Score} \leq 3.3$: regular aspect

$3.3 < \text{Score} \leq 5.0$: well-implemented aspect

Importantly, this assignment of scores has a reference value; first, we have an idea about the current state of maintenance, and, second, we can compare different aspects using the same scale. It is important to be especially careful in the first audit as it will be a reference in the future.

Individual graphics can be generated to show specific items of the survey according to the hierarchical levels or to calculate the dispersion in the results for different people in the same category in the organization.

7.2.4 Audit Implementation Process

An audit applies a questionnaire and considers the actions of a few numerical indicators, such as operational tools. It requires several stages to obtain a result that will be useful in the decision-making of leaders and maintenance managers, as seen in Figure 7.5.

Kaiser and Kirkwood [150] note the need to consider all stages prior to the audit itself, especially when we are going to combine data from surveys and interviews with information and procedures. The authors place special emphasis on preparing a calendar of the audit. They suggest having a plan, a properly selected computer, and trained auditors so that the process is both agile and scheduled.

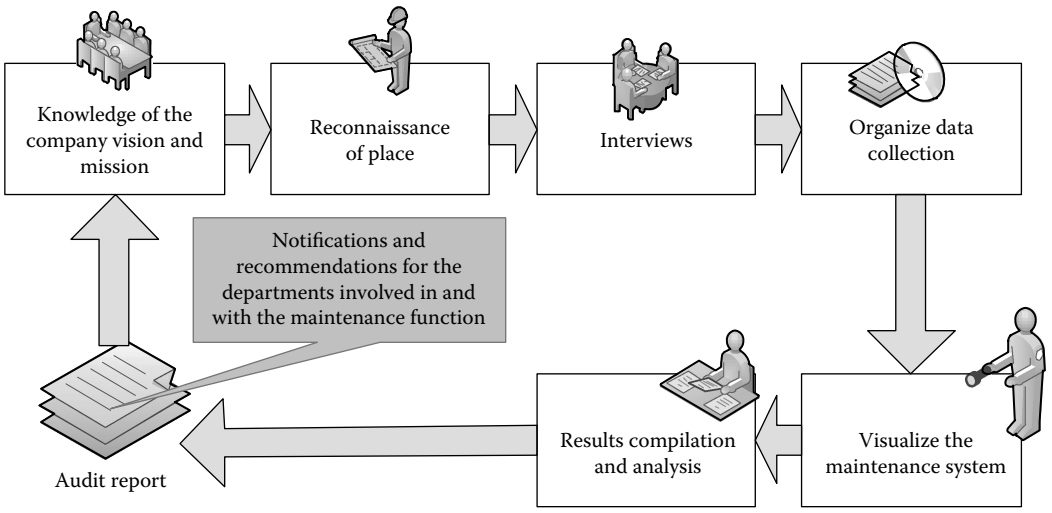


FIGURE 7.5
Schematic audit and previous stages.

7.2.4.1 Strategy, Vision, and Mission

The auditor should review and understand, from the corporate level to the maintenance department, the strategy, vision, and mission of each level in the organization of the company. Kaiser [149] identifies an audit as a framework for an analysis review and improvement so that the corporate objectives and the goals set by the organization can be aligned with the audited department. The plans and tactical actions performed at each level must support the strategy, vision, and mission of the next level of the organization in achieving the objectives.

The strategy, vision, and mission must be defined from the top down, as seen in Figure 7.6. In Campbell's [39] view, it is fundamental to the audit process to highlight the mission and vision of the company and the strategies to achieve them. At the maintenance level, strategic and tactical plans should clearly support the corporate goals and objectives and their related systems. The auditor must be able to define the supporting goals of the higher levels as a maintenance goal. In short, as has been said on several occasions, maintenance must understand what is expected and have the resources required to achieve these goals. The audit represents the customer's perspective in the BSC (see previous chapter), or, in other words, the quality of the service perceived by the customer of the maintenance function based on the requirements requested.

7.2.4.2 Place Recognition

The auditor must know where to focus resources for maintenance, storage of spare parts, and service delivery maintenance. A direct contact provides indications of how to carry out the maintenance in working areas in charge of the maintenance group.

We also need to verify the existence and status of resources such as tools or equipment, their state of readiness, the state of the workshops, their location and proximity to the point of repair, and the communication between people and departments in order to ensure ergonomic practices with a high impact on safety.

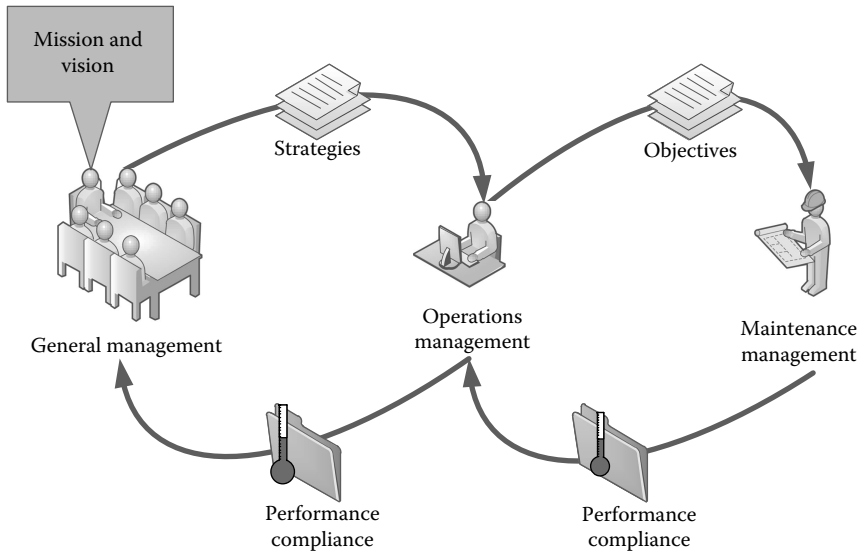


FIGURE 7.6
Communication process and maintenance translation of the mission and vision maintenance.

For a field audit, Vosloo [365] proposes collecting the following data:

- Production and process flow diagrams
- Production and planning policy
- Maintenance work load
- Resources available to the department
- How to perform and control the work planned
- Administrative structure
- Existence or nonexistence of control of maintenance costs
- Maintenance files on computer and paper

7.2.4.3 Interviews

The audit is not only answering a set of questions. We should take advantage of the opportunity to conduct a series of interviews with a significant number of maintenance people, in partnership with people receiving care from or interacting with the maintenance function. Common themes often emerge during the audit, leading to other areas of research. These themes include training, purchasing management, and, especially, the perception of waste or loss of time and excessive paperwork in the face of contingencies for which it is necessary to be agile, and so on. These represent the most commonly recurring themes during the audit process and should be recorded. There should be a space for comments in the template for data collection and evaluation to enable subsequent analysis.

We must consider the size and position of the boxes for commentary. They are designed to record observations with a somewhat negative aspect, an escape valve for personal feelings. Thus, the respondent may pay more attention to the struggle than to the accuracy and fidelity of the data. The auditor should not be carried away by the vehemence of the feelings and should avoid reflecting them in the recommendations.

7.2.4.4 Organize Data Collection

One of the most complex tasks in an audit of maintenance is finding the "right places" to put "sensor management." A large part of the literature proposes useful indicators and metrics but does not worry about the problem of data collection. The auditor must gather data through the maintenance audit. These data must be a representative review of the historical records of the equipment, the cost of labor and materials, movements, inventory, number of work orders (WOs), and so on. It is important that any data entered into the template be validated accurately to reflect the current situation, or the auditor must delve into the concept. Nor should the auditor assume that the first impression of the performance of the factor being measured is the correct one. Rather, the auditor must leave the door open to following audits for the ease of collection and the accuracy of what is collected. The auditor needs to identify reliable sources of information; in the case of updated data, he or she should be aware of the owner of each datum.

7.2.4.5 Maintenance System Visualization

Maintenance work flows and their relationship to manuals of procedure, work orders, and computer systems used by the department represent a key input for the audit.

Often, an auditor can literally walk through the process used in maintenance to determine which areas represent the strengths and which represent the weaknesses. In the case of ACM [17], the vision of the maintenance process is particularly important. A process audit of the maintenance reviews completed WOs as these provide information on programming, requirements, determination of spare parts, and workmanship.

In addition, a review of a WO reveals if there is a suitable coding system, if the prioritization of work is defined, if the staff understands the information contained therein, if the order is supplemented properly, and, finally, if it is a valid instrument to collect real-time information from the plant.

7.2.4.6 Compilation and Analysis

All data must be put together and organized; observational data include numerical indicators and results of surveys. The auditor has made field observations and derived conclusions from these measurements. The final report contains an analysis of the causes behind current weaknesses, areas for improvement, and recommendations for change. It also has a series of recommendations with priorities to help maintenance address the problems detected by the audit.

7.2.4.7 Audit Performance

As Figure 7.5 suggests, data collection, analysis, and reporting assume that we have previously prepared a scorecard and noted the placement of the sensors.

The developed methodology consists of the prior extraction of the scorecard on the basis of company strategy in the maintenance department, as seen in Figure 7.7. The measurements and the control panel reflect what the company expects from the department.

The benefit of this method is the speed of implementation; a sitting only requires knowledge on the part of the audit team. The corporate or business objectives that have been transferred to the maintenance department can be classified as two types: performance

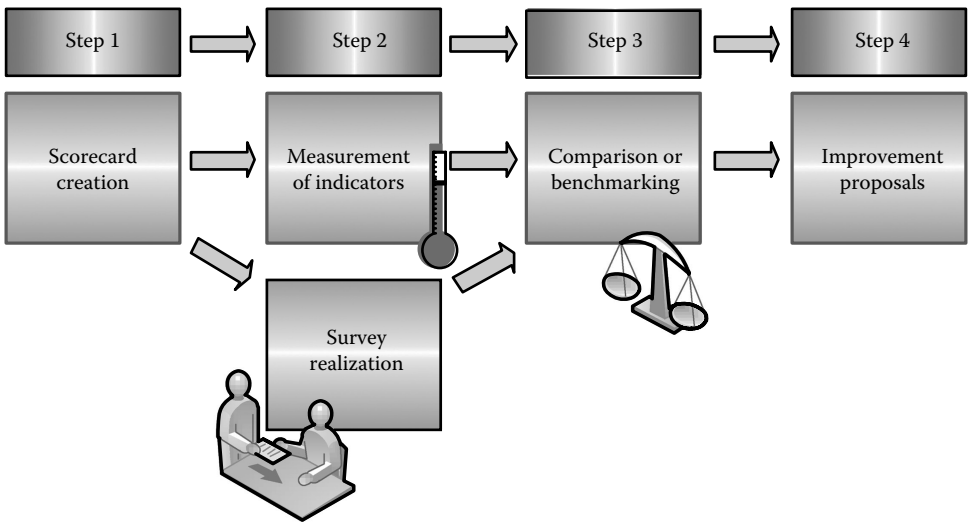


FIGURE 7.7
Steps in the audit.

efficiency and organizational efficiency. These are measured by placing the "sensor management" at the appropriate points. The great advantage, as mentioned, is the speed and, hence, the noninterference in the system by the audit team. Most of the time, interference leads to mistakes in methodology and requires the implementer team to make improvements. The function of the audit team is simply to measure and report without alteration. Something potentially confusing, partly because it is usually immersed in the audit process, is the improvement derived from the recommendations. The proposal of improvements constitutes the last phase of the process; implementation has no relationship with the audit.

Following the methodology described previously, performing a maintenance audit at a facility that has never had one before requires the following steps:

- *Phase 1*: *Creation of a balanced scorecard*

  First, we require the creation of a balanced scorecard with a few clear indicators that can be measured and ensuring that the measures are repeatable under similar conditions. The scorecard is also strongly affected by the process auditor. We will design a command chart based on the four BSC perspectives described previously. We will select the ranked and classified indicators suggested in the previous chapter and will find a relevant and independent indicator to perform the measurements and get enough information to be able to measure maintenance performance from the four perspectives (Figure 7.8).

  This first step aims to filter out those indicators that are strictly necessary from those included in the BSC proposed in the previous chapter. This action reflects a pragmatic and realistic vision of the auditing process; it is impossible to use all measures, especially when we reduce the number of indicators. Some are interdependent, so there is no loss of information; in the absence of measurement, information can be obtained through the evaluation of others.

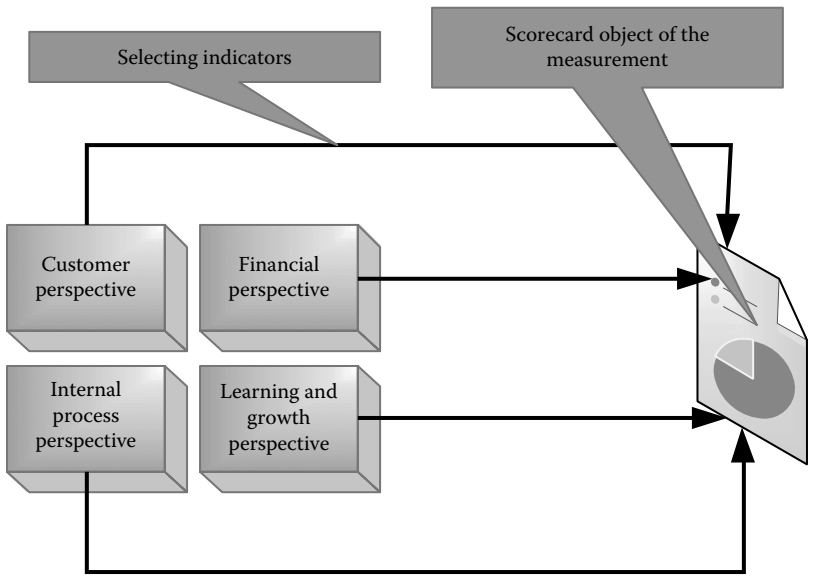


FIGURE 7.8
Extraction of the integral balanced scorecard parameters.

- *Phase 2*: *Indicator measurement and survey implementation*

  This process should be systematic and fast. It does not consume excessive resources that slow the auditing process down. As well as being fast, audits should be reliable. Idhammar [128] recognizes the need to work with performance measures that are standardized and generic but is also aware of the need for applicability to the organization goal. Failed audits do not adapt to the needs and possibilities of the company and are too ambitious with the measures they attempt. Idhammar [128] proposes using nonconventional indicators created by the company to ensure agility; these should be applied only in those areas where improvement may be needed.

  This option does not require benchmarking of existing information systems; not does it require the predetermined indicators to be overly complex.

  Surveys are controlled by human factors, but they are indispensable for precisely that reason. They gather information on the perception and behavior of the individual along with numerical measures.

  As shown in Figure 7.9, there are four possible sources of information on indicators. Having two would be preferable, specifically, surveys and a comprehensive management system that would extract all the necessary data; see Iglesias and Treto [131]. The agility of the survey and the noninterference of the auditor are

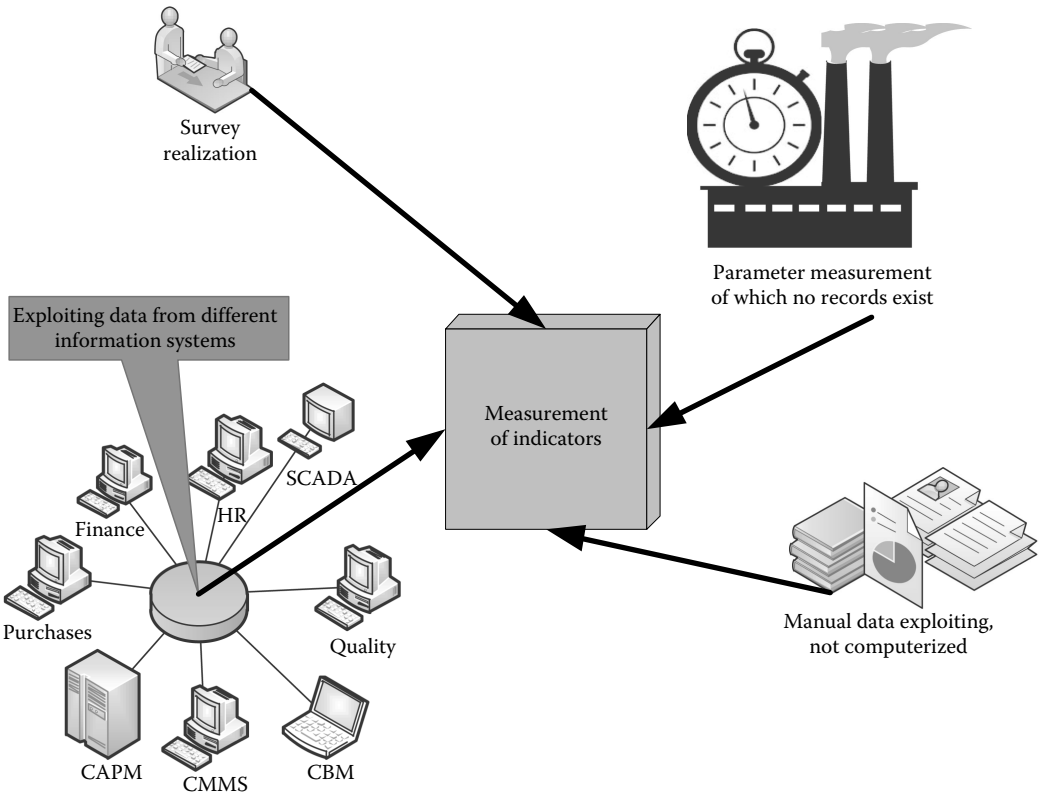


FIGURE 7.9
Information sources to consider in the measurement of indicators.

evident in the figure. In addition, the data entered into the system are more reliable. A case frequently presented is the nonintegration of all data in a system and their dispersion between the different applications and computer equipment; this requires more processing, with special attention to the scattered records.

An undesirable situation is the noncomputerization of some documents such as WOs filed on paper, or documents for purchases of equipment, bills of contractors, and so on, stored without being processed by a computer. Even more negative is the situation when no records exist; in this case, the auditor must create the audit record and take the minimum measures that validate and support the rest of the parameters and the process. This will affect the establishment of an appropriate data collection culture and management of documents.

- *Phase 3*: *Comparison or benchmarking*

  The obtained measures should be linked to the reference points, upper, lower, or desirable targets. The measurement obtained for these references indicates a positive or negative result of the audit. The most frequent reference proposed by De Lemos [66] is benchmarking. De Lemos sets those values lacking references, using the experience of workers and technicians, the yields presented previously by the machinery, the manufacturer's recommendations, or the experience of the audit equipment.

  Some especially relevant references are proposed by EFNMS, an ambitious project for the definition of a single metric of maintenance as described Svantesson [278]. EN 15341 [94] "Maintenance Key Performance Indicators," published in 2007, is another milestone but it suffers from a lack of references that are both valuable and necessary for an audit. Finally, the harmonization project with SMRP described in the previous chapter is of genuine interest to international benchmarking; the project began in 2006; see Svantesson et al. [317] (Figure 7.10).

  In the evolution of indicators, we observe alterations in the evolution itself as increases or decreases can be abrupt; however, this information is not enough to know the final goal of the indicator, where it tends to, where we should position it, or what values we should monitor.

  These reference points have a condition added in successive audits and are dynamic. References for recently created companies or new products will be different from those for formature enterprises or products in decline. Idhammar [128] insists on realistic goals being set for the references; if they are not achievable, this will cause discouragement and the failure of the measurement system, even though the goals are attainable. If they are realistic, they can become a unifying and motivating element.

- *Phase 4: Proposals to improve*

  The audit outcome showing any deviations is important as it suggests remedial measures to be taken before the next review.

There are two important aspects in the performance of the audit contained in these four phases:

1. The first phase is preparing a scorecard. Obviously, we are interested in visualizing the four BSC perspectives in the indicators (as proposed in the previous chapter). However, the BSC approach does not explain the function, maintenance,

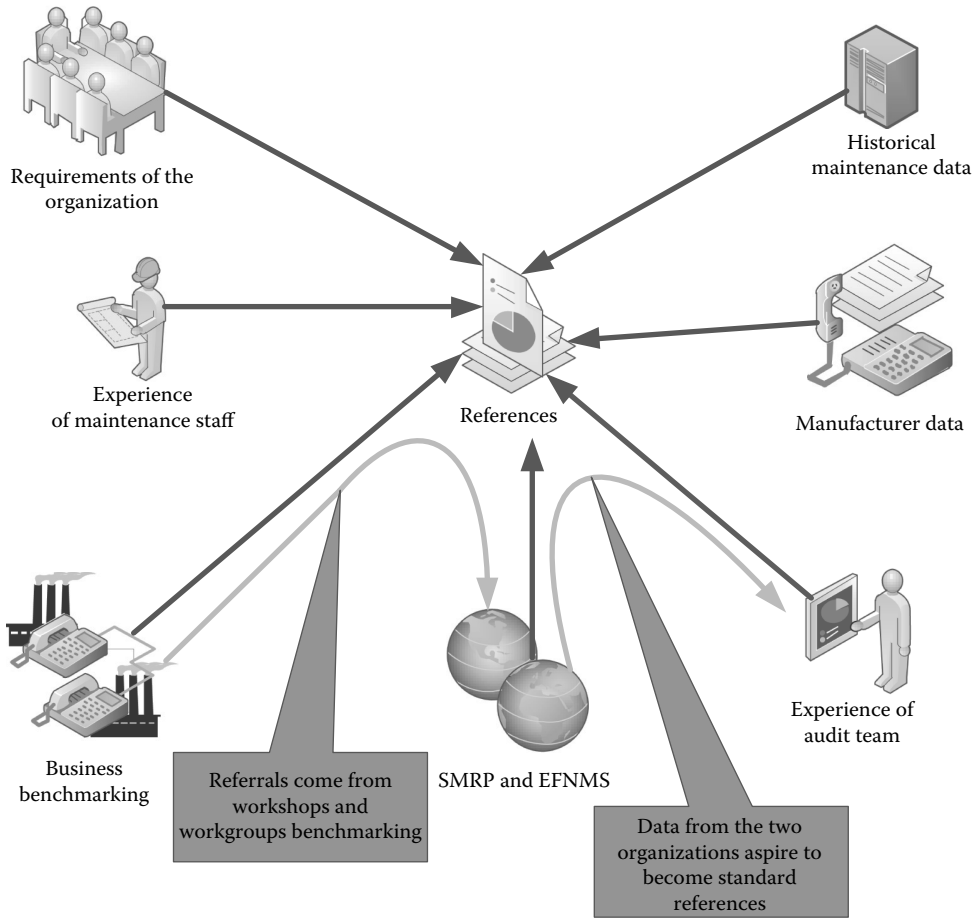


FIGURE 7.10
References to indicators.

or transfer of these indicators to a methodology that is clear and transparent enough to enable their measurement.

2. The second phase is creating an order or sequence of realization. We need to order the measurement of the parameters to achieve partial results throughout the process. Wireman [375] and Campbell [41], as discussed in Chapter 1, outline the evolution of maintenance maturity in an organization, using a series of levels (Figure 7.11). Proper implementation at one level justifies the step to the next, suggesting a schedule or logical succession in the application of techniques and methods. Specifically, Wireman defines the steps as shown in the pyramid here.

Wardehoff [366], Peterson [266], and other authors agree with the general idea of a progression but suggest different stages in the evolution of maintenance.

Given the consensus, an audit should be performed bottom-up, with the object of identifying organizational levels and determining whether the correct steps have been taken, in the correct order. As represented in Figure 7.12, the indicators associated with the different

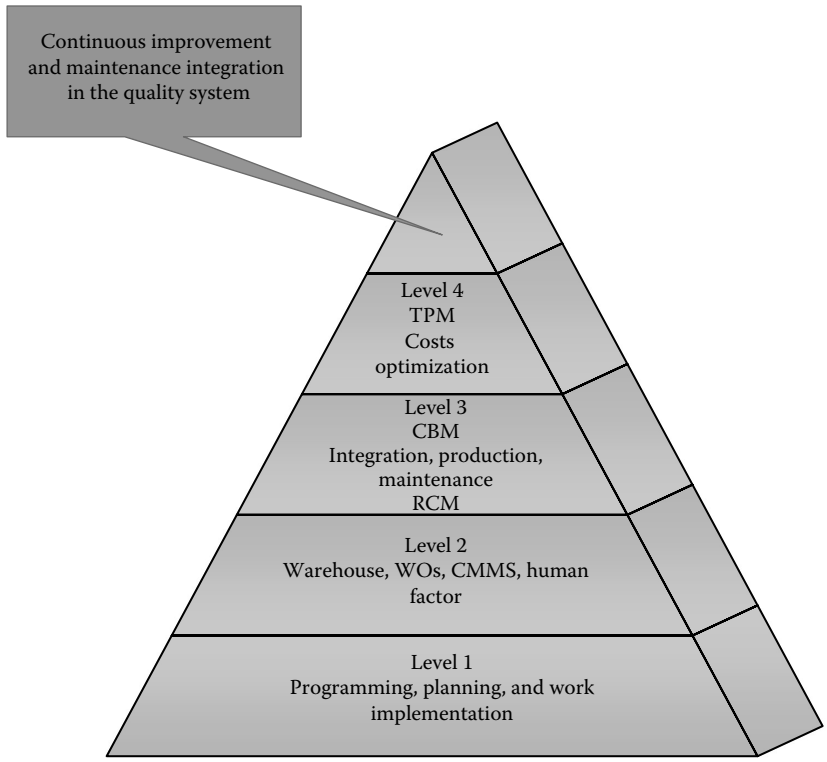


FIGURE 7.11
Maturity levels of maintenance according to Wireman and Campbell.

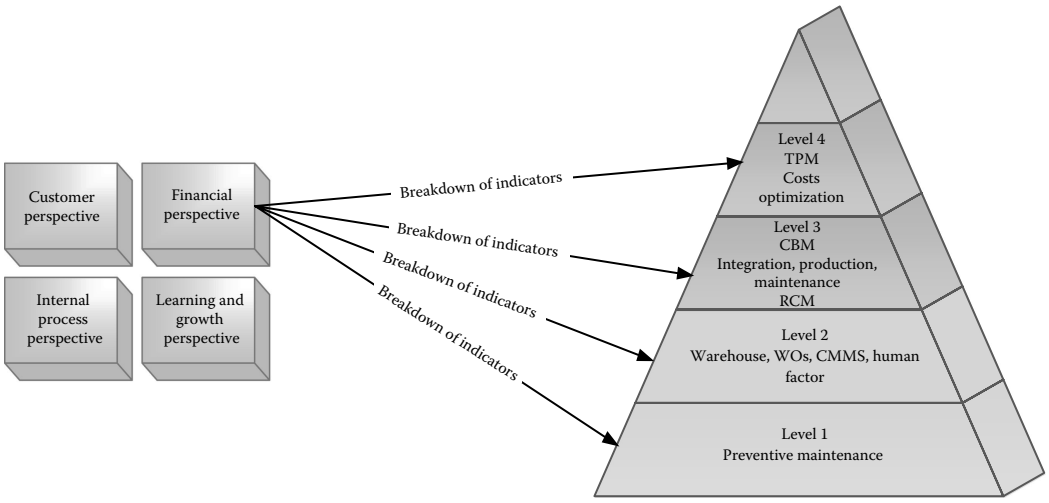


FIGURE 7.12
Breakdown of indicators for audit.

BSC perspectives and the different maturity level of the specific maintenance function should move in a way that creates a new set of indicators for each hierarchy of the pyramid.

Accordingly, as the following chapters make clear, we relocated the indicators for each level of maintenance evolution. The second step is the measurement of each indicator, starting from the base of the pyramid and moving upward. The process should match the reference points associated with each level, so the audit ends at the right time and the organization's level of maturity is not exceeded.

This methodology allows us to obtain partial results throughout the audit process; these results can be reported to the relevant team. However, the audit process may reach conclusions and recommendations that surpass the maturity at that level. Problems may range from small cases of noncompliance to more serious recommendations in more immature levels. Keep in mind that a deficit in a given level will be explained by the indicators of the level immediately below.

As seen in Figure 7.13, when we reach high maturity levels, the audit loses its value considerably as the values obtained will not be relevant. This indicates that it is time to move the indicators measured in the BSC levels and create a new scorecard.

The complete process can be seen in Figure 7.14. The audit begins at the base of the pyramid; we evaluate the indicators associated with that level and make comparisons with the corresponding reference points. This indicates the maturity of that level and whether its methodology is sound.

From here, we continue to ascend, level by level, reaching conclusions about the maturity of each level. At this point, it is time to report on the state of global maturity, that is, whether the lower pyramid is working properly with all levels properly constituted.

We will also know whether the indicators in each level are correct and correctly used. We may discover some that are inappropriate.

The last audit step is the projection of the measured indicators with their reference points on to the BSC's different perspectives. This gives a BSC of maintenance as proposed in the previous chapter but with the completed data and built-in references. We can now see the degree of success in each (Figure 7.15).

As Figure 7.16 shows, an audit comprises of two sets of information.

First, it indicates the state of maturity in the maintenance evolution and ascertains its appropriateness, suggesting logical steps toward the development and helping to create a calendar of future improvement actions and corrections of already existing systems. The pyramid is evolutionary, whereby errors at higher levels have their causes in lower levels; this understanding facilitates the analysis of problems found in the indicators and surveys.

Second, it helps create the BSC with indicator measurements taken in the pyramidal process. As mentioned, only surpassed maturity level indicators are represented in the BSC. This is consistent with MacArthur's [196] definition of the core of asset management as the two following components:

- *Global asset management*: EAM strategy Enterprise asset management (EAM) strategy: getting greater capacity at lower cost
- *Resource optimization*: MRO processes Maintenance resource optimization (MRO) processes: efficiency in small processes immersed in larger strategies

Many authors advocate obtaining these two types of results. Clarke [52] suggests that the audit should provide a maintenance radar (Spider graph type Bell-Manson) to represent

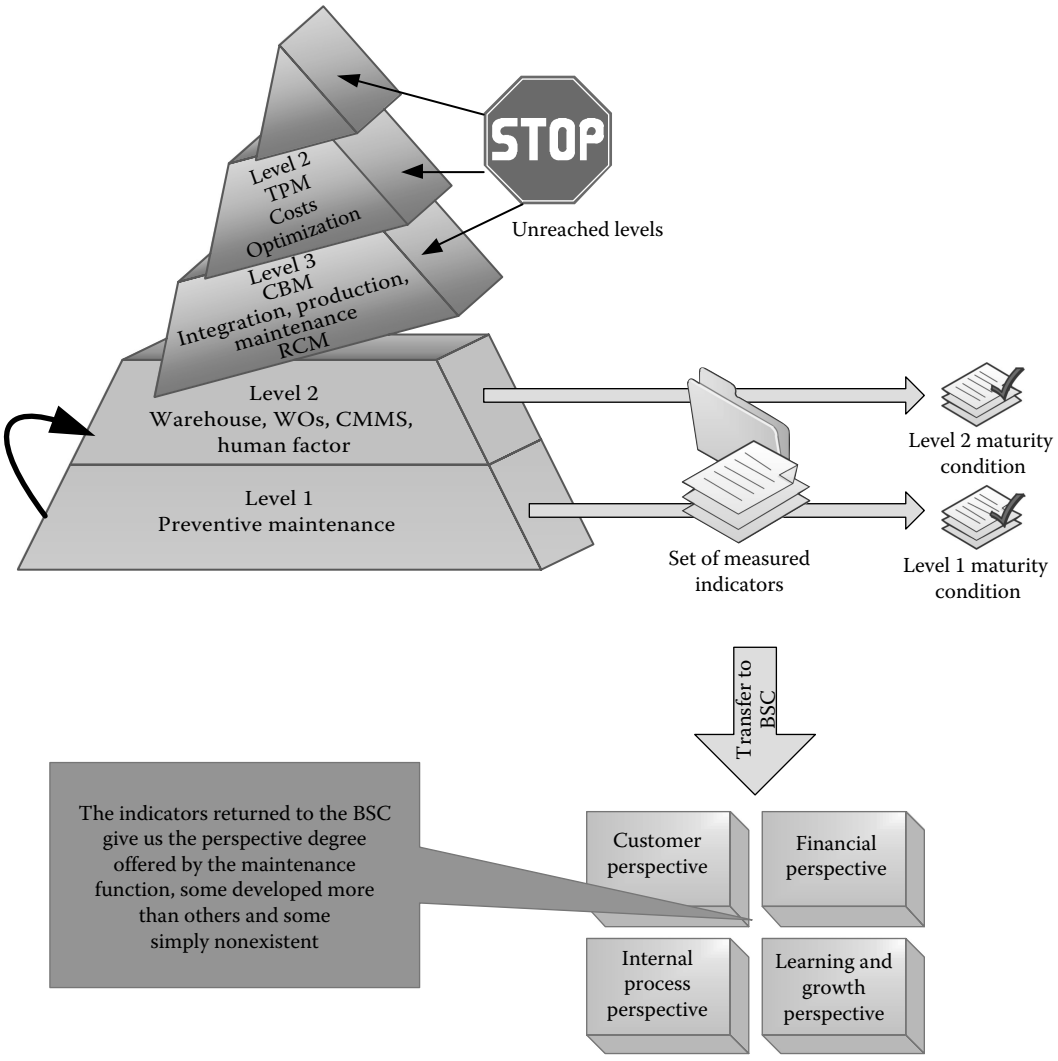


FIGURE 7.13
Audit process as a function of the maintenance maturity.

all aspects, economic, human, and so on, of maintenance, while also proposing that one of the products of the audit must be good technical and operating practices. Like many other authors, Tavares [322] uses the maintenance radar to represent the various areas of influence and dependence of the maintenance function. All authors agree on generating the radar from surveys despite their questionable reliability. Numeric system data are not incorporated into the radar, and the human factor is a strong component.

The results of the lack of maturity on the level reached will be translated, as shown in Figure 7.16, and coincide with MacArthur in the direction of maintenance recommendations for achieving the objectives related to the strategy.

Hierarchical indicators must reflect the objectives and strategies of that level. Therefore, all levels are affected by deficiencies in the measures and subject to the appropriate corrective measures. Those concerned with specific indicators are obviously interested in

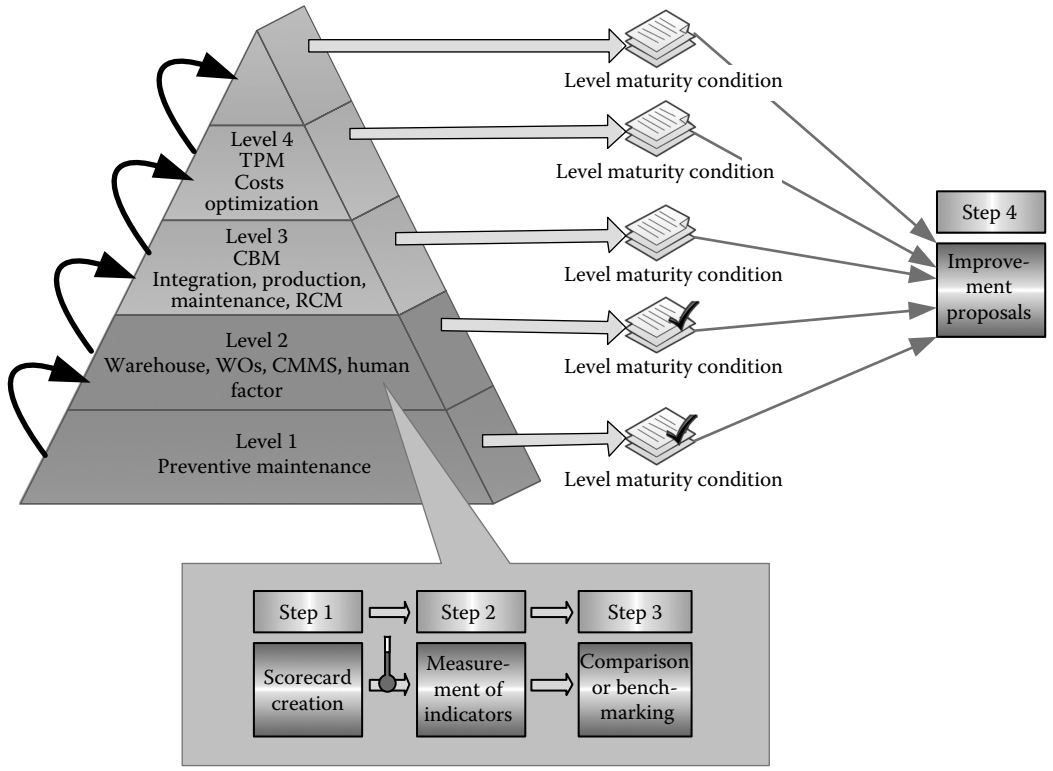


FIGURE 7.14
Audit process associated with maintenance maturity levels.

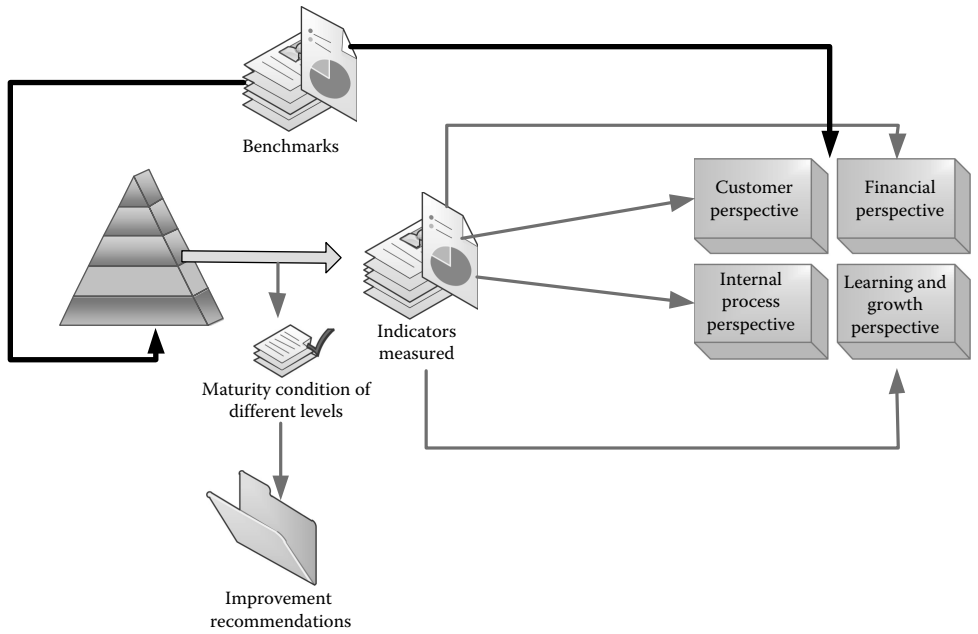


FIGURE 7.15
Transfer of indicators to the BSC.

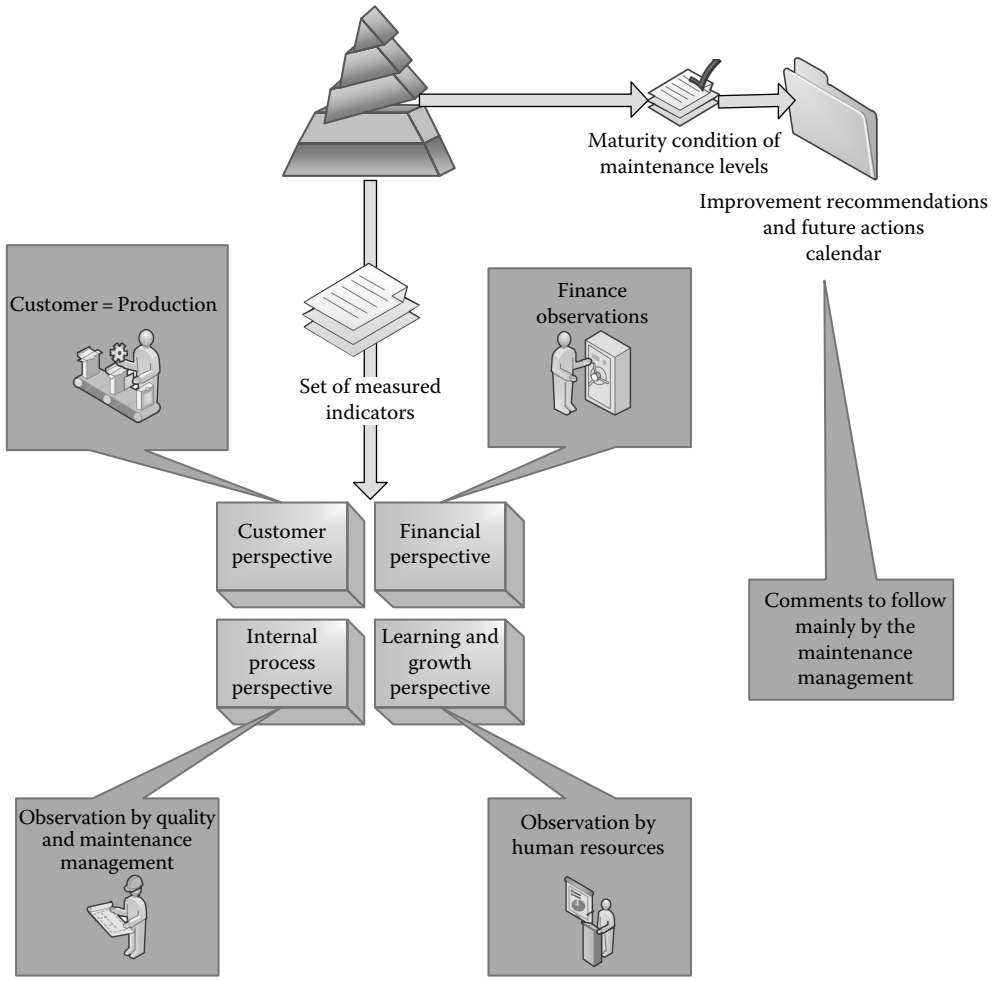


FIGURE 7.16
Audit result.

the results of the measurements as they are involved in the process of improvement. Those at the level of decision-making are also interested.

This whole process requires the use of multiple indicators. The hierarchical levels and methods of data collection are simple, and the evolution of the maintenance is also very simple. At the same time, the audit is dynamic.

A maintenance audit should not be confused with a TPM or RCM audits/analysis. RCM and TPM analysis trigger improvements to the maintenance function, which require the existence of a series of established methods to serve a specific need data specific time.

The introduction of TPM or RCM could be one of the recommendations for improvement following an audit but never the nucleus of an audit. It should direct maintenance toward these policies or methodologies but is not a miracle solution to performance problems. In addition, the process of improvement must be subsequent to the audit of maintenance and not a part of it. RCM and TPM suggest improvements in a given time, while the audit reflects the condition of the maintenance on the basis of fixed KPI indicators.

7.3 Linking Steering with the Maintenance Strategy

Inside the proposed pyramidal model, there is a zero level, the necessary foundation upon which to build a maintenance strategy aligned with the objectives of the organization. This foundation reflects the company directors' knowledge of and concern for the maintenance function.

Maintenance has gained relevance as managers now recognize the need for maintenance to keep production running and to improve the production infrastructure. As a result, maintenance has increased significance in the strategic structure of companies; for example, see Müller et al. [229]; Kardec and Nascif [158]; Swanson [319]; Teixeira [326].

The management commitment to quality in its broadest sense includes the maintenance function. The overall main goal is to raise the quality of the maintenance performed in the organization and to continually improve the management and control of maintenance actions at different levels with the aim of achieving maximum quality and a reduction of the overall cost of maintenance.

It is important, therefore, to measure success using the indicators established in the previous chapter and, based on those parameters, to define the actions needed to improve the system. Not surprisingly, given the greater awareness of the importance of maintenance, it is more frequently included in integral quality systems.

Before starting the audit process to determine the success of the maintenance function, we should have an idea of some relevant general indicators. Together with the survey, these indicators will provide a first approximation of the commitment of a company to maintenance and the managers' desire for improvement. The existence of indicators and their ease of access for calculation will promote or hinder the audit. Their absence and/or negative results in a survey will suggest the need for a complex development of the maintenance function, including greater awareness at higher levels of the company.

A questionnaire given to maintenance decision makers should include the following:

Questionnaire: Commitment of direction to maintenance strategy

1. Is "maintenance" integrated into the company's business plan?
2. Are there specific measurable goals for maintenance?
3. Does the company have a maintenance flowchart with an overall manager and lower level managers defined and located on the chart?
4. Are the goals mentioned in question 2 integrated with general business goals?
5. Do all personnel understand the established goals, along with the need for their involvement for the attainment of the goals?
6. Does the company regularly verify the obtained results against the established objectives?
7. Does the company take action to improve maintenance efficiency?
8. Does the company measure these actions?
9. Is there coherence in the maintenance strategy between the different plants or productive areas of the company? (Figure 7.17)

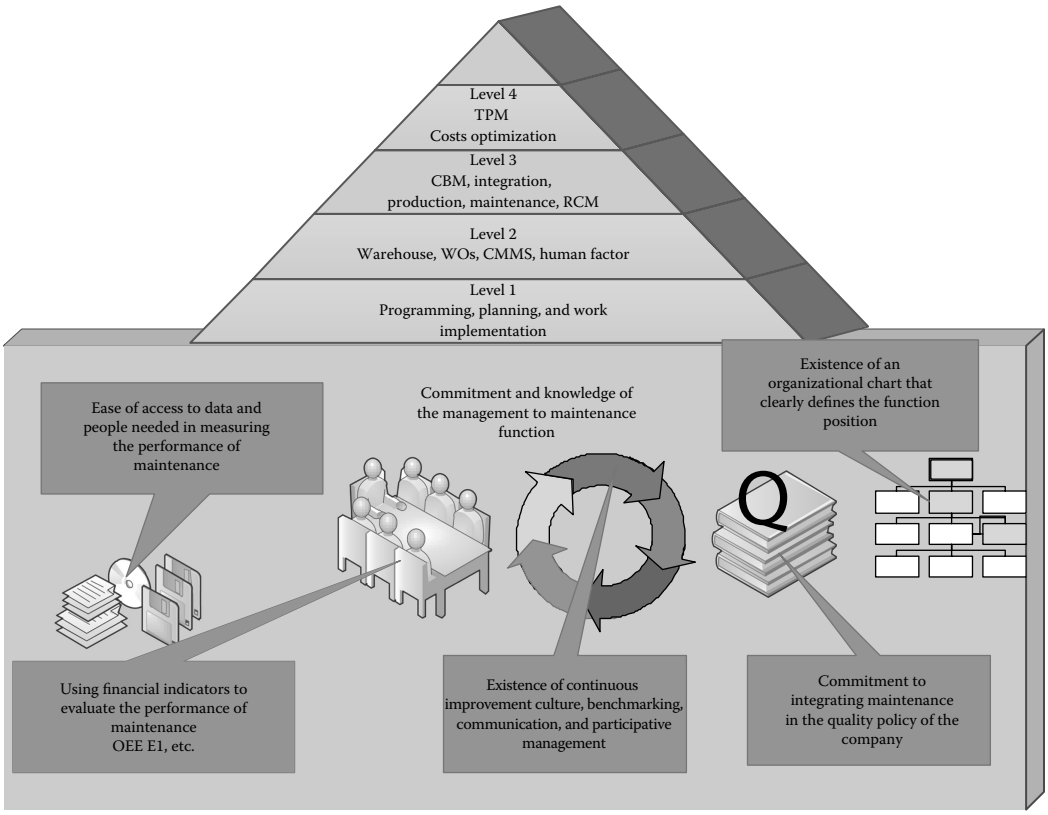


FIGURE 7.17
Level zero of the maturity pyramid in the maintenance evolution.

Real conditions for an audit

The key factor for excellence is the cost of maintenance with respect to the replacement of assets. Expensive maintenance occurs when the cost to maintain does not take into account the asset's productive capacity. The performance is directly proportional to the total cost of the asset.

$$\text{EI1} = \frac{\text{Total maintenance costs}}{\text{Assets' replacement value}}$$

This parameter, according to Peterson [266], must be part of the financial direction, along with a long-term maintenance plan that optimizes the return on investment of the acquired assets. The LCC must include the cost of acquisition, financial costs of maintenance, and so on. This information is crucial for replacement decisions.

The replacement value of assets should be calculated following the SMRP and harmonized with DiStefano and Hawkins' EFMS [71]. Weber and Thomas [367] propose a corporate indicator of utility costs of maintenance with respect to sales in the manufacturing industry; in their view, a world-class reference for this indicator should be between 6% and 8%; the *EI1* world-class reference is between 2% and 3%.

A relevant parameter is the OEE. In the company, operations management controls three macro areas based on this parameter and notes any deficiencies in its evolution. It is a key audit parameter, as proposed by Grenčik and Legat [109]. They suggest auditing differences between global parameters and those in the hierarchical levels to get specific strategies.

$$\text{OEE} = \text{OEEI1} \times \text{OEEI2} \times \text{OEEI3}$$

World-class maintenance (WCM) objectives in this indicator must be between 85% and 95%.

$$\text{OEEI1} = \text{Availability} = \frac{\text{Total activity time}}{\text{Scheduled time}}$$

$$\text{TI1} = \frac{\text{Total operation time}}{\text{Total operation time} + \text{Maintenance unavailability time}}$$

The unavailability relative to maintenance should be, according to EFNMS, at least 95%.

$$\text{TI2} = \frac{\text{Availability time achieved during the required time}}{\text{Required time}}$$

The availability indicator is a main operating parameter. According to Olver [245], total unavailability can be close to 10% but the SMRP proposes setting limits at 90% availability achieved. The EFNMS is more ambitious and advises a 95% availability target for some sectors, such as pharmaceutical or food, agreeing with Olver at 90% in most industries.

$$\text{OEEI2} = \text{Performance efficiency} = \frac{\text{Real production to programmed time}}{\text{Planned production to programmed time}}$$

$$\text{OEEI3} = \text{Quality rate} = \frac{\text{Total production} - \text{Defects}}{\text{Total production}}$$

$$\text{EI3} = \frac{\text{Total maintenance costs}}{\text{Quantity produced}}$$

$$\text{TPMI5} = \text{Decrease the unit production cost}$$

A parameter that handles the company's operations in the maintenance function can observe the cost reduction per unit.

Two parameters assess maintenance in many organizations: how many monetary units are loaded onto the finished product, and how much this amount is reduced by applying new methods and new techniques. The *EI3* parameter and percentage reduction are

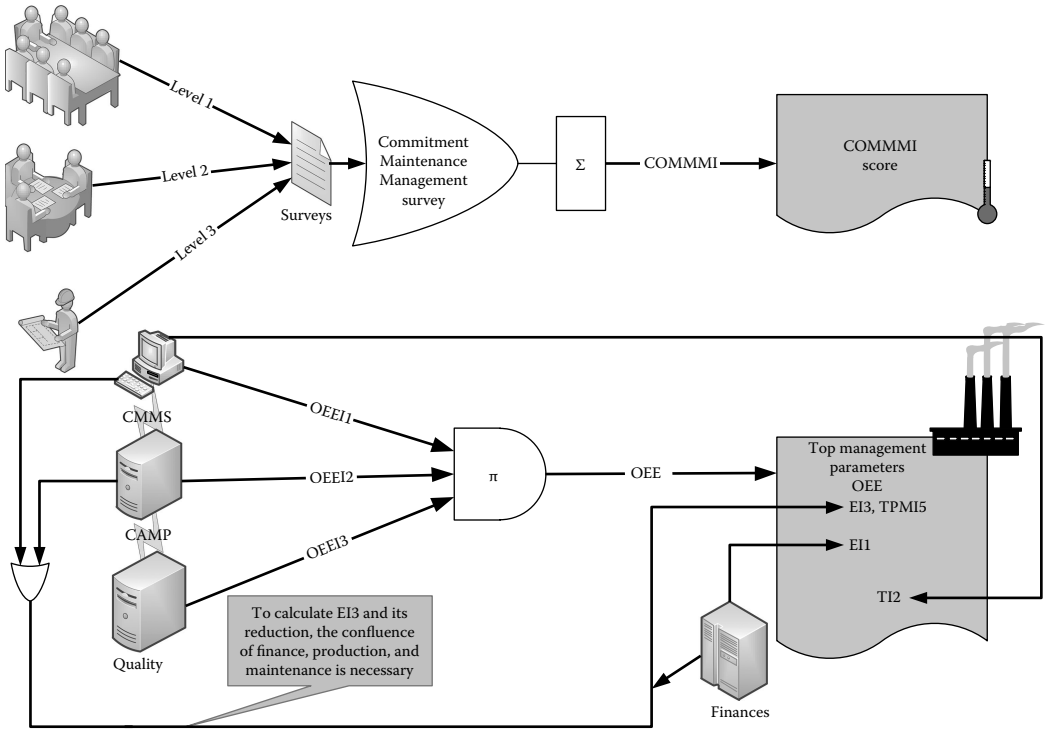


FIGURE 7.18
Audit level of management commitment to the maintenance function.

generally the only goals of maintenance when a financial perspective is expected to be achieved by this function.

Figure 7.18 graphically summarizes the use of surveys to obtain basic scorecard values that underpin the subsequent audit.

7.4 Level 1 Evolution

The basis of any maintenance system is necessarily preventive; that is, the philosophy of prevention values efforts to preclude seeable faults. This is a way of favoring the foreseen and planned over the random. This level will assess the ability of the organization to implement such a plan.

A preventative maintenance plan will take into account the scheduling of job resources and note any deviations in realization. Aspects of planning and execution, such as costs, human resources, or materials, are valued by indicators and noted in the surveys carried out at the different hierarchical levels (Figure 7.19).

7.4.1 Work's Programming, Planning, and Execution

The work of planning indicators is carried out at levels 3, 4, and 5, as the maintenance director and the controller who are interested in this type of indicator.

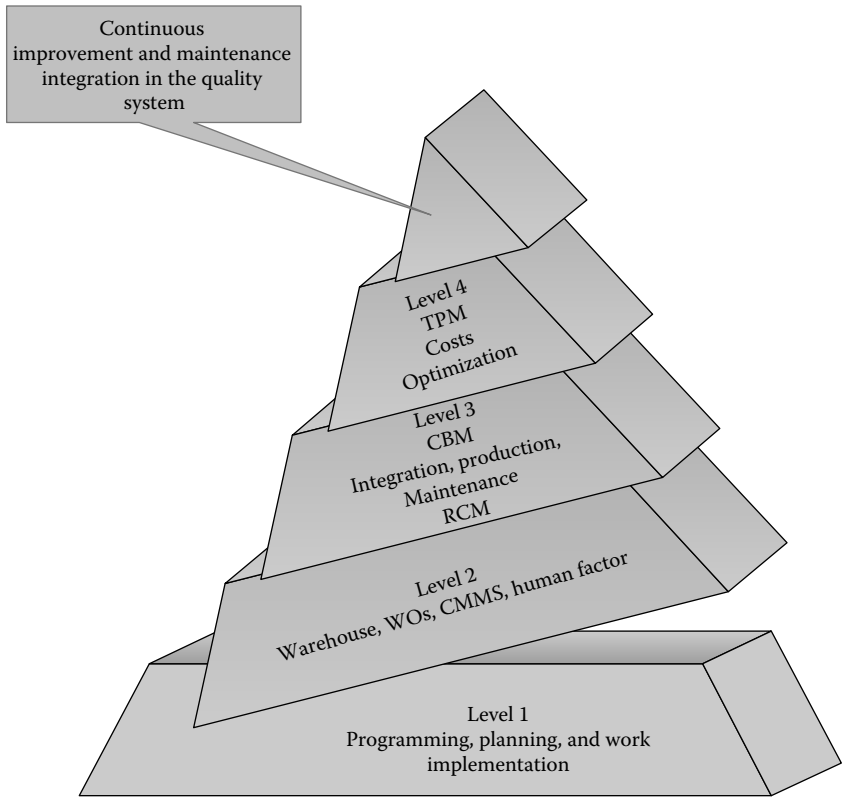


FIGURE 7.19
Level 1 maintenance evolution: preventive maintenance, programming, planning, and execution.

7.4.1.1 Work Planning

Questionnaire: Work planning
W-PLAN: Work planning

1. Is there a work request to the department from other areas, such as production, quality, or labor risks?
2. Is work prioritized?
3. Is there a known workload according to projected work?
4. Is this work programmed?
5. Is this work planned?
6. Is the time required for planned and programmed work known to a certain degree of accuracy?
7. Is there any control over execution and results?
8. Has 95% of the maintenance been programmed at least 1 day before being realized?
9. Are spares, hardware, necessary equipment, and papers prepared and adapted for the work?
10. Do the planners clearly indicate the hardware to use and components to be replaced?

11. Have instructions or procedures for the work been established?
12. Do the personnel know what they are going to do the day before a task is realized?
13. Is the planner's function defined?

7.4.1.2 The Maintenance Execution

Questionnaire: Work execution
W-EXEC Execution of work

1. What the relationship of scheduled shutdowns and unplanned shutdowns?
2. What is the work program of scheduled maintenance?
3. Have the procedures for preventive maintenance been defined?
4. Have the procedures for corrective maintenance been defined?
5. Are there any maintenance procedures defined for periodic inspections (checklist, descriptions, steps, frequency, etc.)?
6. Are the necessary procedures adapted to the abilities or skills, materials, and tools?
7. Is there a method to analyze the differences between the theoretical plan, actual implementation, unintelligibility, deviations, and anomalies?
8. Is the ratio of outstanding work and scheduled jobs known?
9. Is the relationship between overtime and the time for unscheduled jobs and scheduled jobs known?
10. Is preventive maintenance based on the condition/status of the component?
11. How is equipment reviewed when a shift begins?
12. Is there a daily routine?
13. Are daily maintenance and interventions registered?
14. Is the amount of time required to diagnose a fault known?
15. Is the exact number of pending jobs known per period?
16. Does the team have control over the necessary hours to finish work?
17. Is the information useful?
18. Is there an emergency work and program record?
19. Are jobs recorded by the type of mechanical maintenance, electrical, and so on according to the personnel involved?
20. Is lost production time quantified by faults?
21. Are delays quantified for maintenance?
22. How is control maintained over the time spent on repairs?
23. How is the real time compared with the time stipulated in work orders?

The indicators in audits of the work plan are determined by the surveys. It is necessary to remember that the success of the planners is evaluated twice. On the one hand, they must consider the maintenance resources; on the other hand, they must be capable of avoiding important deviations from planned activities, an aspect also found in the evaluation of work execution.

7.4.1.3 Indicators of Human Resource Hours in Planning and Execution

*OI*25 represents a unitary success indicator when no maintenance hours are planned by programmed activities. *OI5* represents planner success using every available hour of resources without requiring abnormal resources.

$$\text{OI25} = \frac{\text{Direct maintenance man-hours in scheduled activities}}{\text{Total planned man-hours for direct staff}}$$

OI25 is discussed by Stegimelle and Olver [306] for SMRP and shown in WO planners. In their calculation of the values indicator, the authors explain that exceeding 120% is not good.

Wireman [375] introduced specific indicators, with the number of WOs exceeding this deviation up to 20%, and included this in his model. This indicator should be calculated monthly; continued or maintained upward deviations must be analyzed in detail, changing the indicator according to work areas or identified planner posts.

$$\text{OI5} = \text{WOI12} = \frac{\text{Planned and scheduled maintenance man-hours}}{\text{Total number of maintenance man-hours available}}$$

The *OI5* or *WOI22* indicator should be around 80%; else excessive overtime and downsizing will result. *OI25* should have little deviation, or planned maintenance will occupy almost every hour, with unplanned taking even more.

Casto [45], from an SMRP point of view, proposes placing this indicator between 60% and 65% leaving a higher margin than unplanned activities. WCM is more generous when dealing with the operators' work and correcting deviations with overtime. It can be calculated from a daily to an annual basis and tends to be a relevant indicator to detect opportunities for improvement.

The following indicator is a classic and reflects the lack of planning or improper use of the available resources. It should, of course, be a low-impact index.

$$\text{WOI13} = \text{OI21} = \text{PMI10} = \frac{\text{Maintenance overtime}}{\text{Maintenance total worked hours}}$$

For Hawkins [113], normal values of overtime are around 6% of the total hours worked. It is, in fact, a common value in the practical examples of SMRP and EFNMS.

Another classic indicator refers to urgent corrective measures, which under the rule of the preventive culture must represent less than 10% of human resources used.

$$\text{PMI2} = \frac{\text{Man-hours spent on emergency works}}{\text{Total worked man-hours}}$$

For Mather [206], a world-class perspective would leave little room for emergency work; to reduce this to 5%, we need strong planning.

7.4.1.4 Indicators of Task Fulfillment

The following two values represent deviations from the preventive maintenance tasks in an attempt to create programming appropriate to the resources available.

$$\text{PMI4} = \frac{\text{Preventive maintenance tasks performed}}{\text{Preventive maintenance tasks scheduled}}$$

As a compliance index, *IMP4*, according to WCM, must be at least 90%.

The audit date is relevant to pending preventive tasks when they are delayed due to failure in the planning. This represents an inefficiency index. In the same way, the extra hours worked are an inefficiency index indicating poor planning.

$$\text{PMI9} = \frac{\text{Number of PM delayed tasks}}{\text{Number of PM pending tasks}}$$

The WCM perspective requires that 95% of work requests or WOs be carried out within the dates provided. Therefore, the *IMP9* indicator will keep a temporal evolution around 5%. This indicator detects the delayed percentage but does not measure the extent of the delays that can be innocuous or disrupt the entire program.

Nelson and McLean [237] considered a delay indicator by the scheduled task. They showed the result between the delay in execution and the frequency (weekly, monthly, etc.) of the task program. Obviously, a detailed analysis will identify the location of the problem and analyze the causes. The authors emphasize that scheduling a task strongly affects the average delay. For example, a delay of 3 days in a weekly programming task involves a delay of 40%, while if programming is monthly, the delay is only 10%.

7.4.1.5 Economic Indicators

The corrective amounts for preventive maintenance and the unplanned budget that goes to these items represent a planners' nightmare. The diversion of costs will result in a correction in the planning.

Three economic indicators reflect deviations in preventive costs, which obviously must be reduced as much as possible.

$$\text{PMI5} = \frac{\text{Tasks estimated costs PM}}{\text{Tasks real costs PM}}$$

First, Stegimelle and Olver [306] proposed the *PMI*5 indicator to display the accuracy of predictions of planned maintenance costs (excluding urgent corrective actions). Their proposal included a reverse indicator that must be analyzed per planner to evaluate individual skill. It finds a value of about 116%, whose reverse adapted to *PMI*5 is 86% accuracy, the right percentage in the evaluated schedule. Although it does not correspond to the harmonized indicators in the proposed audit, it can be used, according to Stegimelle and Olver, as it is useful to all planning with respect to total execution, whose deviations are more or less important to evaluate WOs clusters or specific planners.

A second economic indicator presents the cost proportion for corrective and preventive maintenance values as around 85% or 90%.

$$\text{PMI11} = \frac{\text{Preventive maintenance total costs}}{\text{Preventive maintenance total costs} + \text{Corrective maintenance total costs}}$$

Third, a complex indicator evaluates the downtime cost for maintenance, which must be very limited unless there is a very important stop or modification that generates some unusual costs.

$$\text{EI20} = \frac{\text{Cost of programmed maintenance stops}}{\text{Total maintenance costs}}$$

The *OI5* and *EI20* indicators give priority to the accuracy of planned hours and work hours as well as the associated costs. The planner's goal is to anticipate emergencies that normally add costs to planned work.

7.4.1.6 Technical Efficacy Indicators

Several indicators reflect availability in planned and implemented maintenance. It is important to mention that any value of availability between 30% and 50% indicates a poor planning system.

TI20 contributes to the planning of foreseen unavailability. It is, therefore, a key parameter for planners. The indicator of inefficiency *TI7* indicates the planned unavailability that must be kept at a minimum. *OI11* must be reduced by its numerator to avoid having to correct large unavailability.

$$\text{PMI12} = \frac{\text{Preventive maintenance unavailability time}}{\text{Preventive unavailability time} + \text{Corrective unavailability time}}$$

$$\text{TI20} = \frac{\text{Planned and scheduled maintenance time causing unavailability}}{\text{Planned and scheduled maintenance time that requires unavailability}}$$

$$\text{TI7} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailability time due to planned maintenance}}$$

The SMRP unavailability for planned maintenance is a supplement to the *TI7* indicator and is assigned a maximum indicative value of 6%; see Olver [246]. According to Olver, it is important to take three components of planned unavailability into account: preventive tasks, corrected programmed time, and delay time in work preparing.

$$\text{OI11} = \frac{\text{Time spent on emergency corrective maintenance}}{\text{Total unavailability time linked to maintenance}}$$

General information that must be provided by the audit includes the time distributions of maintenance by types and associations. Auditing the planning aspect will also reveal

the percentage of time distribution of maintenance. Depending on the type of scheduled maintenance downtime, these variables change radically in the application of different methodologies, as discussed. Unavailability is reduced with preventive and systematic maintenance, generally CBM, which is not intended to stop the machine.

$$\text{TI8} = \frac{\text{Preventive maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{TI9} = \frac{\text{Systematic maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{TI10} = \frac{\text{CBM time that causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

It is useful to calculate the complement of these three components. SMRP awards the greatest significance to the unavailability produced by unplanned maintenance; see Olver [247].

Guild distribution of total maintenance hours.

$$\text{OI12} = \frac{\text{Man-hours of mechanical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI13} = \frac{\text{Man-hours of electrical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI14} = \frac{\text{Man-hours of instrumentation maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

Hour distribution according to types of maintenance.

$$\text{OI16} = \frac{\text{Corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

Hawkins [116] says that the *OI16* indicator proposes a form of harmonized calculation that includes planned corrections and emergencies. Further, it shows that a normal 25% of work time (for external and internal maintenance) is devoted to this type of activity. Hawkins proposes a weekly or monthly measurement of this indicator.

$$\text{OI17} = \frac{\text{Emergency corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

The *OI17* indicator considers reactive maintenance. WCM sets a percentage between 10% and 15% for this type of maintenance. Olver [249] describes how to calculate this indicator,

called O17 in the UNE-EN 15341 [356] and harmonized by the author between SMRP and EFNMS. Olver specifies that this indicator should be below 5% (more restrictive than world-class indices) and measured monthly, or possibly weekly. This index shows the 5% recommended by EFNMS. The same organization supports correcting values around 13% of benchmarked values as these are the results of bad practices.

The author shows the differences and dangers of calculating an index not based on hours of maintenance but on the WOs and tasks. The index will include emergency work and work accelerated unnecessarily.

$$\text{OI18} = \frac{\text{Preventive maintenance man-hours}}{\text{Total maintenance man-hours}}$$

Olver [250], in his documents for SMRP, harmonizes the O18 indicator as the sum of all maintenance to prevent failures, including preventive, predictive, and corrective preventive or predictive inspections. It would be interesting to include time data analysis for RCM, RCA, or from predictive maintenance as they are a constituent part of the proactive work being evaluated. The calculations can be made weekly, but the author proposes monthly ones. Again, we must be careful with the restricted calculation tasks and work orders. The author suggests that the indicator for proactive maintenance should be around 40%.

$$\text{OI19} = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI20} = \frac{\text{Systematic maintenance man-hours}}{\text{Total maintenance man-hours}}$$

The WCM perspective, as mentioned, is more conducive to planning and resource use; Mather [206] proposes a division of worker hours as follows:

- 50% preventive maintenance
- 30% reductive maintenance
- 15% corrective maintenance
- 5% emergency maintenance

This WCM perspective is severely criticized by authors such as O'Hanlon and Nicholas [241]. They contend this represents an abuse of preventive maintenance and lacks logic. If only between 11% and 17% of the failures result from the age of the equipment, cannot be explained, the use of temporary preventive and periodic maintenance and periodic basis is justified (Figure 7.20).

The audit process of the preventive maintenance program is summarized in Figure 7.21. The surveys and their weighting and validation are highlighted by two key parameters for planning and implementation. Once obtained, these data from survey and associated indicators selected as representative of the success of the program must check the consistency of answers and verify their veracity. If we have indicator values within reasonable limits and the responses of the different organizational levels are consistent and fit with the knowledge and use of the preventive program, we can conclude that

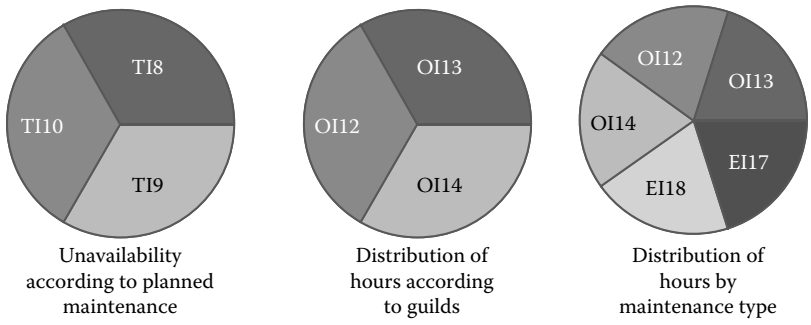


FIGURE 7.20
Indicator sectors corresponding to the planning audit and maintenance execution.

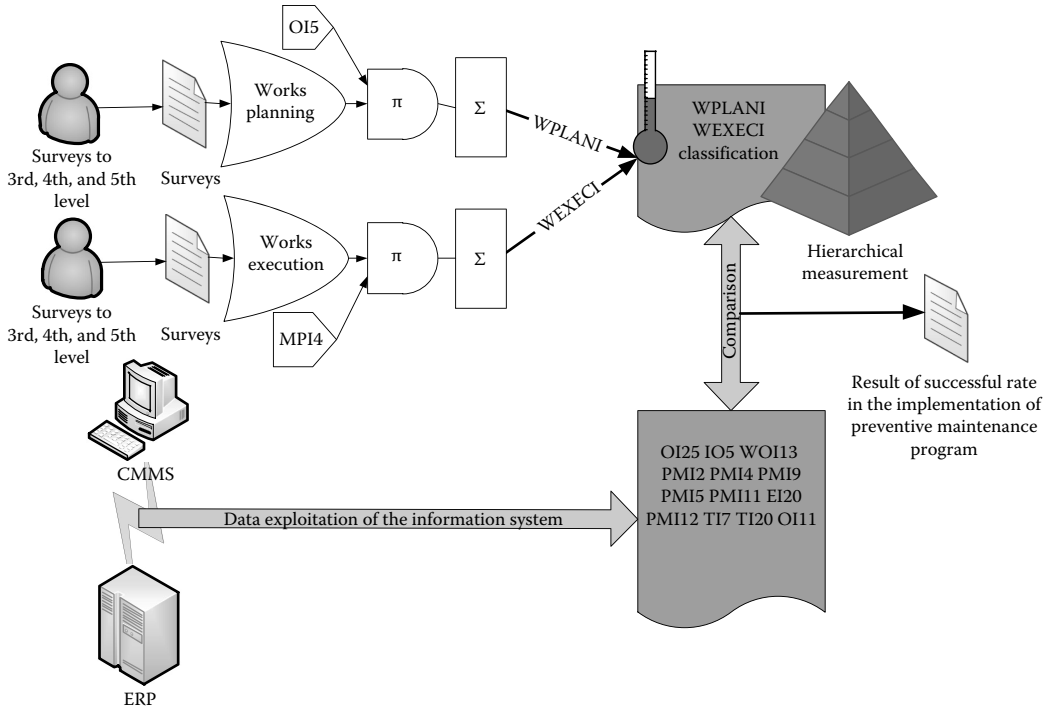


FIGURE 7.21
Preventative maintenance system audit process.

the preventative maintenance is properly implemented, and we may audit the top level (Figure 7.21).

7.5 Level 2 Evolution

Once the preventative maintenance has been tested, level 2 has two necessary elements of maintenance management to be audited: a document management adapted for computerized maintenance management systems (CMMSs), WOs, and an efficient store (Figure 7.22).

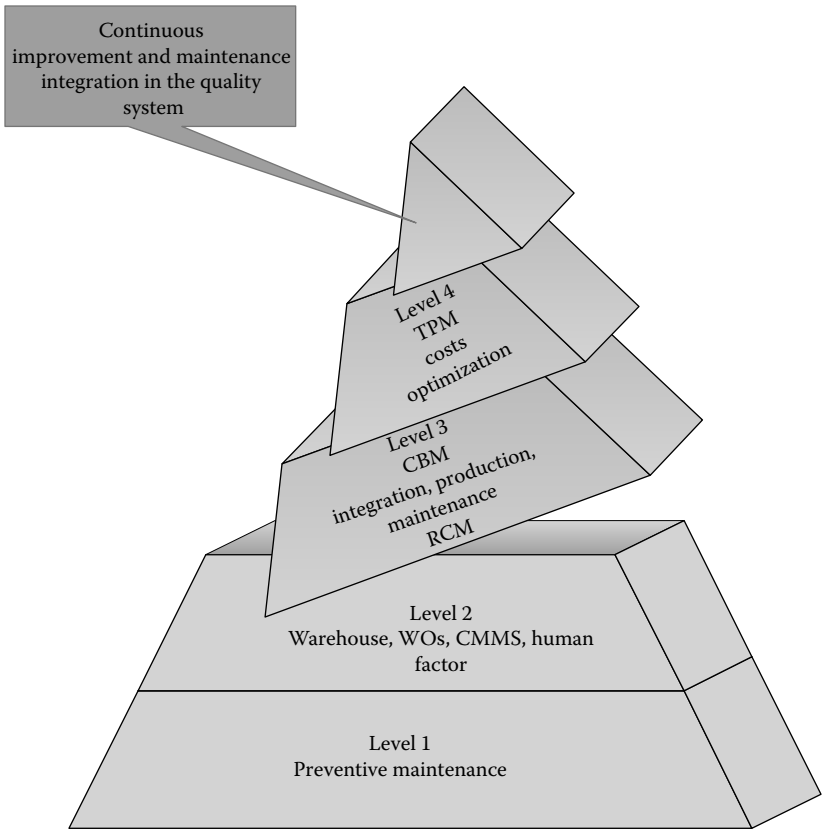


FIGURE 7.22
Level 2 in the maintenance evolution.

7.5.1 Maintenance Storage and Purchasing Management

7.5.1.1 Purchasing

Questionnaire: Purchases
PUR-PRO Purchasing procedure

1. Is there a procedure for purchasing in the company? Is it applied?
2. Is a purchasing procedure for management of spare parts applied?
3. Does this procedure specify the authorization levels required for the amount of the order?
4. Does the purchasing procedure meet the requirements of flexibility and speed?
5. Does the purchasing procedure have emergency plans and priorities? Does it require signatures or special authorizations?
6. Are costs associated with a purchase order, such as transport, call, and fax, known?
7. Are there alternative means to make an urgent purchase?
8. Are the specifications for orders sufficient?

9. Is each purchase order checked for technical specification?
10. Does the purchasing department participate in the definition of purchase specifications?

SUP-MAN Supplier management

1. Is there a broad knowledge of market availability (price/suppliers)?
2. Is there a procedure for approval/acceptance of suppliers?
3. Are there formal agreements with general suppliers?
4. Are these agreements applied in everyday purchases?
5. Do negotiations with the supplier include purchases and maintenance together?
6. Is there a supplier evaluation (service/price) done periodically?

7.5.1.2 Spares

Questionnaire: Spares
MAT-REC Materials reception

1. Is there a suitable system of quality control for purchased materials?
2. Are the reception personnel reliable?
3. Can all kinds of supplies be accepted?
4. Is there a defined procedure for where spares are stored?
5. Have storage conditions been defined for spares (temperature, rotation, moisture)?

WAR-MAN Management of the store

6. Is there an analysis of risks and critical conditions to define the minimal stock?
7. Is the store inventory value known?
8. Are order costs taken into account to determine the ideal delivery date?
9. Is there a control system for spares management: place, quantity, rotation, and so on?
10. Is there a defined breakpoint for the spares quantity?
11. Is there any guide or procedure that defines whether a component is repaired or is replaced with a new one?
12. Is the service quality known? In other words, what percentage of the time does maintenance take to obtain the requested spare?
13. Are entire or partial inventories done?
14. Is stock rejected because of technological obsolescence, scarce use, or damage?
15. Does a stores catalog exist for each piece of critical equipment?

Certain indicators constitute efficiency indices of the warehouse and are combined with surveys at levels 3 and 4 on involvement in the management of the warehouse. Stock that is inactive because of disuse or obsolescence, as well as the WOs waiting for spare parts, are inefficiency indices whose desired value is zero, making them complementary values in the rating of the overall efficiency of the warehouse.

The filling of orders and the percentage of control over the stored stock are positive efficiency rates that directly affect the attainment of the desired goals.

$$\text{WMI1} = \frac{\text{Line articles in the inactive stock}}{\text{Total line articles in stock}}$$

Depending on the WCM, articles that are inactive due to various forms of obsolescence, new suppliers, and so on, must be less than 10% of the contents of the store. This requires constant updating of the utilization rate of each spare.

$$\text{WMI3} = \frac{\text{Total controlled spare parts in the warehouse}}{\text{Total available inventory(controlled + uncontrolled)}}$$

For WCM cannot have a store with more than 2% of inventories without control i.e., the WCM fixed control WMI indicator store 3 into a greater value to the 98%.

$$\text{WMI4} = \text{OI26} = \frac{\text{Total number of spare parts fulfilled by order}}{\text{Total number of spare parts requested}}$$

The world-class references for spares are the *WMI*4 and *OI*26 indicators at values up to 90%.

$$\text{WMI8} = \frac{\text{Maintenance work orders awaiting spare parts}}{\text{Total number of work orders}}$$

The *WMI*8 indicator in the world-class perspective is fixed at a maximum value of 2% in a predetermined period. It is important not to blame this deficiency on the purchase system because this index covers WOs that would not have discerned the shortcoming in the store. It is, therefore, a mistake not to properly check inventory status during planning. A similar indicator is proposed to test the compliance of the warehouse in stocking the required articles. The WCM shows values of 5% for unavailable stock, that is, 5% of situations in which the quantity stored is incorrect and the store cannot meet a contingency that requires the unavailable spare.

It is in this way that the information about these four parameters is combined with the results of the relevant surveys according to the following expression:

$$\begin{aligned}\text{WMANI} &= \text{Survey results (Warehouse management)} \cdot \overline{\text{WMI1}} \cdot \text{WMI3} \cdot \text{WMI4} \cdot \overline{\text{WMI8}} = \\ &= \text{Survey results (Warehouse management)} \cdot (1 - \text{WMI1}) \cdot \text{WMI3} \cdot \text{WMI4} \cdot (1 - \text{WMI8})\end{aligned}$$

Overall, *WMI6*, *WMI7*, and *WMI9* indicators represent a unitary quality index of the procurement system. Urgent purchase orders should be reduced in an adequately managed system because a high rate would mean the collapse of the system and inadequate prioritization and coding of the orders, as all become urgent. Similar to the purchasing procedure, there are discounts for multiple purchased items or shipping charges; *WMI7* will indicate the inefficiency of isolated order items, normally urgent orders or caused by

mismanagement. Finally, not making systemwide purchases, for example, if management shows a lack of interest, represents a severe setback to the system.

$$\text{WMI6} = \frac{\text{Total number of urgent purchase orders}}{\text{Total number of purchase orders}}$$

The WCM perspective proposes a maximum value of 10% in urgent purchase orders.

$$\text{WMI7} = \frac{\text{Total number of one-article purchase orders}}{\text{Total number of purchase orders}}$$

Costs generated by the issuance of a purchase order are fixed and are not negligible, and sometimes exceed the cost of the order. As Wireman [375] notes, costs generated by big companies are five times greater than in small companies. For all companies, however, the problem will have a big increase point, and for this reason, the indicator should be reduced to zero.

$$\text{WMI9} = \frac{\text{Material costs charged to credit card}}{\text{Total costs of maintenance materials}}$$

This undesirable indicator must be matched with material not imputed to any work order. Historical information should be reduced and used as the risk of unmatched material.

The three indices whose tendencies should be avoided are weighted against purchasing procedure surveys, and the units are normalized.

$$\text{PURPROI} = \text{Survey results (Purchases procedure)} \cdot \overline{\text{WMI6}} \cdot \overline{\text{WMI7}} \cdot \overline{\text{WMI9}} =$$

$$= \text{Survey results (Purchases procedure)} \cdot (1 - \text{WMI6})(1 - \text{WMI7})(1 - \text{WMI9})$$

The *EI12*, *EI7*, *EI11*, *WMI10*, and *WMI2* indicators are not percentages but relevant data. Obtaining these parameters will result in combining the information of three computer systems. The ERP contains financial information in the form of purchase invoices of assets and corresponding depreciation rates, as well as the book value of itself. The CMMS and the computer system of the warehouse (if the systems are not integrated) will provide data to estimate the inventory or the total cost of use of the stores.

Reference values to observe trends will depend on the agreements with suppliers and the availability of spare parts. A drastic stock decrease to optimize the parameter of idle capital can generate delays in the provision of spare parts, resulting in a high cost of failure and creating a rebound effect against the desired reduction of the store.

$$\text{WMI2} = \text{EI12} = \frac{\text{Total cost of maintenance articles}}{\text{Average inventory value of maintenance articles}}$$

The *WMI2* indicator coincides with the UNE 15341 EI12 WMI2 [356], and provides valuable information on the use of spare parts and available inventory. Obviously, it is desirable to have high values between 1.5 and 2 as these show a certain rotation of inventory.

However, this indicator is misleading because companies with foreign machinery will tend to take stock of spare parts because of delays in getting them.

Nevertheless, it is a widespread practice to tend toward *WMI2* as it has a higher sample sign of organizational efficiency.

To reduce storage costs and certain expensive stock, the WCM recommends using suppliers who allow companies to have a virtual store.

EI7 and *EI11* indicators have their reference values set by the applicable technology. The choice of machinery determines the manufacturer's recommended cost of spare parts. As in the previous indicator, we should observe its evolution; it should not show an excessive tendency toward reduction in the number of spares but should optimize spare part availability and cost. Historically, *EI11* has been considered a 30% upper threshold spare with respect to maintenance costs.

$$\text{EI11} = \frac{\text{Total cost of maintenance articles}}{\text{Total maintenance costs}}$$

$$\text{EI7} = \frac{\text{Average inventory value of maintenance articles}}{\text{Assets replacement value}}$$

DiStefano [72] recommends that the *IE7* measure be harmonized between the SMRP and EFNMS, proposing a reference value of ~3%. The WCM perspective is more restrictive and proposes only 0.5% for spares versus the replacement of assets.

Recent indicators refer to the indirect costs of the purchase service and store when it is desirable to minimize both.

$$\text{WMI10} = \text{Internal costs to process a purchase order}$$

This indicator is not effective in organizations where the costs associated with internal processes are not controlled. In Figure 7.23, we see the implementation chart of the audit process in procurement and spares, taking into account the two levels of the survey objectives. Purchasing is a goal in both operations and the maintenance warehouse. Implementation is associated with the internal process of the function.

7.5.2 WO System

The WO system is part of level 2. It is important to mention the need for adequate data and fields in the WO. According to world-class standards, 95% of WOs are filled in a comprehensive manner. Aspects to consider at this point include planning and execution, with special emphasis on the document management system of the WOs and the accuracy of the work.

The emergence of the *WOI5*, *WOI6*, and *WOI7* indicators introduces an element of distortion in all planning systems that appear at present. Opening the "floodgate" permanently charges all those spare parts or hours that are not logical or involve excesses in a WO.

The WO indicates the excellence of the maintenance function. It is extended to three levels that make up the target audience of the surveys given in the following. It should be noted that without the certainty of WOs being generated by other departments such as production, the survey should be relegated to maintenance.

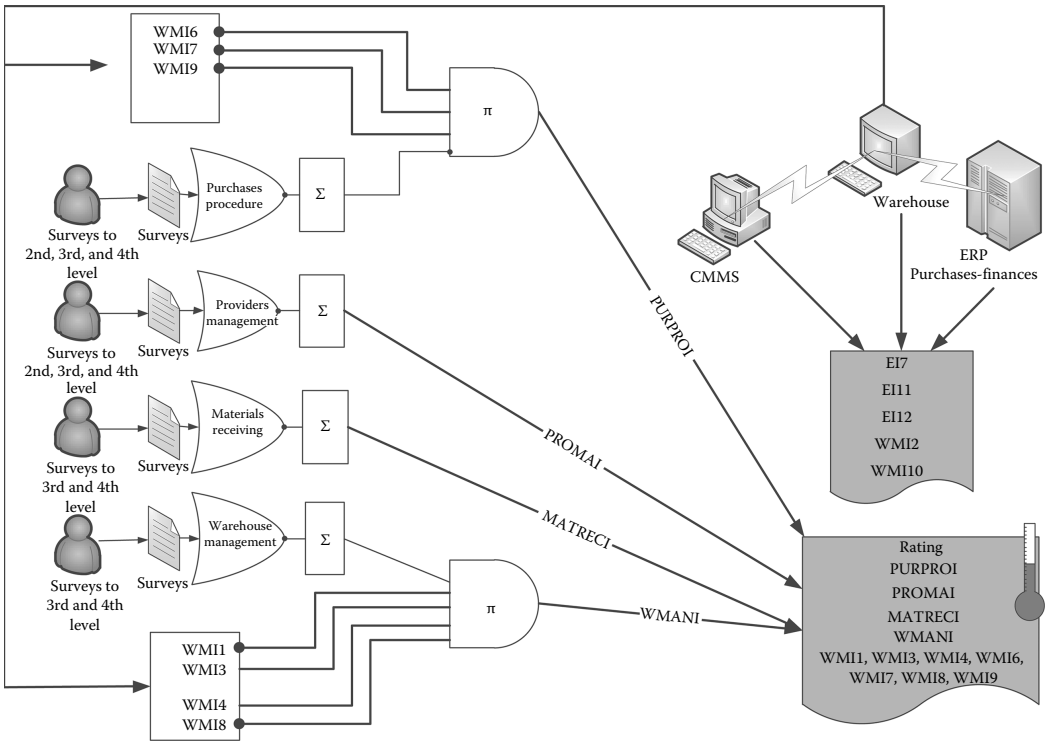


FIGURE 7.23
Store and purchasing audit.

Questionnaire: Work orders
WO-SYS Work order system

1. Is there a work order system?
2. Does this system analyze all maintenance activities (predictive, preventive, and corrective)?
3. Does it use the WOs?
4. Can WOs include other maintenance departments?
5. How are the WOs managed through CMMS?
6. Is there a control of the progress of the WOs?
7. Are there permanent or blank WOs to upload certain items within hours?
8. Is the length of time between the failure warning and the WO issuance known?
9. Is the average time for approval of a WO known?
10. Are people and necessary times, as well as work fulfillment, seen clearly?
11. Are WOs safety instructions clear?
12. How are the WOs used for all types of work (planned, unplanned, mechanical, electrical, improvements, etc.)?
13. Does the WO procedure as a machine provision include work at height, cutting and welding, fire risk areas, electrical, confined spaces, ATEX zones, or other according to the work performed?

14. Are priorities defined in the WO?
15. Do workers inform the WOs scheduler when they have completed a task?
16. Are control deviations from the plan in WO relative to time or materials to the reality of execution periodically performed?
17. Are the WOs archived according to the equipment and component?
18. Is it possible for the person or persons performing the WO to indicate in the WO observation results of the done work, such as the problems identified?
19. Is it possible for personnel performing the WO to make additional comments, either about the machinery condition or on possible improvements to implement?

The following indicators, as mentioned, represent a system deviation that should be removed because its very existence subverts the planning system. The use of this type of order invalidates the root audit planning and execution process.

$$\text{WOI5} = \frac{\text{Maintenance labor costs charged to a permanent work order}}{\text{Total maintenance labor costs}}$$

$$\text{WOI6} = \frac{\text{Costs of maintenance materials charged to permanent work order}}{\text{Total costs of maintenance material}}$$

$$\text{WOI7} = \frac{\text{Costs of a specific equipment charged to a permanent work order}}{\text{Total costs of a specific equipment}}$$

Padesky and Hawkins [254] use the SMRP to regulate the use of standing orders, making their scope, warranty periods, reforms, or activities such as cleaning very clear. Their unwanted use due to a lack of control generates useful data to be exploited later.

The metric calculation is monthly or weekly and warns of the danger of substituting WOs in an emergency. These WOs should close monthly and reopen to collate developments. Their abuse represents a failure of the work system with respect to the orders. Padesky and Hawkins take into account values from 5% to 7%, which will void the current WOs.

The WCM perspective coincides with that of Padesky by setting the use of loaded maintenance man-hours to permanent WOs at around 5%.

Other indicators, related to WOs, as were mentioned in the previous chapter, are

$$\text{WOI1} = \frac{\text{Maintenance labor costs over WOs}}{\text{Total costs of maintenance labor}}$$

$$\text{WOI2} = \frac{\text{Maintenance material costs over WOs}}{\text{Total costs of maintenance material}}$$

$$\text{WOI3} = \frac{\text{Subcontractor costs over WOs}}{\text{Total costs of maintenance contractors}}$$

$$\text{WOI4} = \frac{\text{Maintenance inactivity registered in WOs}}{\text{Total maintenance inactivity}}$$

Other WO indicators, as cited in the previous chapter, include efficiency indicators that measure the accuracy of the project data in the WOs by checking those data on other computer systems in the organization, such as SCADA systems or accounting and finance files. The accuracy of the WOs should be 100%.

IT16 provides a KPI from maintenance management, which is useful for completed work orders.

$$\text{TI16} = \frac{\text{Total operating time}}{\text{Number of maintenance work orders}}$$

EFNMS has benchmarked business values of 90–100 hours of operation for processed WOs; see EFNMS [91].

The WOs, together with lower-level planning, will correctly represent the information: all WOs, open WOs, and parallel documentation. This will determine the success of planning WOs and note WOs requiring changes in important resources.

$$\text{OI22} = \frac{\text{Number of works orders performed according to planification}}{\text{Number of work orders programmed}}$$

According to the WCM perspective, at least 80% of the WOs must be reviewed and approved within 5 days, taking into account that some organizations require a request for a formal release of WO work.

Stegimelle's [307] harmonization of the *OI22* indicator between two international organizations coincides with the WCM perspective in seeking 80% compliance over the course of a week. As in WCM, the week represents the basis for normal calculation, but it can be made monthly or yearly to compare this indicator with other indices. We must be especially careful with overdue WOs that come a week later than planned as these are not considered in this calculation.

$$\text{WOI15} = \frac{\text{Number of work orders with more than 20\% of estimated labor}}{\text{Total number of maintenance work orders}}$$

Estimates of labor according to world-class levels are set in a more ambitious way, reducing the WO deviation by 10% and 90%; this deviation is not accepted by WCM.

$$\text{WOI16} = \frac{\text{Number of work orders with more than 20\% of estimated materials}}{\text{Total number of maintenance work orders}}$$

The combination of these two indices is used by Smith [299] for SMRP to propose a weekly or monthly calculation. This proposal includes a cost diversion exceeding 20%.

Figure 7.24 shows three numeric indicators, whose objective is to return the unit's percentage to zero. Their optimal use resides in a balance of the three indicators depending on the type of industry, technology used, and so on.

The emergency orders are the only surprising aspect but they must also tend to zero as they may result from a RCM policy that does not impose priority or preventive WO for

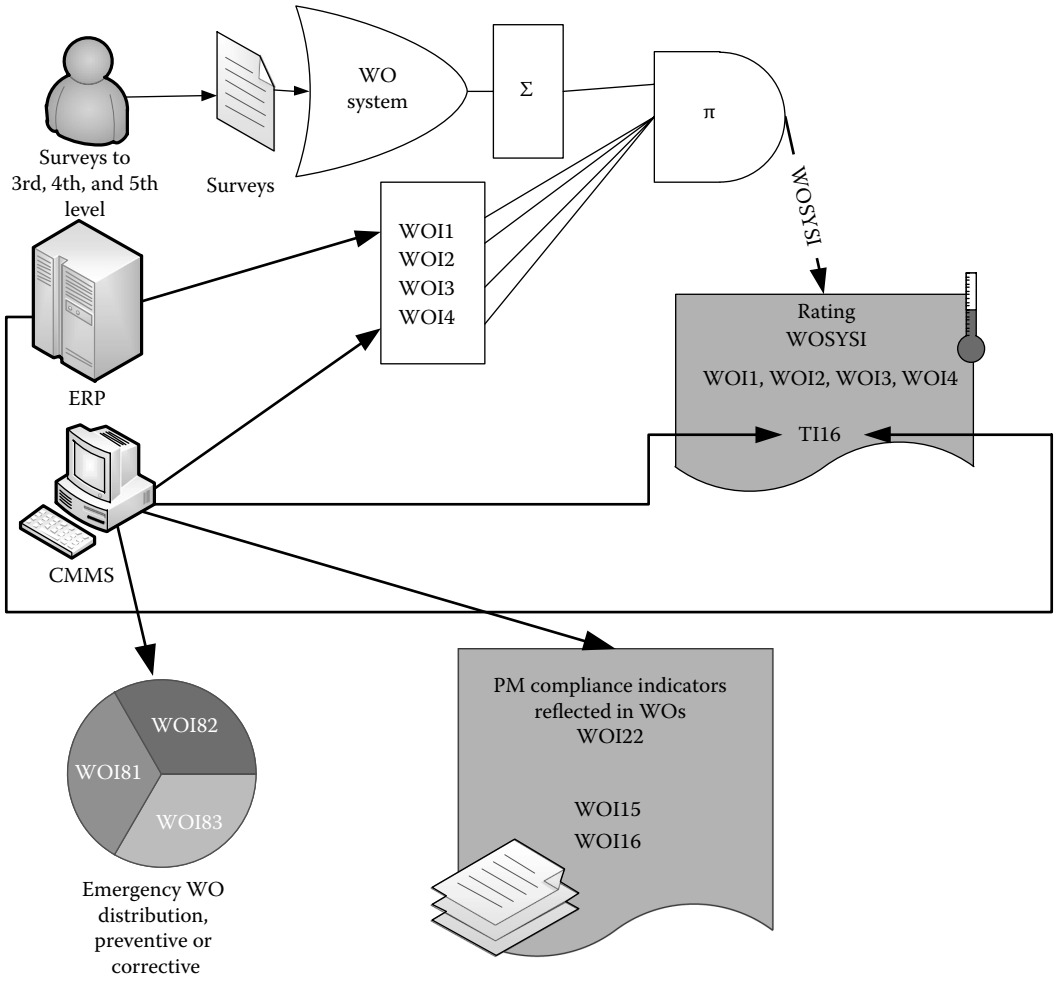


FIGURE 7.24
Auditing the WOs system.

equipment of low criticality. Corrective or emergency WO will depend on the company's policy in these cases.

$$\text{WOI81} = \frac{\text{Emergency orders}}{\text{Total number of work orders}}$$

$$\text{WOI82} = \frac{\text{Preventive orders}}{\text{Total number of work orders}}$$

$$\text{WOI83} = \frac{\text{Corrective orders}}{\text{Total number of work orders}}$$

For WCM indices, at least 95% of the WOs issued must correspond to scheduled jobs. So, the WOs for the *WOI81* emergency rate should be lower than 5%.

ERP checks the accuracy of information entered into the CMMS. The indicators must validate the survey values. The results will be modulated by the veracity of the data as reflected in the numeric indices.

$$\text{WOSYSI} = \text{Survey results (WOs)} \cdot \text{WOI1} \cdot \text{WOI2} \cdot \text{WOI3} \cdot \text{WOI4}$$

7.5.3 Computerized Maintenance Management System

Large-volume data management requires the use of a computing tool capable of storing, processing, and extracting information that may be required at any moment.

Questionnaire: CMMS
CMM-SYS

1. Does the plant have maintenance management or CMMS software?
2. Does everyone have access to the software with a corresponding ID?
3. Is CMMS allocated for an hour according to operator's instructions?
4. Does the CMMS have the component technical information of equipment?
5. Is there a CMMS system for equipment and its components with a specified code?
6. Is this numerical system used in a formal way as part of the technical documentation, applications for replacement, and/or WOs?
7. Is technical information updated in each computer system?
8. Are maintenance plans/tokens reported in this system and periodically generated automatically?
9. Is CMMS used to plan work and control pending jobs?
10. Are maintenance work software procedures established?
11. Does each team have an associated maintenance program that can be displayed in a simple way?
12. Does CMMS have records of historical maintenance for each team?
13. Does CMMS have records of performed maintenance?
14. Does CMMS have a register of the availability of all spare parts in the store?
15. Does the documentation update in a systematic and regular way in the system?
16. Does the information compare in a systematic and regular way with similar records on other systems?
17. Does CMMS have a connection with other systems, such as purchasing, finance, or HR to refresh and interchange information?
18. Is there easy access to the information contained in the system?
19. Does CMMS have records of production operators who work on the equipment?
20. Is a training program implemented for the use of CMMS?
21. Does CMMS have accurate information to take control of efficiency indices?

The relevant indicators of the proper implementation of CMMS are the degree of knowledge of the system and equipment, administrative and maintenance officers, and how closely the documentation deposited in the system corresponds to reality.

$$\text{OI24} = \frac{\text{Effective of the maintenance internal staff using computer}}{\text{Effective of the internal or direct staff}}$$

Dean [61] proposes that 90% of maintenance personnel should use a computer and be familiar with the CMMS program implanted in the plant. This is the minimum target to achieve, taking into account that the maintenance function is 90% a management process with CMMS and 10% engineering.

$$\text{CMMSI1} = \frac{\text{Total labor costs in the CMMS}}{\text{Total maintenance labor costs in ERP}}$$

$$\text{CMMSI2} = \frac{\text{Total material costs in the CMMS}}{\text{Total material costs in ERP}}$$

$$\text{CMMSI3} = \frac{\text{Total subcontractors costs in the CMMS}}{\text{Total subcontractors costs in ERP}}$$

The three big indicators must have values close to 100% for this level to be mature. A suitable cost model must be built on an infrastructure of management system and reliable documents.

$$\text{CMMSI4} = \frac{\text{Total number of machines in the CMMS}}{\text{Total number of machines registered in the plant}}$$

Looking at the CMMS indicator, Olszewski and O'Hanlon [244] consider a value of 80% and show this value to be insufficient for assets recorded on a plant's CMMS. The indicator should cover 100% of all computers that affect the maintenance function.

$$\text{CMMSI5} = \frac{\text{Total spare parts number in the CMMS}}{\text{Total spare parts number in the plant}}$$

Olszewski and O'Hanlon also mention a medium average close to 70% of CMMS spares. This is an extremely low value, associated with the cost of purchasing unnecessary articles over time.

$$\text{CMMS7} = \frac{\text{Total maintenance cost of equipment in the CMMS}}{\text{Total maintenance costs in ERP}}$$

This manipulated indicator allows us to see traceable cost values at the equipment level by comparing the charged costs to unspecified machinery from standing orders, credit cards,

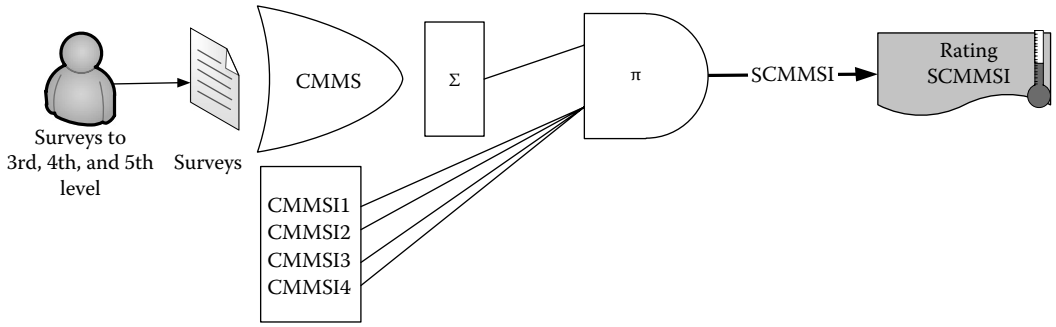


FIGURE 7.25
Survey ratification in the CMMS.

and so on. The problem lies in the fact that in an audit we can assign fraudulent costs to equipment.

The survey value is valid, with four indicators relating to the accuracy of the actual data on the information in the system. These indicators should reflect the validity of the system as a repository for information on costs, labor, material, and inventory assets (Figure 7.25).

$$\text{SCMMSI} = \text{Survey results (CMMSs)} \cdot \text{CMMSI1} \cdot \text{CMMSI2} \cdot \text{CMMSI3} \cdot \text{CMMSI4}$$

The audit of the CMMS system, including the indicators, surveys, and sources of information to collate, is shown in Figure 7.26:

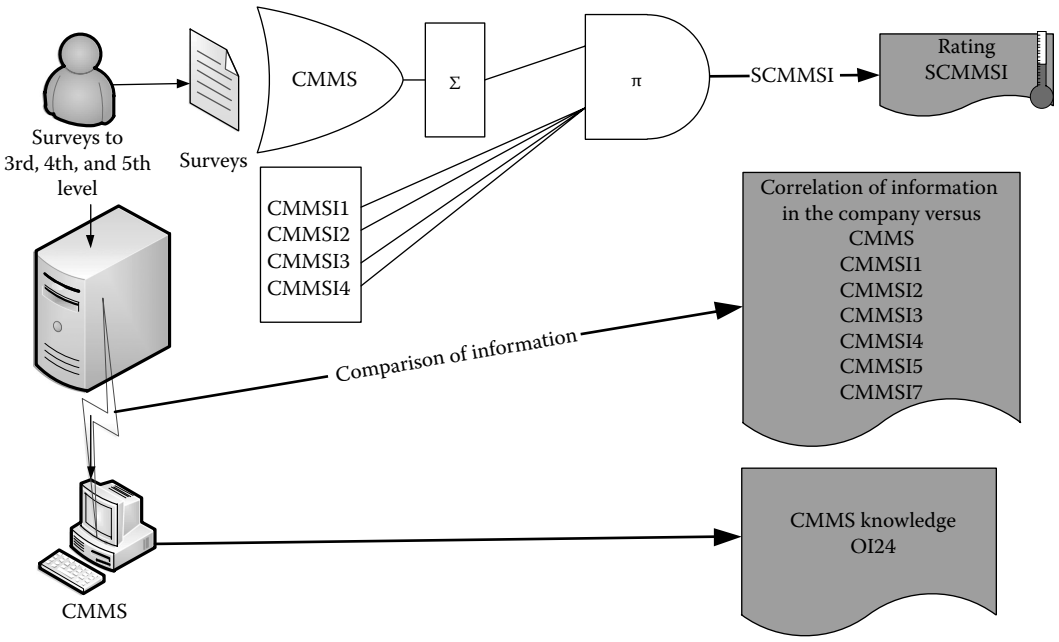


FIGURE 7.26
Audit of the CMMS.

7.5.4 Personnel Management and Subcontracting

7.5.4.1 Staff Structure of the Department and Definition of Jobs

Surveys of the management of staff and subcontractors are done at different levels of the hierarchy. In fact, the first corresponds to the definition of positions and is completed by the director of maintenance and the person(s) responsible for human resources provide information on the structure of the department and the professional profiles of the staff hired. WPLACEI is a survey indicator based on the views of these two hierarchical levels.

Questionnaire: Personnel management and subcontractors
WOR-PLA Work place

1. Is there a definition of the job of each maintenance operator?
2. Is there a detailed description of the knowledge required for each job?
3. Are these job descriptions reviewed periodically?
4. Are descriptions used to identify training needs as well as to define them?
5. What is the definition and content of these descriptions as they relate to a department's established goals and strategies for future operation?
6. Is there versatility among the maintenance personnel?
7. Is there balance between officers and administrative controls in the maintenance department?
8. What is the premier specialization among the staff?
9. How are descriptions of staff expertise used to define levels of staff and assign jobs?
10. Is the burden of remaining work of the staff known?
11. Is the location of the distributed daily working hours of the operators (tasks) known?
12. Is there a control system for input and output staff?

The indicator on the labor climate and knowledge of the company's mission corresponds to the two levels mentioned before, as well as to the controls and official documents included in all measurement gauges and measured.

MIS-CLIM Company mission and labor climate

1. Is the maintenance work considered a mixture of physical and intellectual effort?
2. Is there a climate of pride in the company among the maintenance personnel?
3. Is there a sense of isolation in the maintenance department?
4. Do the staff have all technical means and amenities required in the workplace?
5. Are autonomy and initiative considered important in maintenance work?
6. Do the staff have autonomy and show initiative?
7. Is there camaraderie and collaboration among maintenance personnel?
8. Is there a policy on staff rotation in the company?
9. Does it apply to maintenance?
10. Is there a feeling that the maintenance personnel play an important role in the company?

11. Is there a career plan for maintenance personnel?
12. Do maintenance personnel know the company's goals, mission, and vision?
13. Do personnel have the main mission of focusing on the availability of the installation or equipment?
14. Are the staff familiar with the company's goals?
15. Do the maintenance staff have seniority in the company?
16. Do they have regular meetings to learn about the department's goal and talk about themselves?
17. Are the vision and objectives clearly known and understood by the department?
18. Do the staff recognize the difference between preventative work that anticipates major problems and corrective work?
19. Is the relationship positive and collaborative between production and maintenance?
20. Is the attitude positive toward higher levels of maintenance?
21. Do departments related to maintenance collaborate well together?

Motivation and training are measured in the following survey. In this case, the maintenance team and human resources department that supervises training are audited.

MOT-TRA Motivation and training

1. Are staff members treated equitably?
2. Is (positive or negative) feedback provided for errors and successes?
3. Has a climate of respect been established so that staff are listened to?
4. Are there periodic meetings with the staff to communicate the results of the department with respect to the evolving goals and/or plans for the future?
5. Does the system provide for both suggestions and effective management?
6. Is there a system of performance evaluation and professional development or career plans?
7. Is the system used to detect training needs?
8. Is the system used to establish objectives and ensure the workers achieve them?
9. Is the system used to "reward" employees on the basis of fulfilled "objectives"?
10. Are there sufficient tools and equipment for the work to be done?
11. Is the training level sufficient for the technology of the equipment?
12. Are training results evaluated? Is this evaluation ongoing?
13. Does the training ensure versatile technical staff?
14. Do staff give training information about technologies and methodologies to their colleagues in the classroom, workshop, or field?
15. Do staff make proposals to their superiors about training needs?
16. Do staff evaluate the positive impact of the training acquired?
17. Does good information reduce the training errors and downtime? Does this feeling exist?
18. How high is the turnover of maintenance staff?

7.5.4.1.1 Structure of Human Resources

This section presents the indices related to the structure of the human resources of the maintenance department in level 2. The indicators reflect the organization of the company, including internal staff, external staff, and so on. These indicators can suffer severe variations during technological changes or major plant modifications, as well as enlargements or changes in methodology or company policy, for example, a commitment to outsourcing certain services.

$$\text{CMMSI8} = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of supervisors}}$$

WCM proposes the number of employees per supervisor in first line between 15 and 20.

$$\text{CMMSI91} = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of planners}}$$

WCM proposes between 30 and 60 employees per supervisor, including both external and internal labor. A scheduler can be included for every two or three supervisors.

$$\text{CMMS92} = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of trainers}}$$

$$\text{CMMS10} = \frac{\text{Total number of maintenance technicians}}{\text{Number of administrative support staff}}$$

Wireman [375] proposes between three and five technicians per administrative assistant in maintenance. A higher ratio would mean either the collapse or the administrative waste of a technician performing tasks of inserting data in the control system.

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI13} = \frac{\text{Cost by indirect maintenance staff}}{\text{Maintenance total costs}}$$

$$\text{OI1} = \frac{\text{Effective of internal maintenance staff}}{\text{Total effective of internal employees}}$$

$$\text{OI2} = \frac{\text{Effective of indirect maintenance staff}}{\text{Effective number of internal maintenance staff}}$$

$$\text{OI3} = \frac{\text{Effective of indirect maintenance staff}}{\text{Effective number of direct maintenance staff}}$$

The HRI2 indicator is an excellent measure of labor longevity and retention level.

$$\text{HRI2} = \frac{\text{Employees sum of years in payroll}}{\text{Total number of employees}}$$

The two relevant indicators in the job description are versatility and shift work. The job description and staff ability must reflect both. Their implementation requires a clear definition of the needs of the company and indicates its organizational maturity.

$$\text{OI15} = \frac{\text{Effective of internal maintenance staff with various activities}}{\text{Effective of internal maintenance staff}}$$

$$\text{OI10} = \frac{\text{Direct maintenance staff working in shifts}}{\text{Total effectives of direct maintenance staff}}$$

Padesky and Mitchell [255], in their harmonization of the prompt PAY O10, suggest the usefulness of maintenance personnel working in shifts to prevent failures and increase the reliability of the machinery. Yet they say industry currently has less than 20% of maintenance personnel working in shifts.

7.5.4.1.2 Labor Climate

The results of the staff survey should be compared with the company survey to study the correlations and see if the satisfaction index is adequate, particularly for working methods, the scope of workers, and communication and relationship with the controllers.

The organizational climate is a multilevel variable that considers factors from individuals, groups, and the organization. In other words, it integrates organizational behavior. The integrated concept means that the assessment of the working climate contemplates all those things having an impact on a person in the organization. These surveys are not frequent but yield very relevant information for the management and performance of maintenance.

The definition of the working climate refers to shared perceptions. The climate concept, such as a variable descriptive of organizational effectiveness, is often used without a comprehensive discussion of the definition or measurement; it also introduces subjective aspects. Therefore, surveys are used for quantification.

Most authors understand the labor climate as shared perceptions of the organizational situation; see Denison [67]. They are individual perceptions, but there must be a higher degree of consensus to be considered as a climate; that is, perceptions must be shared. The organizational climate is concerned, therefore, with the insights shared by the members of an organization, especially the policies, procedures, and practices. Shared perceptions are very important in the maintenance area; they relate to overall satisfaction with the status of the department and its way of acting. As has been noted, the human factor affects both performance and satisfaction.

In general, climate refers to perceptual processes of each member of the organization as an essential element of the organizational climate. It is a subjective reality. Reichers and Schneider [280] think climate is formed by shared perceptions of the policies, practices, and procedures in both formal and informal ways. It indicates the organizational goals and suggests appropriate means to achieve them. Therefore, it follows that a bad labor

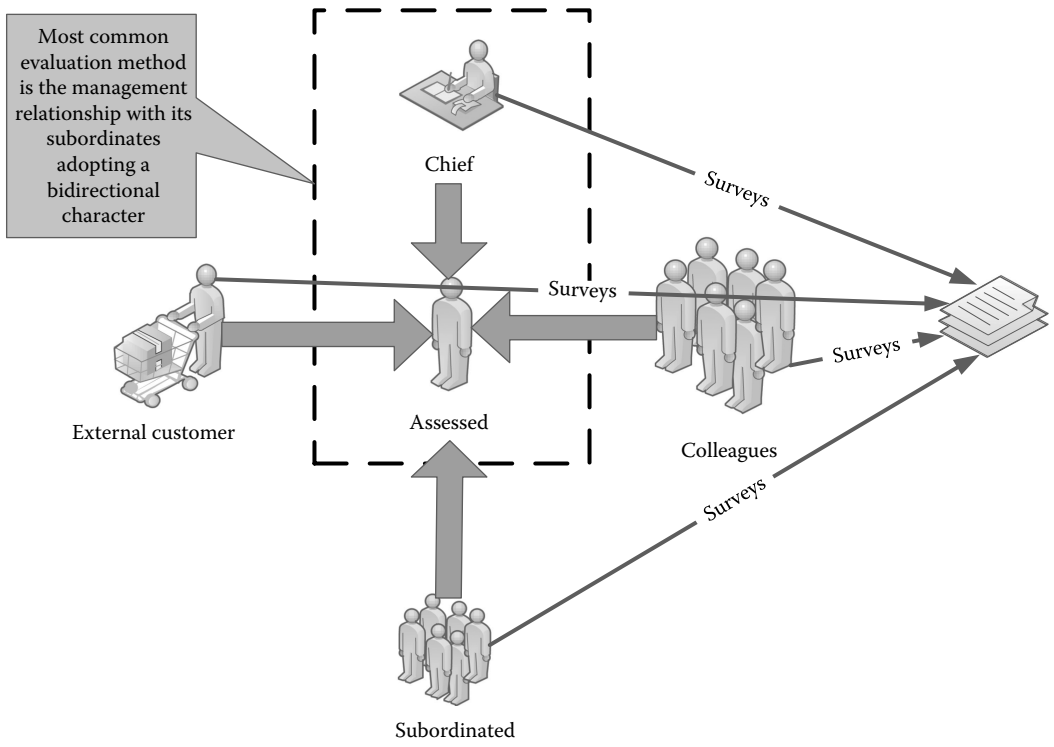


FIGURE 7.27
Evaluation of labor climate.

climate, for many years associated with the maintenance function, occurs when an area is oblivious of the overall objectives of the company or no appropriate rewards or even feedback are given (Figure 7.27).

Tagiuri and Litwin [321] say that the labor climate is a relatively stable aspect of the internal environment of an organization.

- The climate is experienced by its members.
- The climate influences behavior.
- The climate can be described in terms of values as a particular set of characteristics (or attitudes) of the organization.

These shared perceptions can be broken down into dimension. Here, not all authors are in agreement. For example, Campbell et al. [38] identify four basic dimensions:

1. Degree of individual autonomy degree
2. Degree of structure imposed
3. Orientation toward reward
4. Consideration, support, and affection

These dimensions determine the evolution of maintenance organizational charts and the stable relations they create between members.

The core maintenance must have autonomy, decision-making capacity, and the ability to troubleshoot problems with some independence. Excessive attempts at control can lead to a decrease in performance. The other dimensions of the human factor mentioned in this chapter also emanate from the organizational chart and the associated incentives or rewards for a job that is well done.

Restrictive definitions are not the only problem with the concept of climate. Rousseau [289] argues that labor climate focuses on descriptive beliefs influenced by individual characteristics and the position of individuals in the organization. Drenth et al. [77] and Rousseau [289] suggest that the organizational climate is not monolithic, but there may be subclimates. The existence of subclimates is harmful to the maintenance area because of the different perceptions of the organization, primarily from the three operational areas: quality, production, and maintenance.

Subclimates, or labor microclimates, are often hostile.

Some authors suggest theoretically there should be differences in the perception of climate at three levels: organizational, departmental, and individual, but the differences between departments will be weaker than the inter-organizational ones as climate is mainly an organizational attribute.

The maintenance area is overly sensitive to this because of its so-called herd mentality. This type of thinking is the subject of frequent criticism; it is caused by the lack of social integration and the overly strong hierarchy commonly found in traditional organizations.

This thinking is not generally found in other departments, who usually have some kind of job rotation and an exchange of human resources. This does not frequently occur in maintenance largely because of the high degree of specificity of the jobs and the impossibility of having rotations with simple replacements.

Most authors believe that the organizational climate and labor climate rest on the two following conditions:

1. Having an intraorganizational consensus, whereby workers perceive they are all working for the same company and its minor work units, such as plants, departments, or work groups
2. Having different perceptions in organizations or differences among workers' evaluations of climate in the company and its minor work units, such as plants, departments, or work groups

In addition to the two conditions, there are two properties of climate: force and level. These are theoretically and empirically distinguishable. The strength of the labor climate refers to the level of consistency in the workers' perceptions in the same group (company, department, etc.).

In a strong climate, the workers' perceptions are very close. A good example is the field of peacekeeping.

The climate level of the maintenance department is the average level for all workers. Thus, it is possible to have a high level of labor climate if, on average, the workers' perceptions of the policies, procedures, and practices of the organization are evaluated positively. Of course, we can have a climate that is homogeneously good or bad. In this case, both the concepts and the force level can be distinguished.

7.5.4.1.3 Motivation and Training

For training, the indicators are a multiple list referring to the distribution of the training budget by operators in the audit process, training hours, or type of training carried out

either with an external trainer or internally with people in the department. Data, with the exception of *ITI*22, are the direct responsibility of the chief of maintenance in human resources, level two of the organization.

$$\text{EI21} = \text{ITI1} = \frac{\text{Maintenance staff training cost}}{\text{Effective of maintenance staff}}$$

Padesky [257] proposes a calculation working with SMRP and EFNMS to *EI*21 in the harmonization process. The typical cost is $3500 (about €2000) per employee annually. Padesky's recommendations [257] are widely used for the calculation of *E*21 by the organizations mentioned before.

$$\text{ITI21} = \frac{\text{Total training hours}}{\text{Total number of employees}}$$

$$\text{ITI22} = \frac{\text{Total interpersonal training hours}}{\text{Total number of employees}}$$

$$\text{ITI6} = \frac{\text{Total number of trainers}}{\text{Total number of maintenance employees}}$$

$$\text{ITI11} = \frac{\text{Annual training budget}}{\text{Annual workers payroll budget}}$$

Padesky [257] exemplifies the use of the *E*21 indicator with an approximation of *ITI*11, which assumes 3%, approximately, of the training budget references the total amount of the payroll department.

$$\text{OI23} = \frac{\text{Number of man-hours for maintenance internal staff training}}{\text{Total maintenance man-hours}}$$

Padesky's recommendations [256] show that the values of the *OI23* indicator belonging to UNE-EN 15341 [356] is ~3% of the training budget. The proposal harmonizes the indicator for SMRP and EFNMS.

The indicator that determines the efficiency of training actions is *ITI5*. This indicator can be measured in two ways. The first is the standardized average of the initial actions, that is, the degree of success suggested in the rating of these actions. There is a problem using formative actions, however. For example, courses may end with the issuance of a certificate of attendance and achievement, leaving the actual level of success unmeasured. The measurement of the efficiency of the training must be deeper and in line with what has been learned. It is more appropriate to assess the success of training actions by judging errors caused by a lack of knowledge of the training matter.

ITI5 = Correspondence level between training provided and abilities acquired

For this purpose, we can use indicators similar to *ITI7–ITI10*.

Parameters *ITI7*, *ITI8*, *ITI9*, and *ITI10*. These should be survey results and in-depth interviews because WOs and work reports do not give sufficient information. To work properly, the surveys must be well developed, and all conclusions should be stripped of any punitive aspects.

$$\text{ITI7} = \frac{\text{Inactivity time operating mistakes due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI8} = \frac{\text{Inactivity time maintenance mistakes due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI9} = \frac{\text{Time lost due to lack of knowledge}}{\text{Total worked time}}$$

$$\text{ITI10} = \frac{\text{Repeated maintenance time due to lack of knowledge}}{\text{Total worked time}}$$

Padesky and Dunlap [253] analyze the possibility of calculating the return on investment (ROI) to the maintenance staff. This aspect affects *ITI*5 as it is related to training and acquired skills. In addition, higher losses are generated by a lack of knowledge. The authors speculate on the possibility of an ROI greater than 200% in the maintenance area if training needs are properly detected. Nevertheless, it is a highly complex indicator to measure.

The *ITI3* and *ITI4* indicators are difficult to measure and are associated with surveys conduct and real comparisons. These indicators point to expensive tends.

$$\text{ITI3} = \text{Workers' reading level}$$

$$\text{ITI4} = \text{Skills level sectorals and nationals tests}$$

Gold and Packer [105] consider the reading habits of maintenance workers. They stress the importance of daily readings and suggest that maintenance workers read the following daily:

- Documents and forms such as guarantees, budgets, purchase orders, and work orders
- All kinds of labels and in several languages
- Equipment manuals, catalogs, and products
- Tables with instructions and procedures
- All types of magnitude gauges
- Directions of the connection between departments, suppliers, and so on
- All types of signs for danger and other signs

The maintenance direction must be alert and record incidents resulting from a misunderstanding when reading or interpreting any document or sign. Proactive policies will encourage the development of the skills deemed necessary for the proper performance of the maintenance function.

To Gold and Parker [105], the maintenance personnel must have certain capabilities:

- Communication skills, including the English language as the common language in documentation
- Ability to write reports, draft WOs, and others
- Ability to understand and quickly read instructions, technical data, procedures, and so on
- Problem-solving skills

We must encourage workers to read signs and documents.

In terms of motivation, a relevant indicator of the employee's motivation level and the last training level associated with *KAII*4 is the number of suggestions per employee in the studied period; this indicator should increase until a certain maturity level is reached in the system.

$$\text{KAII4} = \frac{\text{Number of suggestions given by maintenance employees}}{\text{Total number of maintenance employees}}$$

The motivation level of the staff shall be weighted by lower indicators result whose degree of compliance is the first three approaches taking into account that one of the most important factors in the maintenance technicians is the satisfaction with the equipment that they have for their professional performance.

$$\text{T\&UI1} = \frac{\text{Satisfied maintenance operators with personal equipment}}{\text{Total number of operators}}$$

$$\text{T\&UI2} = \frac{\text{Maintenance officers satisfied with the technical equipment available}}{\text{Total number of maintenance officers}}$$

$$\text{T\&UI3} = \frac{\text{Performed investments in maintenance equipment}}{\text{Planned investments in maintenance equipment}}$$

The last parameters considered here are absenteeism and turnover. Absenteeism indicates inefficiency; because its desired value is zero, it is weighted by its complement (supplemental staff). It is relevant that among maintenance personnel, turnover and absenteeism are clear indicators of the level of satisfaction. Therefore, the rate of supplemental staff is considered to show satisfaction.

$$\text{TPMI6} = \frac{\text{Total absenteeism hours}}{\text{Total considered hours}}$$

$$\text{HRI1} = \frac{\text{Voluntary severance}}{\text{Total number of employees}}$$

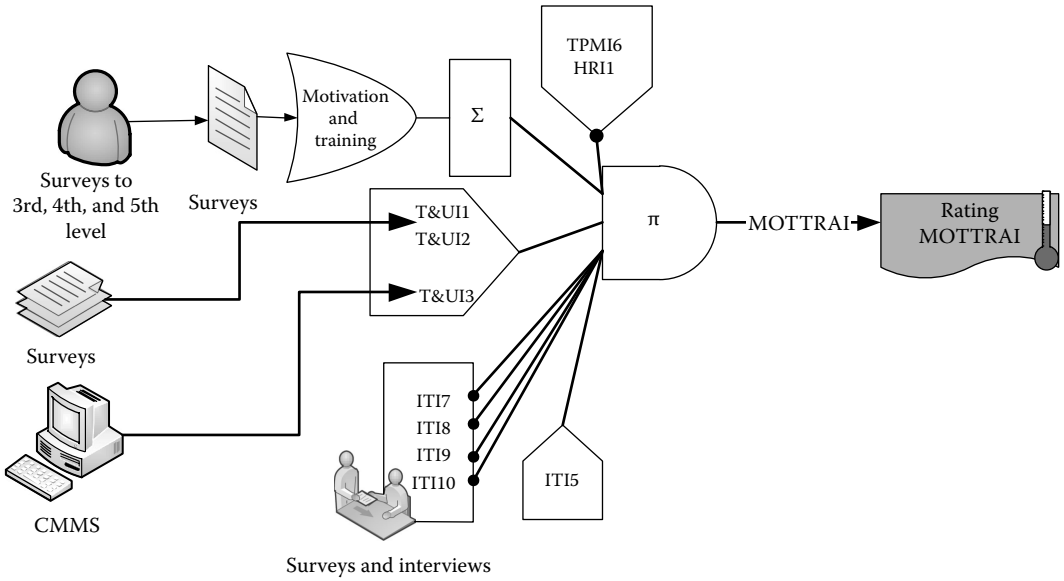


FIGURE 7.28
Motivation evaluation and training.

Figure 7.28 shows the survey results. When we cannot estimate a value, it must be eliminated from the validation process.

Figure 7.29 provides a schematic way to evaluate three facets of the human factor. These data must be combined with external data, surveys, or indicators to become more plausible.

7.5.4.2 Subcontracts

Questionnaires on contract work are completed at levels 2, 3, and 4. These levels are directly involved in recruitment and follow-up. It is noteworthy that the auditor can follow up on allegations made in the survey process. The auditor will not check the years of technological expertise or the certification of quality for each supplier, even though the essential indicators are associated with a contract in the maintenance management. However, the auditor can request a certificate from a company or ask for the safety manuals associated with certain work.

Questionnaire: Subcontracts
REC-POL Recruitment policy

1. Can the company subcontract services because of a lack of qualified personnel and following a view of workloads?
2. Are staff available at all hours for routine maintenance work?
3. Are outsourcing costs considered a service to be managed by the company's own staff?
4. Is there a standard defined contract?
5. How does the company compose contracts, taking into account the recommendations of UNE-EN 13269:2003?
6. Is there a policy for or formal methodology of work recruitment?

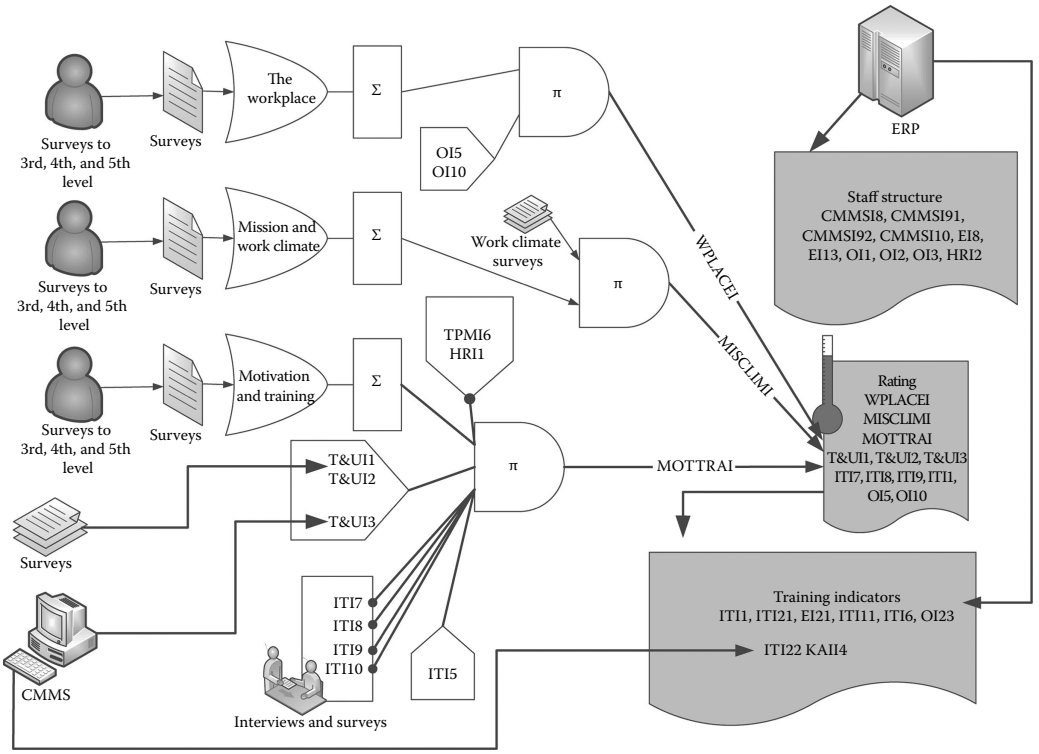


FIGURE 7.29
Evaluation of the human factor in the maintenance audit.

7. Is the recruitment policy effective and efficient?
8. Are the specifications for contracts clear?
9. Is the service quality clearly defined?
10. Are the service scope and trading conditions defined?

CONT-SEL Contractors selection

1. Are there processes of evaluating suppliers based on know-how, response time, cost, experience, compliance with safety regulations, and so on?
2. Does the maintenance supervisor participate in the selection of contractors and awarding of work?
3. Does the contractor know the labor policy of the company?
4. Does the company know the economic solvency of the contractor?
5. Does the company know the professionalism of the contractor?

CONT-OVER Contractor oversight

1. Is there a follow-up handbook on subcontracting?
2. Is there a formal mechanism of work control of contractors?
3. Is there a fluid and friendly relationship between internal and external staff?

4. Is there a formal mechanism to ensure the quality control of contractors' work?
5. Is there a formal mechanism to monitor safety in contractors' work?
6. Is there a formal mechanism for deadline control in the work of the contractor?
7. Are there any penalties for delays?

The survey refers to the three relevant aspects in the recruitment process: contract selection, realization of the contract, and subsequent verification of the work. These steps are part of the UNE-ENV 13269:2001 experimental standard and the final UNE 13269:2003 [353], with special emphasis on maintenance contracts.

Hawkins [114] establishes an indicator for companies that outsource labor almost constantly for routine work, major repairs, and so on. The author considers that the companies opting to outsource the labor in routine maintenance can put about 40% of the total time of maintenance under outsourcing.

The financial aspects relevant to recruitment correspond to *EI*9 and *EI*10 indicators. The first refers to all external staff hired by the hour, and the second includes all invoices issued by the contractor. These data, as shown in Figure 7.30, are often in the possession of the procurement department, human resources, and finance. The reference points for these indicators are affected by the company's strategy and the process and the desired degree of outsourcing for the maintenance function.

$$\text{EI9} = \frac{\text{Total cost of external staff used in maintenance}}{\text{Total maintenance costs}}$$

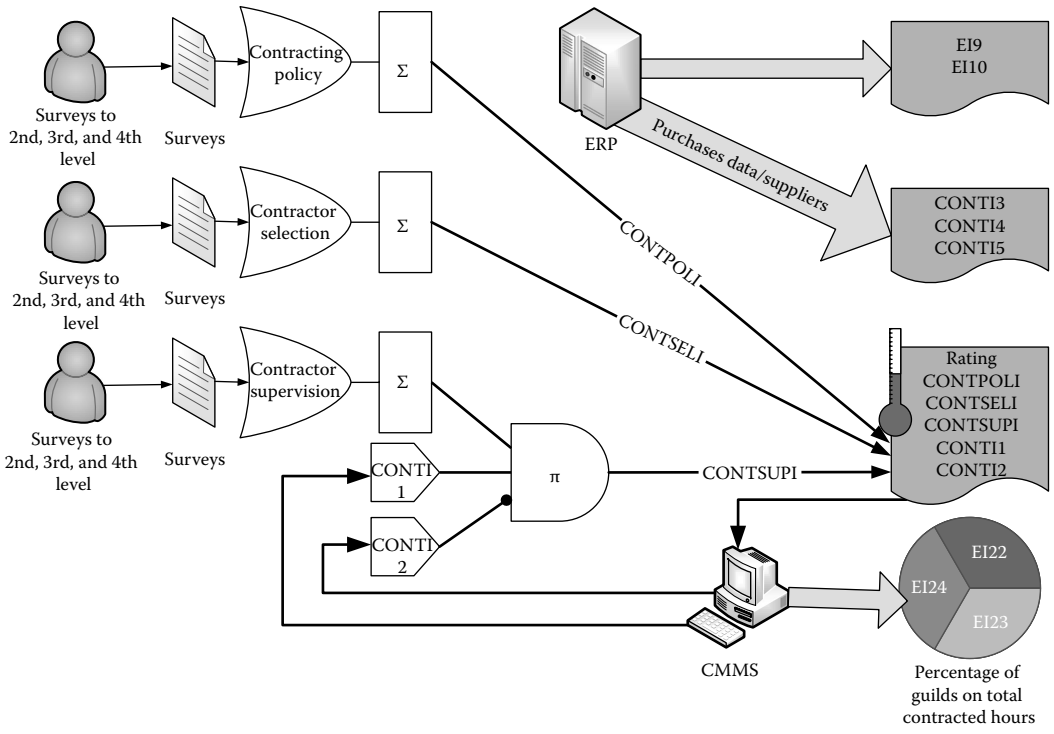


FIGURE 7.30
Audit of the recruitment process.

DiStefano [73] evaluates these costs of recruitment as a key point for determining the size of the permanent maintenance staff. The *EI10* indicator (not yet harmonized) includes the cost of personnel and material subcontracted, but as Hawkins proposes, only permanent jobs should be considered, not routines linked to improvement or expansions. The period of measurement should be annual but can be calculated at lower levels; the author considers that ~25% of the budget should allocated to this type of maintenance.

$$\text{EI10} = \frac{\text{Total contracting cost}}{\text{Total maintenance costs}}$$

The *CONTI1* and *CONTI2* indicators represent the quality of the services provided. These indicators should be fixed as specified by UNE 13269 [353].

$$\text{CONTI1} = \frac{\text{Availability time of contracted services}}{\text{Required time}}$$

$$\text{CONTI2} = \frac{\text{Number of works requiring repetition}}{\text{Number of works performed by contractors}}$$

The *CONT2* indicator can be generalized to all jobs requiring the repetition of the contract. The indicator must be considered world class and must not exceed 3%. The repetition is easily measurable by the negative impact. In this case, personnel assume that a job is not good if it is normally under WOs. The SMRP indicator is also proposed as a key factor, with Olver [248] fixing it at 4%.

For the *CONTI1* and *CONTI2* indicators, the natural desired tendency is toward zero value. These indicators are combined with the results of the quality service surveys. The results of the survey are assessed on five points and averaged for hierarchical levels. They evaluate the quality of contractors and have a validated index according to the following expression:

$$\begin{aligned}\text{CONTSUPI} &= \text{Survey results (CONT_SUP)} \cdot \text{CONTI1} \cdot \overline{\text{CONTI2}} = \\ &= \text{Survey result (CONT_SUP)} \cdot \text{CONTI1} \cdot (1 - \text{CONTI2})\end{aligned}$$

The survey results and two quality factors will reflect the goodness of the service provided by the contractors and the degree of supervision to which they are exposed and whose trends may be represented and analyzed as a function of the three parameters.

These indicators are stored in the CMMS. The reference values should be the current measure and its reference units, considering 85% of the value as a world-class indicator.

Indicators related to the technical evaluation of the contractor usually reach the purchasing and finance department. They manage contractors when this function is not delegated to the chief of maintenance (i.e., in a small organization). As mentioned, the detailed evaluation of each contractor is not the subject of an external audit. For that reason, the surveys and confidence factor in the assertions have a weighting factor of multiple surveys at different levels. An in-depth internal or external audit should be carried out before an alarm is triggered in the recruitment system.

We require careful review of the contractor's documentation as well as the rest of applicants for the contract.

CONTI3 = Years of experience in the reference field

CONTI4 = Quality certifications as supplier

CONTI5 = Technological level of outsourced staff

The audit projects a diagram to report the distribution, depending on the maintenance type, over the total work contracted. Large blocks of mechanical, electrical, and electronic maintenance give information about the type of maintenance contractor to hire. Electronic maintenance tends to be associated with CBM, settings of equipment by the manufacturer, or implementation of new technologies. The other two are associated with large stoppages or overhauls.

We frequently have a fixed starting point for electrical and mechanical maintenance when we have a template made in the factory for routine maintenance work done by outsourcing the function due to internal staff decrease.

$$\text{EI22} = \frac{\text{Total contracting cost of mechanical maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI23} = \frac{\text{Total contracting cost of electrical maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI24} = \frac{\text{Total contracting cost of instrumentation maintenance}}{\text{Total maintenance costs}}$$

Figure 7.28 explains the audit process of recruitment in maintenance, starting with surveys on the questions asked at managerial levels in operations, head of maintenance, and so on. Once carried out, the surveys and responses are processed and combined with indicators from other sources. At the end, the CONTSELI, CONTSUPI, and CONTSELI indicators enter the audit result.

We get the financial data and information on providers from the management systems; from CMMS data, we get the hours worked by subcontracted labor as well as the work repetition of the contracted company. Availability can be calculated using CMMS data. The answer or the number can be previously set by the contract. It is removed from the ERP and is not necessary for the collection of this parameter.

7.6 Level 3 Evolution

It is time to observe the technologies and methodologies implemented for improvement and some factors with an impact on the maintenance function (Figure 7.31).

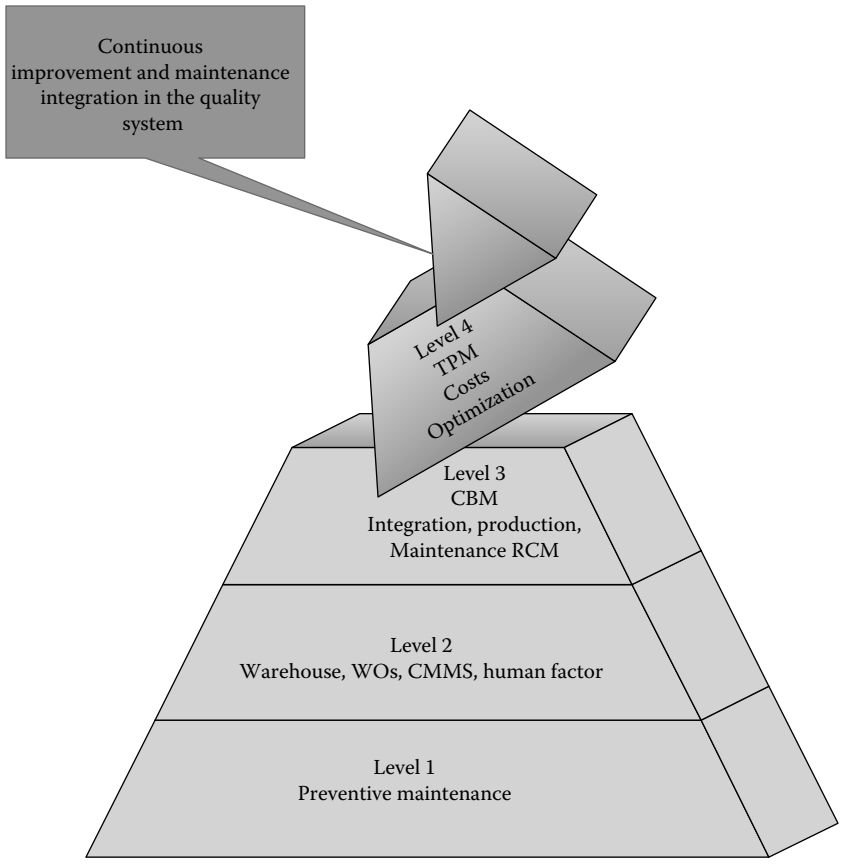


FIGURE 7.31
Level 3 in the evolution of the maintenance.

7.6.1 Maintenance Based on Condition

To evaluate the predictive program, we propose the following questionnaire. The questions looking for "yes" or "no" answers should rate at the extreme ends of the scale: that is, 5 or 1.

Questionnaire: CBM
CBM Condition-based maintenance

1. Is maintenance performed when doing the inspection?
2. Are there any predictive maintenance routines for critical equipment?
3. Is there a defined frequency for these routines?
4. Is there a procedure for each of these routines?
5. Is there an analysis of the results of predictive maintenance (i.e., future trends) versus production data?
6. Are preventive maintenance actions performed based on that analysis?
7. Is there a reduction in the number of breakdowns since CBM was started?

8. Have maintenance habits and the corrective and preventative percentages changed since CBM started?
9. Do the calculations justify the use of these techniques as avoided costs?
10. Do the internal staff perform the predictive analysis?
11. Are the staff trained in CBM?
12. Is there a mechanism to improve or add routines of predictive maintenance?
13. Is monitoring based on established indicators such as vibration, temperature, and so on?
14. Do they hold short daily meetings to review and control the scheduled tasks, analysis, and results obtained in the routes?
15. Are corrective actions defined and assigned to the staff in daily maintenance interventions?

The results of this survey are given to two target audiences, levels 3 and 4. Eventually, results go to official maintenance to enrich technical knowledge and clarify the relevance of the CBM program.

These data are combined with two parameters linked to maintenance based on condition.

IMP6 is an indicator that reflects the inefficiency of the program, showing faults that have been overlooked and/or not identified by failures.

$$\text{PMI6} = \frac{\text{Number of failures that should have been avoided}}{\text{Total number of failures}}$$

In the same manner, the CBM philosophy involves a review of the machine either through visual techniques or complex vibration techniques to provoke minor outages.

$$\text{TI10} = \frac{\text{CBM time which causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

The *IMP7* parameter should grow significantly while reducing other parameters associated with the WOs generated by corrective maintenance. This should be inevitable with the implementation of a predictive program in which faults and emergencies are replaced by WOs in the aftermath of an inspection. There is no lower limit because the machinery condition, time, and previous conservation set a threshold. The ICBM4 parameter described in the following is associated with this decrease because the MTBF increases to the maximum inherent reliability of the system, which is unknown.

$$\text{PMI7} = \frac{\text{Total number of work orders generated in MP inspections}}{\text{Total number of work orders generated}}$$

In his document for SMRP, Mitchell [222] discusses the predictive and preventative forms of maintenance in the WOs with regard to the total corrective orders. The indicator is very similar to *PMI7*, in that the author recommends monthly calculation. Further, it can be separated into predictive and preventative components to analyze the effectiveness of both programs independently. Mitchell takes into account the WOs generated in inspections,

looking specifically at the corrective WOs. He suggests that around 60% of order generation should be on the basis of inspections. If the parameter is calculated in relation to all work orders, it will be reduced somewhat. The predictive efficiency should be around 70%, with the preventive less than 50%.

The next parameter refers to the percentage of CBM-related computer maintenance tasks and the portion of man-hours devoted to them. The references are linked to the type of company and machines using CBM. Specifically, they consider a residual percentage of hours and budget when CBM is applied to one or two rotating machines. CBM is only performed for thermographic inspection of electrical panels up to a pillar. It confirms continuous process and monitors the status of all machines at hundreds of points. The parameters should remain stable once the system has been established in CBM. These data are usually stored in the CMMS; they correspond to working hours of the company's staff or contract workers.

$$\text{OI19} = \text{CBMI11} = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

The *CBMI4* parameter represents the MTBF of the considered equipment or line and supplies data relevant to an audit. One objective is to learn the impact of a predictive policy on a specific piece of equipment or line. Rotating machinery should show visible improvement in a few months, with replacement costs substituted by corrective interventions for small improvements or preventive work such as alignments and lubrications.

$$\text{MTBF} = \text{CBMI4} = \frac{\text{Total hours considered}}{\text{Number of breakdowns in an equipment}}$$

Finally, the relevant data for an audit are those relating to the benefits of the implementation of a CBM program. There are costs involved in setting up CBM routines, and we should allow a minimum of 6 months to produce the desired methodology and results. The calculation of these costs includes the replacement of systematic preventive and corrective measures to reduce predictive and scheduled jobs. The positive difference of these two items indicates the avoided costs per used unit. Knowing that these data are part of the introduction of CBM, we can make a fairly accurate forecast of the benefits. The reduction in cost will ensure that *ICBMS3* evolves toward a savings of between 20% and 30% of the total maintenance costs when the predictive maintenance will cover over 80% of the productive assets of the company.

$$\text{CBMI2} = \text{Avoided costs due to use of predictive maintenance}$$

$$\text{CBMI3} = \frac{\text{Current maintenance costs}}{\text{Maintenance costs prior to CBM program}}$$

EI17 involves in the same way as the *CBMI12* parameter. It represents the suitability of an initial investment, with the expenditure maintained until it has the desired effect. For the maintenance head, however, this represents a radical change in the budgetary

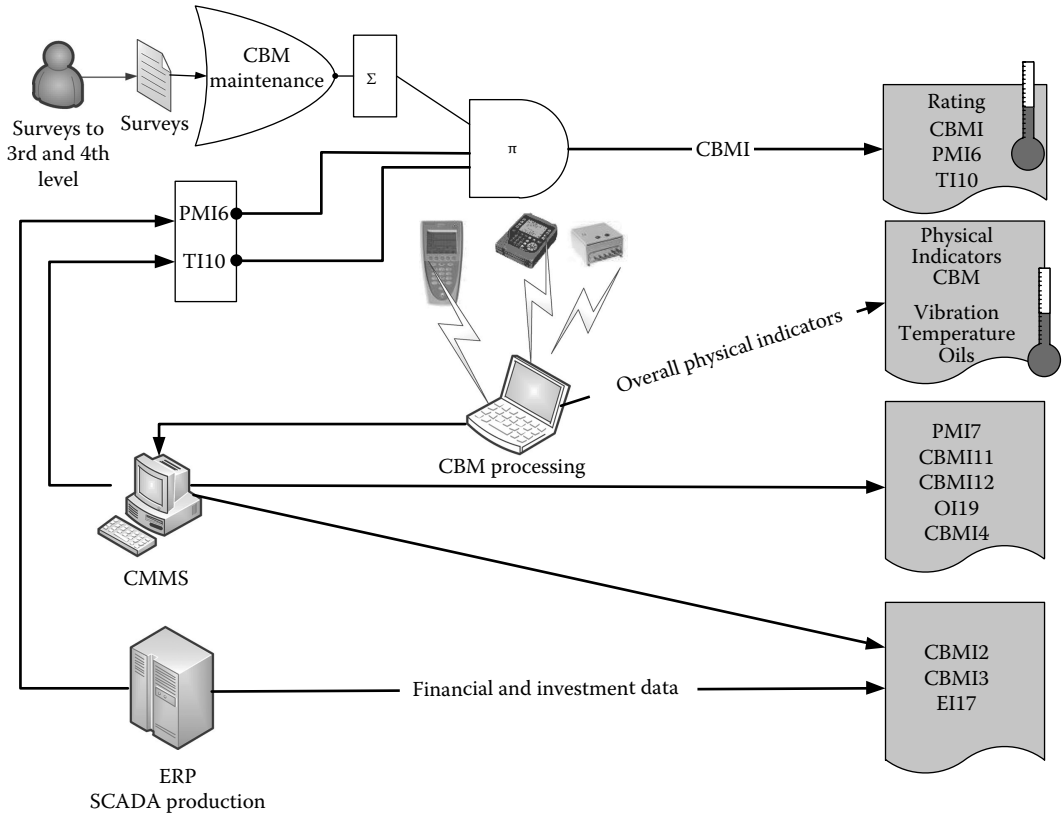


FIGURE 7.32
Maintenance audit based on the condition.

breakdown of the department; it will significantly change the way of assigning human and material resources.

$$\text{CBMI12} = \text{EI17} = \frac{\text{Predictive maintenance costs}}{\text{Total maintenance costs}}$$

Figure 7.32 provides a flow diagram corresponding to the data extraction and presentation of parameters in the audit of the CBM system. The relevant physical audit of the system includes electrical consumption (including global consumption), critical machinery, overall vibration of the plant, average temperatures of critical components, and overall performance analysis. When the machinery under analysis is high-use or the monitored machines are critical, these data provide valuable information; the evolution of these parameters is often directly related to the reduction in the number of corrective interventions and the increase of the MTBF unit.

7.6.2 Relationships between Production and Maintenance

An important aspect of the audit is the relationship between production and maintenance. This is shown in many indicators, and three aspects are especially important. First, production and maintenance must work together to schedule corrective maintenance, preventive

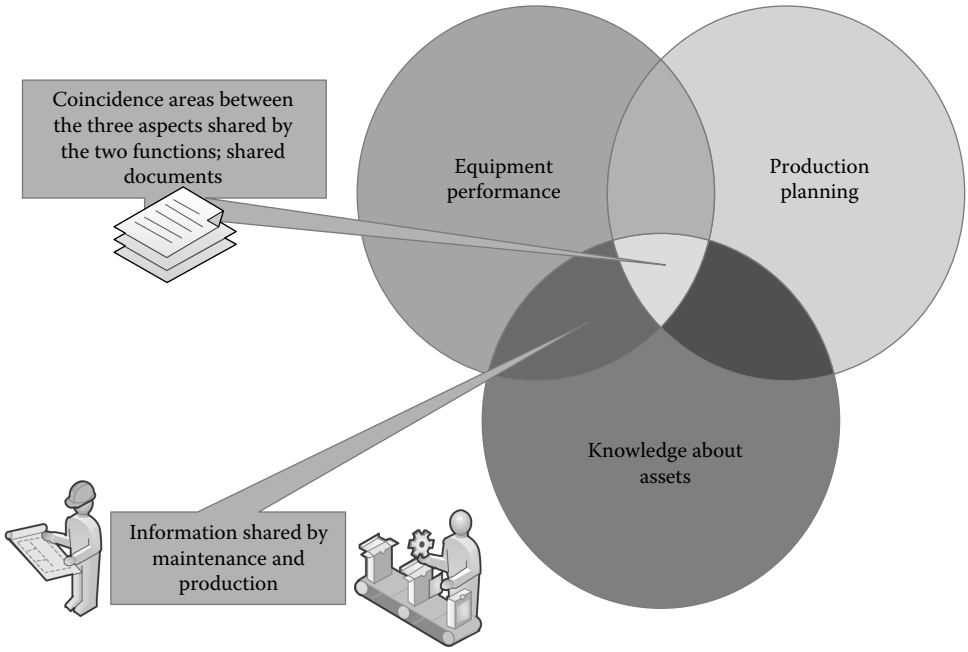


FIGURE 7.33
Overlapping areas of production and maintenance.

maintenance, improvements, and so on. Second, the information shared by the two functions should include criticality, configuration, policy to comply and bottlenecks. Finally, they must share specific information on system yields and the capacity to produce with respect to both quantity and quality (Figure 7.33).

Questionnaire: Integration of maintenance and production
PROD-PLAN Production planning

1. Is there a plan for daily production?
2. Is there a weekly agreed-upon maintenance program?
3. Does this program include planned stoppages?
4. Are there established times for stops and format changes?
5. Is this daily production and maintenance program reviewed?
6. Are there times stipulated for equipment maintenance?
7. Has the volume of maintenance work that can be done without harming production been calculated?
8. Is there a long-term plan of production that includes major maintenance activities?

KNO-AS Knowledge of assets

1. Is there a list of company assets? Is the list coded?
2. Is there a technical sheet for each team?
3. Is there any connection between the management software for maintenance and production?

4. Is there a shop floor layout to describe and identify all the computers?
5. Does the production system have lines in parallel?
6. Are the lines identified based on the critical process?
7. Are production areas separated by some criterion?
8. Has a criticality analysis been performed to concentrate resources on critical assets?
9. Can the incidence of equipment failure be quantified for other equipment?
10. Has each asset been analyzed from the point of view of regulations?
11. Are these rules met?
12. Does some equipment produce bottlenecks?
13. Does the company know how much time each process on the production line takes?
14. Is there a diagram of the installation process?
15. Are there any diagrams for pipes (electrical, air, water, others) to be installed?
16. Are there PID diagrams for instrumentation and processes?
17. Are catalogs and technical information available for all computers?
18. Do production and maintenance share technical information?
19. Is the technical information accessible in case of stoppage or failure?

PERF-CON Performance control

1. Is there a system for recording failure times and sharing this information with both production and maintenance?
2. Is there a restriction on the time from the point a machine stops until it returns to use, with all phases of maintenance timed?
3. How is WO production entered into the system?
4. Are stoppage times and performance recorded for each machine/production line?
5. Are stoppage times and their causes analyzed?
6. Are maintenance and production analyzed together with the costs generated by stoppages?
7. Are the lost time and volume generated by these stoppages measured?
8. How are the different availabilities linked to maintenance calculated?
9. Are the yield reductions of critical equipment recorded?
10. Are corrective actions implemented to eliminate the causes?

The indicators to evaluate the three aspects mentioned before include the following:

First, the production plan is assessed using available parameters for the production function. Next, maintenance must take into account the programming of its activities as the key parameter is the availability achieved by maintenance. In other words, there is a clear link between maintenance and production.

$$\text{TI2} = \frac{\text{Availability time achieved during required time}}{\text{Required time}}$$

Other relevant parameters are the availability linked to maintenance and the availability linked to faults. These reflect proper planning and foresight, allowing maintenance to properly interact with production.

$$\text{TI1} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailable time due to maintenance}}$$

EFNMS sets the *TI1* value at 91.5% for manufacturing sectors.

$$\text{TI6} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailable time due to failures}}$$

The knowledge of the asset's production is reflected in two parameters. The first is a percentage and represents knowledge of the maintenance function of all systems purchased and registered in the CMMS. The second, the number of critical elements analyzed, represents the developments in implementation policies that correspond to the total number of critical elements to be considered.

$$\text{CMMSI4} = \frac{\text{Total number of machines in the CMMS}}{\text{Total number of machines registered in the plant}}$$

$$\text{TI18} = \frac{\text{Number of systems covered by criticality analysis}}{\text{Total number of systems}}$$

Results show the quantity produced with respect to the availability of maintenance (Figure 7.34).

$$\text{EI6} = \frac{\text{Availability linked to maintenance}}{\text{Quantity produced}}$$

7.6.3 RAMS and RCM Analysis

In this section, we evaluate the degree of knowledge of the RAMS parameters and their implementation in daily work. We do not attempt to evaluate the successful deployment of RCM; performing criticality analysis or reaching any of the milestones of this methodology does not mean a company has implemented the complete methodology. As in other areas, the audit questions seek answers for the reliability and maintainability of the systems. For this reason, the survey and indicators are not intended to be educational but to assess the degree of understanding and realization of the RAMS parameters in everyday work.

Questionnaire: RAMS and RCM analysis
RAMS-KNO RAMS knowledge and concepts

1. Is there a list of critical and important equipment for the company?
2. Do employees know the difference between critical, priority, and secondary equipment?

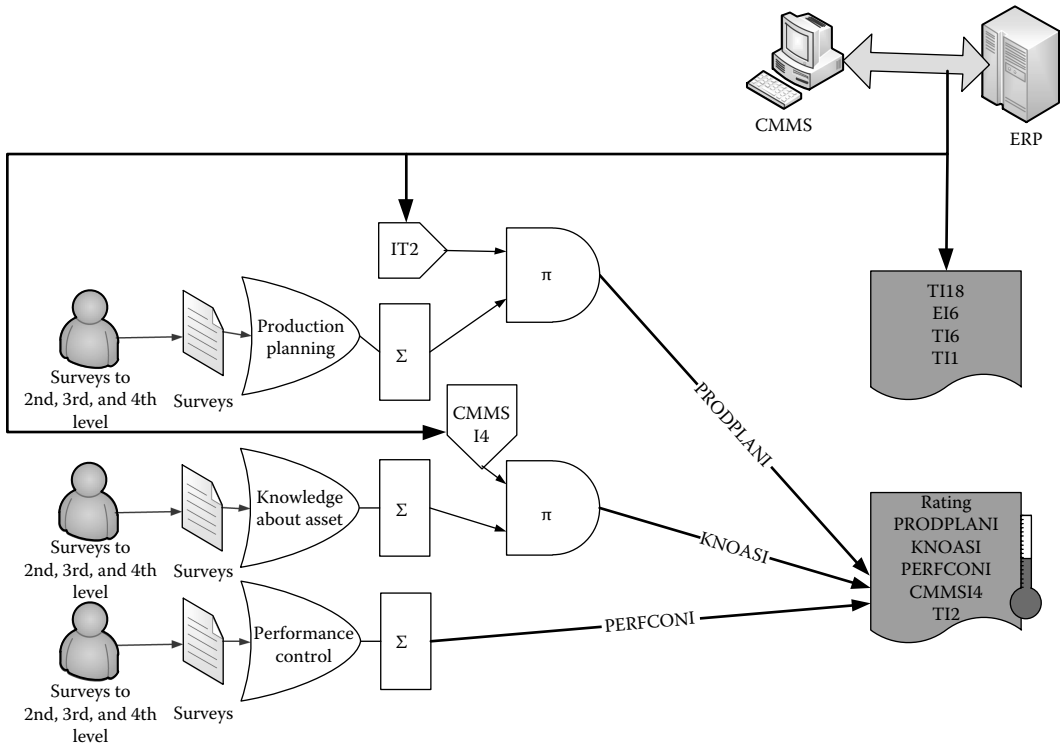


FIGURE 7.34
Relationship between production and maintenance.

3. Have the equipment's critical parts been identified?
4. Are the main causes of failure known?
5. Are spares fixed depending on their condition?
6. Are the critical components of key equipment regularly checked?
7. Do these revisions generate corrective actions and give answers?
8. Is there a formal inspection plan for components?
9. Is there a procedure for equipment modification?
10. Does this procedure take into account maintenance issues?
11. Does the modification procedure explain how to update the existing technical documentation?
12. Is it audited?
13. Is the experience of the maintenance department used to select new equipment or to modify current equipment?
14. Are maintainability and reliability considered in the design or purchase of new equipment?
15. Is the accessibility of each component of the new machine considered, that is, to be able to adequately perform inspections or other maintenance tasks?
16. Are the reliability concepts known?
17. Can the reliability of critical equipment be determined?

18. Is the failure of critical equipment understood?
19. Are maintenance costs in the cycle life of equipment analyzed?
20. Do the FMEA concepts include maintenance, production, procurement, and engineering?
21. Is FMEA a tool used in machinery acquisition?
22. Who participates in FMEA analysis used in the equipment selection process?
23. Are FMEA techniques used to develop preventive plans for critical equipment?
24. Are these techniques good enough to eliminate unnecessary inspections?
25. Is the value of the FMEA results quantified?
26. Is FMEA used to implement improvements and technical modifications?
27. Is FMEA used to design new equipment?
28. Is current maintenance analyzed with respect to RCM?
29. Is RCM implemented?
30. Are the RCM principles understood?
31. Are historical data used to improve the reliability of critical equipment?
32. Are data/historical equipment used to improve the reliability of all equipment parts?
33. Are MTBF and MTTR indicators calculated systematically for the equipment and its parts?
34. Are these indicators regularly reviewed to detect improvement or reverse?
35. Are the improvements implemented in the equipment preserved and archived?
36. Are tests performed and checked?
37. Are previous measurements used to prevent the recurrence of problems? (Figure 7.35)

We must operate software to collect reliability and maintenance information from the fault data and repair times entered in the WOs. The access to the failure times is complex and often involves manual work. We must use the MTBF and MTTR as reference parameters.

We will have to resort to operating software for the reliability and maintenance collection from the fault data and repair times entered in the WOs. In case the access to the failure time is complex or involves excessive manual work, we have to look the MTBF and MTTR as reference parameters.

RAMSI1 = $R(t)$ Reliability of equipment or system

RAMSI2 = $M(t)$ Maintainability of equipment or system

RAMSI3 = MTBF of equipment or system

RAMSI4 = MTTR of equipment or system

RAMSI5 = $\lambda(t)$ Risk rate of equipment or system

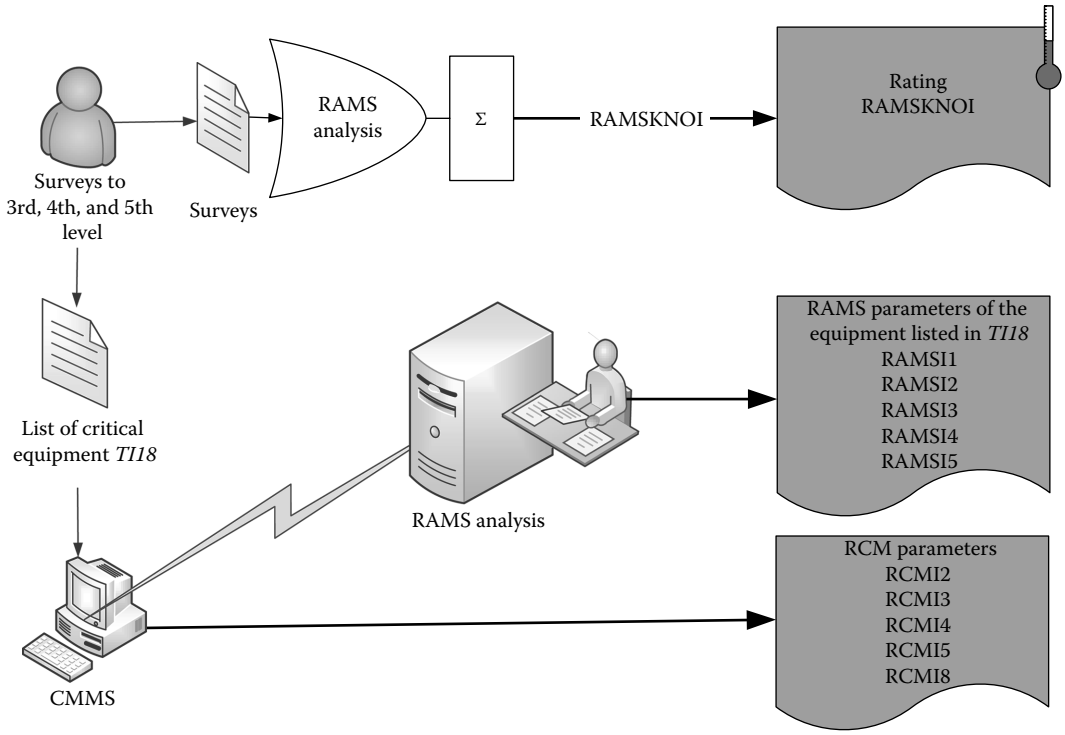


FIGURE 7.35
RAMS audit and critical studies.

The rest of the indicators listed here refer to the critical analysis of the equipment to prioritize the application of resources. This progressive analysis should cover all aspects of the equipment to measure the adequacy of the maintenance policies applied. As this is accumulative, it should be close to 100% of featured equipment, spare parts, and tasks proposed.

It is important to mention the level required by this type of proposal. O'Hanlon and Nicholas [241] discuss a survey on RCM implementation and its results. Only 60% of the companies they mention had worked with RCM and, of these, only 15% had used RCM successfully.

Those able to implement the indicators observed the following:

- 44% increase in availability
- 15% reduction in spare inventory
- 21% less overtime
- 23% OEE increase
- 13% better knowledge about the equipment among officials
- 8% TEE increase

$$\text{TI18} = \frac{\text{Number of systems covered by criticality analysis}}{\text{Total number of systems}}$$

WCM requires the system to have at least 20% analyzed by RAMS. It configures the proportion of 20%–80%; a minimum 20% will be the equipment that contributes to 80% of the productivity. Therefore, TI18 should be higher than 20%.

$$\text{RCMI2} = \frac{\text{Number of equipment failures where they perform cause analysis}}{\text{Total number of equipment failures}}$$

$$\text{RCMI3} = \frac{\text{Number of reviewed preventive tasks in critical equipment}}{\text{Total number of preventive tasks in critical equipment}}$$

$$\text{RCMI4} = \frac{\text{Number of reviewed predictive tasks in critical equipment}}{\text{Total number of predictive tasks in critical equipment}}$$

For the EFNMS, the revised tasks in the critical equipment must achieve a minimum threshold of 50%, with 70% considered an important achievement of WCM. Therefore, *RCMI3* and *RCMI4* must lie between 50% and 70%.

$$\text{RCMI8} = \frac{\text{Number of reviewed spare parts in critical equipment}}{\text{Total number of spare parts in critical equipment}}$$

These policies will reduce unnecessary predictive inspections as well as preventive tasks that become part of the revised tasks following the audit.

$$\text{RCMI5} = \text{Avoided costs due to use of RCM}$$

If analysis is continued, the savings will grow. The economic benefits of RCM tend to be high. Some authors may be too optimistic; O'Hanlon [242] mentions figures of 10-1 or 15-1. The investment is not onerous, however, and savings are generated by eliminating waste in preventive and predictive maintenance.

7.6.3.1 Safety

RAMS parameters pay special attention to safety and environmental damage. This aspect combines the qualitative perceptions of the maintenance employees of safety with quantitative indicators offering reliable data reaffirming or contradicting the surveys. These indicators validate (or not) the results, detecting possible manipulated measures.

An event that influenced the core development of research on work climate/safety culture was the Chernobyl disaster, which identified an inadequate safety culture as the most significant factor of the accident; see IAEA [132,133].

We should differentiate two terms, often confused: safety climate and organizational climate.

The latter refers to perceptions shared among members of an organization; as explained before; these refer to perceptions of procedures and practices. The former refers to perceptions of the policies, procedures, and practices relating to safety. A multilevel interpretation suggests the following:

- Policies define strategic goals and objectives.
- Procedures provide tactical guides for action related to these goals.

- Practices relate to the execution of the policies and procedures by the managers through the organizational hierarchy; see Zohar [385].

Zohar [386] suggests three validation criteria for safety climate:

1. There should be homogeneity or consensus of perceptions.
2. There should be variability among groups, that is, the different organizations or subgroups inside an organization.
3. The analyzed groups should correspond to natural social groups, such as working groups, departments, or organizations.

We must not forget that individuals share similar perceptions of safety in a particular working environment. The safety climate of a group leads to the establishment of an environmental security variable in the maintenance process.

A theoretical model should specify the relationship between the perceptions of safety and records of organizational security. Zohar [386] says the perceptions of the safety climate affect safety records in the following way:

- Perceptions of safety influence expectations of behavior.
- Expectations influence the occurrence of safety behavior.
- Security behavior influences the safety records in the company.

Zahra combines data on indicator measures with surveys of the climate of safety. Figure 7.36 includes mediators of security policies, unsafe behaviors, and the percentage of injuries. The feedback loops suggest that unsafe behaviors can induce managers or supervisors to modify their emphasis on security measures.

Figure 7.36 suggests two types of exogenous variables. One includes variables likely to affect the level or strength of the climate. For example, strategic objectives and shareholder pressures can induce a higher security climate, but financial pressures or the belief that security is the ultimate responsibility of the workers may cause a lower one.

The second type includes exogenous variables that seem to predict the results of security, for example, the workers' ages. These should be included as control variables in statistical models, especially when audit security is a priority in maintenance areas with high levels of danger, such as the chemical or nuclear industry.

It should be assumed that perceptions of the safety climate can influence the employees' attitudes in carrying out their work and interacting with other employees, along with other security issues. Each factor can have a direct impact on the results of security, such as accidents. The framework or model shown in Figure 7.37 focuses on behaviors relating to the individual's safety. The behaviors comprising of the individual's safety are determinants of safety behavior.

Campbell et al. [39] propose three determinants of individual differences of behavior: knowledge, skill, and motivation. There are many potential safety background factors; Figure 7.37 shows background examples at the individual and organizational levels. The organizational approach to the safety climate tends toward individual safety.

Finally, any theoretical position on the concept of safety climate has no major implications on the types of content that will be measured or the types of techniques to do so. In this case, the measurement virtually always involves asking the "organizational actors," and this is normally done through self-assessment questionnaires. The fundamental

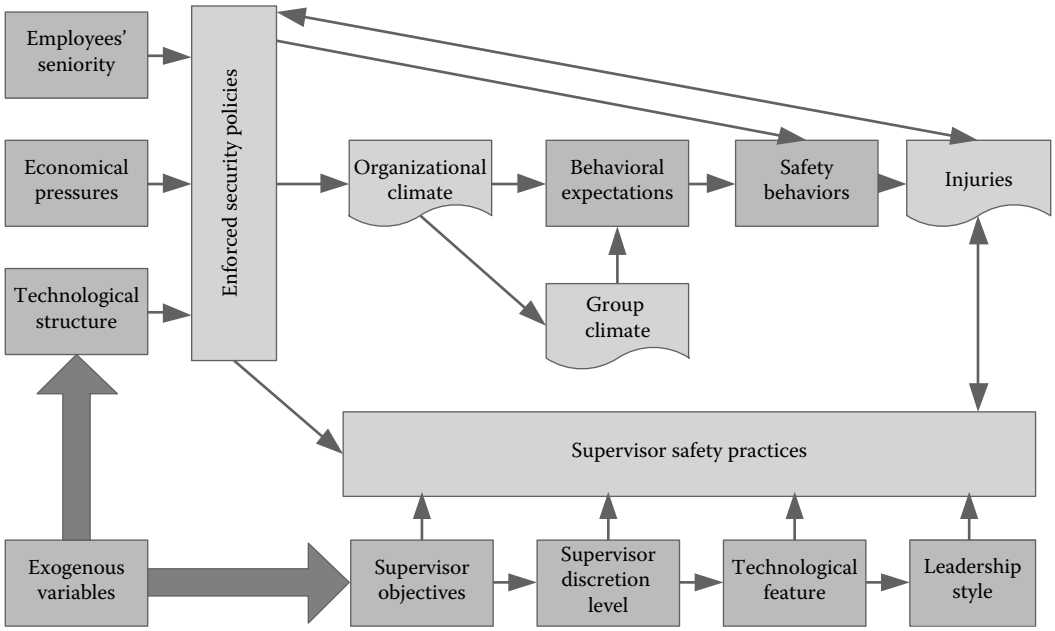


FIGURE 7.36
Multilevel security climate model. (Adapted from Zohar, D., Safety climate: Conceptual and measurement issues, in: Quick, J.C. and Tetrick, L.E., eds., *Handbook of Occupational Health Psychology*, American Psychological Association, Washington, DC.)

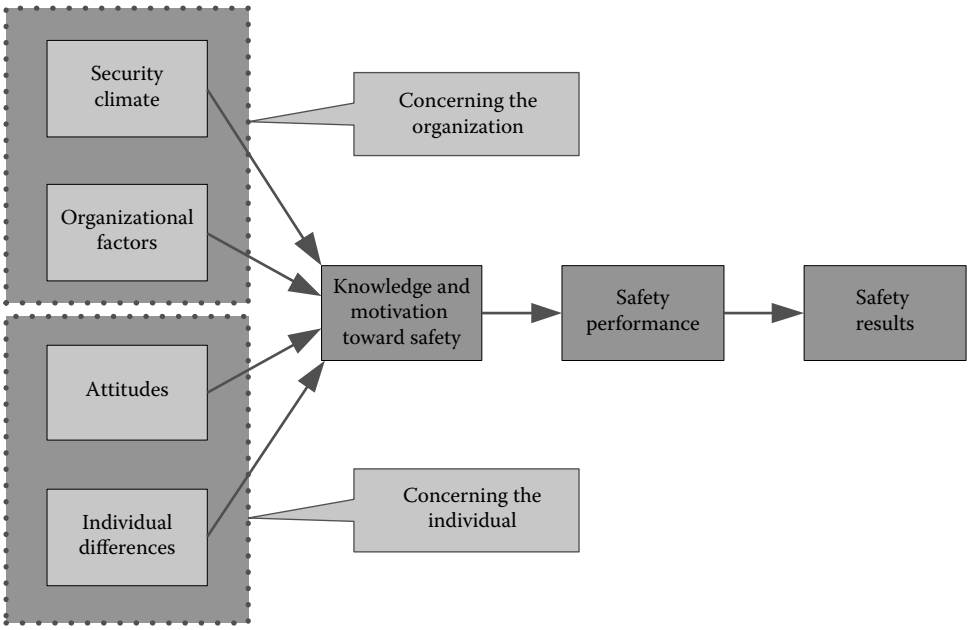


FIGURE 7.37
Meanings of safety climate and safety behavior. (Adapted from Neal, A. and Griffin, M.A., Safety climate and safety at work, in: Barling, J. and Frone, M.R., eds., *The Psychology of Workplace Safety*, American Psychological Association, Washington, DC.)

difference between authors and the questionnaires they employ lies in the specific content to analyze.

Zohar's [384] work is considered by many researchers to be the first empirically relevant input on the theme of safety climate. Zohar [384] says its measurement should include the following dimensions:

a. Perceived attitudes toward safety
b. Perceived effects of safety conduct on promotion
c. Perceived effects of safety conduct on social status
d. Organizational status perceived by the safety officer
e. Perceived importance and effectiveness of safety training
f. Perceived risk level in the workplace
g. Perceived effectiveness of effort versus safety promotion

Questionnaire: Safety
SAF-KNO Safety knowledge concepts

1. Does the company have or show safety posters at work?
2. Are safety aspects considered a priority by the company?
3. Do mechanisms inform management about unsafe conditions?
4. Does the company have safety and health committees at work?
5. Does the company provide safety workshops or lectures?
6. Is safety the first thing in work maintenance?
7. Are specific safety meetings held?
8. Are safety policies or regulations and hygiene generally known?
9. Does the company have a department responsible for health and safety?
10. Is the company aware of the added risk encountered by maintenance workers?
11. Does the company have some kind of system to reward and incentivize security?
12. What is the interest in the company about safety and hygiene in the workplace?
13. Do staff receive written or verbal instructions about security?
14. Are there regular inspections of safety control?
15. Are the safety committee's functions and hygiene in the workplace generally known?
16. Is the safety policy respected?
17. Are risks evaluated according to the job?
18. Have procedures been established, along with specific regulations for the safe performance of maintenance?
19. Is compliance with safety regulations a priority of the department?
20. Have the risks been identified to relevant operators?
21. Are maintenance program equipment and tools available?
22. Is there a calibration procedure for equipment and measurement tools?
23. Are the calibrations and the equipment inspections archived?

Clearly, the results of this survey should yield a positive feeling about the enforcement of rules and safety. As the survey suggests, equipment and tools should be well maintained to ensure the physical safety of operators.

Some security aspects are due to maintenance that has generated damage.

$$\text{TI5} = \frac{\text{Number of staff injuries due to maintenance}}{\text{Working time}}$$

Machines may contain dangerous substances; if small leaks are produced during repairs, this can affect production staff. Improving the safety of the equipment will lead to fewer accidents.

$$\text{OI7} = \frac{\text{Man-hours lost by injuries of maintenance staff}}{\text{Total man-hours worked by maintenance staff}}$$

There will be a reduction in accidents after the implementation of critical analysis in audits.

$$\text{TI3} = \frac{\text{Number of failures due to maintenance that generate environmental damage}}{\text{Calendar time}}$$

RCMI6 = Reduction of noncompliance and accidents from use of RCM

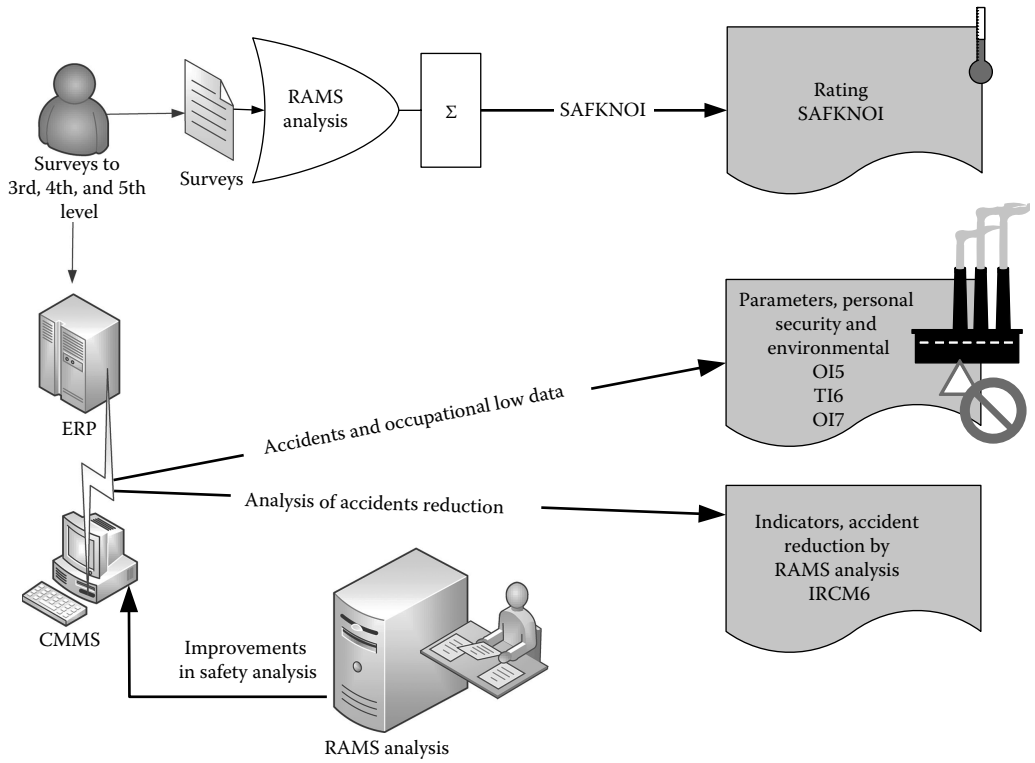


FIGURE 7.38
Audit of security level.

Figure 7.38 illustrates the full audit of safety. As we can see, a security audit contributes three types of information. First, the indicators from the surveys reflect the existing safety climate; they give the collective perception of the prevailing security in the company. Second, we have accident figures, and so on. These reflect the security policy and the perception of the policy by employees. Long periods may pass without accidents or without environmental problems. Finally, there are improvement indicators. These represent proactivity with respect to the safety. As mentioned in previous chapters, it is imperative to anticipate events through studies of risks to prevent the occurrence of accidents.

7.7 Level 4 Evolution

CBM maintenance streamlines maintenance and production by sharing information and enriching historical knowledge. It prevents equipment from reaching a critical state and failure. At this point, we enter level 4 with the analysis of two mature aspects: first, the financial management level and cost model applied in the department; second, TMP implementation or similar programs (Figure 7.39).

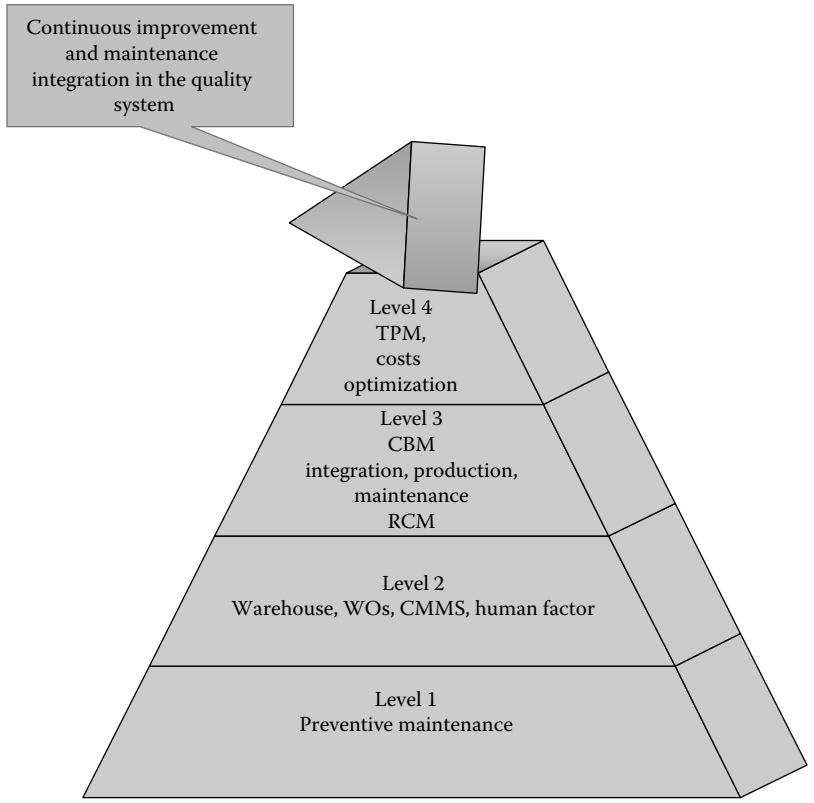


FIGURE 7.39
Level 4 maintenance evolution.

7.7.1 Cost Model and Financial Optimization

Costs are indicators of relevance on the questionnaire, especially in the attempt to ascertain the existence of a consensual and operating model. The survey is divided into two distinct parts; the first assesses the degree of knowledge of the budget, its control, and its execution. The second adds the established cost mode with regard to depreciation, asset substitution, and so on.

Questionnaire: Cost model and financial optimization
BUD-MAN Management and budgetary control

1. Is there a previously approved budget for the department?
2. Is there monthly control of costs?
3. Is there cost control with reference to some previously set indicators?
4. Do the periodic control results and indicators arrive at intermediate drive production and maintenance lines?
5. How is the deviation between the actual and budget costs measured?
6. Do maintenance costs control equipment?
7. Do expensive costs control by the type of maintenance applied?
8. Does each team perform statistical control of maintenance costs?
9. Is the inventory size defined for available equipment?
10. Does each team know the relevant spares cost?
11. Is the labor cost for maintenance known?
12. Is it more cost effective to outsource than work with own resources?
13. Can maintenance policies be defined on the basis of alternative costs?

COST-STR Cost structure

1. Is there a cost structure of well-defined maintenance?
2. Does that model include direct and indirect costs?
3. Is that cost model used for future decisions?
4. Are costs defined by production areas?
5. Is the acquisition date of the equipment known?
6. Are costs defined by equipment as well as each of the equipment's components?
7. Is the value of acquisition of the equipment known?
8. Is the depreciation rate defined for equipment?
9. What is the amount of lost production cost because of faults known?
10. Does the cost model include traditionally hidden faults?
11. Are equipment replacements annually assessed?
12. Is the cost relationship between maintenance and total cost of the product known?
13. Is the total cost of a new piece of equipment known?
14. Is the cost of disuse known and broken down?

15. Are costs broken down into temporal and variables costs, that is, temporal (staff, planned maintenance, investment), variable (staff, spare parts, energy, rent)?
16. Is there a relationship between maintenance personnel and production?

In this case, the surveys play a parallel role but are not combinable with the maintenance indicators. The cost audit will provide a series of financial indicators, along with the survey's results on the knowledge of the budgetary policy.

The extracted data from the ERP and CMMS are a necessary combination for certain indicators.

The *EI1* indicator shows waste in the use of resources allocated to the maintenance of certain assets. This parameter can be useful to the top level of maintenance; when it is broken down by areas, we can see high concentrations of resources of little value when replacements are cheap.

$$\text{EI1} = \frac{\text{Total maintenance costs}}{\text{Assets' replacement value}}$$

For Weber and Thomas [367], as commented, the *EI1* world-class reference is about 2% or 3%, considering the annual maintenance budget.

The following three indicators provide information on the relationship of the maintenance budget to production in value transformation and the quantity or cost of that transformation. There is a low margin of profit in a unit with high processing costs; through benchmarking, we can observe this type of indicator.

$$\text{EI2} = \frac{\text{Total maintenance costs}}{\text{Added value plus external maintenance costs}}$$

$$\text{EI3} = \frac{\text{Total maintenance costs}}{\text{Production quantity}}$$

$$\text{EI4} = \frac{\text{Total maintenance costs}}{\text{Transformation cost to production}}$$

For Weber and Thomas [367], the *EI4* world-class reference is lower than 10%, and disturbing if it exceeds 15%.

A very important parameter for the higher levels is the total maintenance cost with respect to the manufactured product. In other words, how many monetary units of maintenance lead to the final product?

The audit of costs is shown in three pie charts in Figure 7.40. Two items represent approximately 70% of the maintenance budget.

$$\text{EI5} = \frac{\text{Total maintenance costs} + \text{Unavailability costs linked to maintenance}}{\text{Quantity produced}}$$

The first graph represents the portion of the budget aimed at the three types of maintenance staff in the plant: internal staff, subcontracted staff doing the work of internal staff,

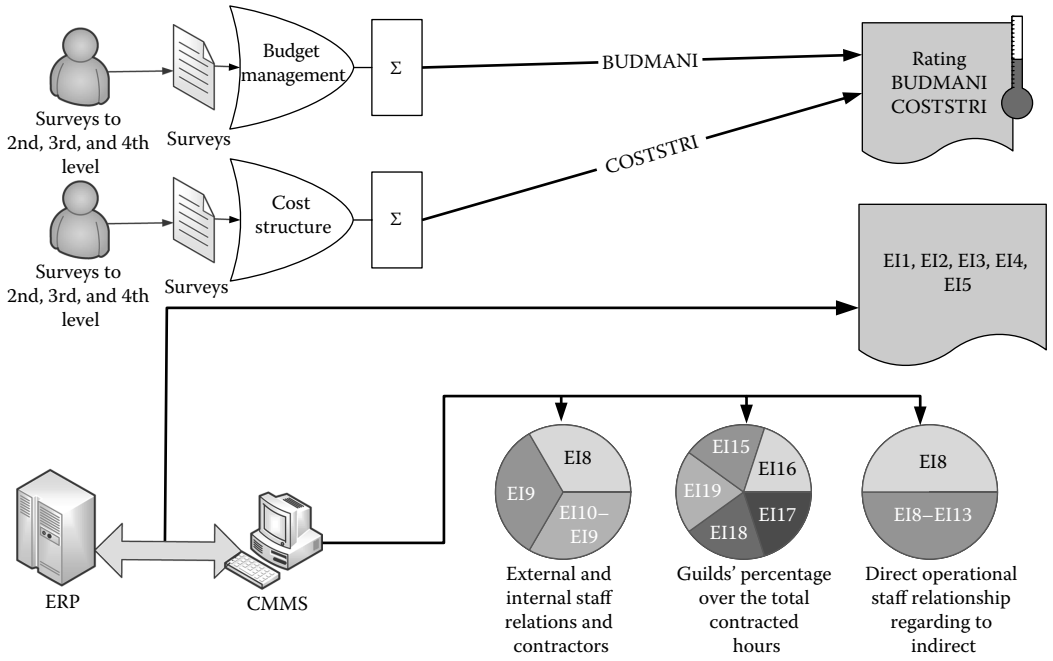


FIGURE 7.40
Cost audit of the maintenance model.

and subcontracting aimed at specific jobs. These costs are determined by the company policy on outsourcing.

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI9} = \frac{\text{Total cost of external staff used in maintenance}}{\text{Total maintenance costs}}$$

$$\text{EI10} = \frac{\text{Contracting cost}}{\text{Total maintenance costs}}$$

In the second, the internal staff can be divided into direct and indirect staff; some staff provide administrative support, while others work on the machines. These are shown (*EI8–EI13*), along with maintenance hours for production operators.

$$\text{EI13} = \frac{\text{Cost due to maintenance by indirect staff}}{\text{Total maintenance costs}}$$

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Total maintenance costs}}$$

Finally, a chart is included in the audit report with the budget percentages allocated to the various items or maintenance modalities. The reference points are not standard, although statistics are associated with the different business sectors, and the indicator evolution will be reported with respect to the chosen methodology.

CBM should reduce the corrective function in a few months; a well-established CBM will mean a graph of rapid mutation.

$$\text{EI15} = \frac{\text{Corrective maintenance cost}}{\text{Total maintenance costs}}$$

Hawkins [115] proposes the *EI15* methodology for calculating good practice and harmonization. A monthly calculation is proposed for this indicator, with around 25% of the maintenance budget going toward corrective maintenance. Note that this includes corrective scheduled maintenance and emergency interventions. The indicator has been harmonized by Hawkins.

$$\text{EI16} = \frac{\text{Preventive maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI17} = \frac{\text{CBM maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI18} = \frac{\text{Systematic maintenance cost}}{\text{Total maintenance costs}}$$

$$\text{EI19} = \frac{\text{Improvement maintenance cost}}{\text{Total maintenance costs}}$$

7.7.2 Maintenance Performed by Production Personnel

A high degree of maturity and integration of the maintenance function in the plant is conducive to the implementation of TPM policies where maintenance operators are replaced by production workers in routine tasks. We are not going up the pyramid. Rather, we are deepening the auditing process methodologies that require complex technologies. Such methods require a high level of organizational maturity and correct methodologies.

Questionnaire: Maintenance performed by production staff
TPM Total productive maintenance

1. Is the basic level of maintenance performed by the staff handling the machine?
2. Are operators taught how to do these small maintenance tasks?
3. Are there clearly defined routes (cleaning, lubrication, inspection) for the maintenance performed by the operators?
4. Are the staff aware of the importance of order and cleanliness?
5. Does the maintenance by production operators include the basic tasks of cleaning, inspecting, and greasing?

6. Do production and maintenance staff work together in agreement with established maintenance plans?
7. Are the operators responsible for housekeeping?
8. Has the management team raised awareness of the importance of maintenance implementation and the need to involve maintenance and production?
9. Does each facility have a clearly defined and accessible maintenance plan?
10. Is there a realization (mode) and compliance (periodicity) audit of the maintenance plan?
11. Are there any visual indicators such as graphics or figures that show the success or failure of the maintenance program?
12. Is there a checklist for the realization of defined tasks?
13. Have the production staff received training in maintenance and safety regulations?
14. Is there a daily schedule that includes all maintenance activities?
15. Is a daily check performed and are results communicated to the staff/affected area?
16. Is there a follow-up in accordance with some established indicators?
17. Is there a policy on eliminating waste by analyzing a process involving all employees?
18. Are short daily meetings held to review and control the scheduled tasks?
19. Are corrective actions defined and assigned to the staff to see the result of detected problems in daily maintenance interventions?
20. Is there a defined and assigned follow-up for these corrective actions?

The indicators of the TPM autonomous maintenance are mainly based on the hours devoted to it by the production staff and the year-to-year development. It is relevant to the auditor that the teams involved in the 5S policy better preserve assets; they should also show pride in their role.

$$\text{OI4} = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI9} = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of production operators}}$$

$$\text{OII1} = \frac{\text{Preventive maintenance hours by production operators}}{\text{Total preventive hours}}$$

For WCM, the *OII1* indicator must be around 30% or 40% considering the minor preventive tasks such as adjustments, cleaning, or greasing. If we consider all the preventive tasks, the indicator can be reduced by half.

$$\text{OII23} = \frac{\text{Preventive maintenance hours by operator's year } n}{\text{Preventive maintenance hours by operator's year } n-1}$$

$$\text{TPMI3} = \frac{\text{Critical equipment included in 5S activities}}{\text{Total number of critical equipment}}$$

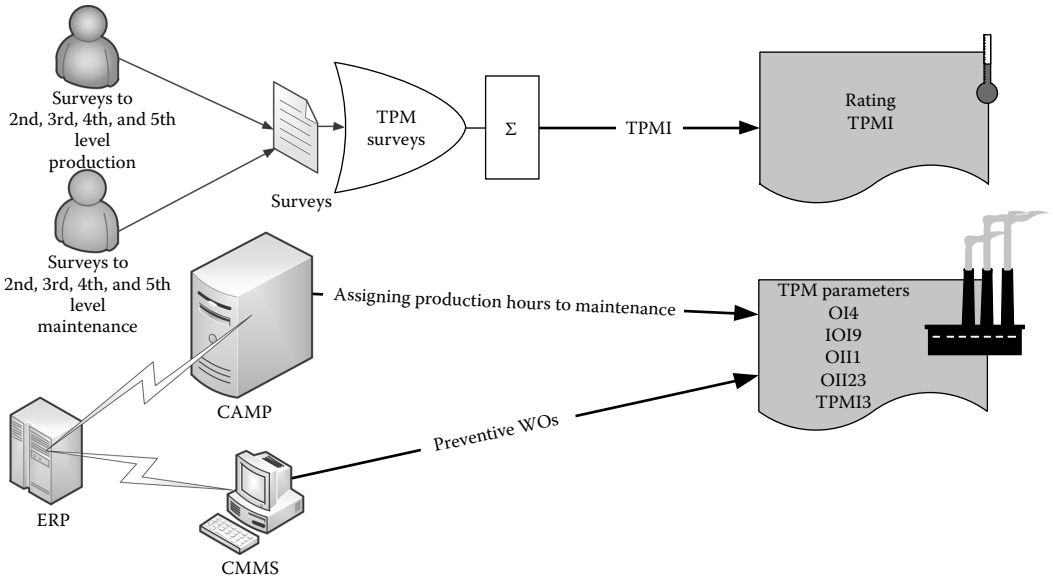


FIGURE 7.41
Autonomous maintenance auditing process by operators.

In Figure 7.41, we can observe the auditing process for a TPM system; it is important to correlate the maintenance surveys with those of production to ensure perceptions are the same.

7.8 Level 5 Evolution

Level 5 includes a quality policy and a continuous improvement function. It is not, as we can see, a complex technique requiring numerous researchers, but it represents a change of mentality to see problems as an opportunity for improvement. This represents a very high degree of maturity; it is both complex and intangible because of the method and the absence of reliable indicators (Figure 7.42).

The following survey is conducted in levels 2–5 for consistent results on the global perspective of continuous improvement in the organization.

Questionnaire: Continuous improvement
QUA-KAI Quality and continuous improvement

1. Are there established procedures for maintenance?
2. Are these procedures in the ISO 9000 quality system?
3. Does each team in the system have a maintenance work program?
4. Is a "Poka Yoke" philosophy used to avoid errors?
5. Does each team have maintenance records?
6. Is a register updated systematically and regularly?
7. Is there a procedure to maintain and update this information?

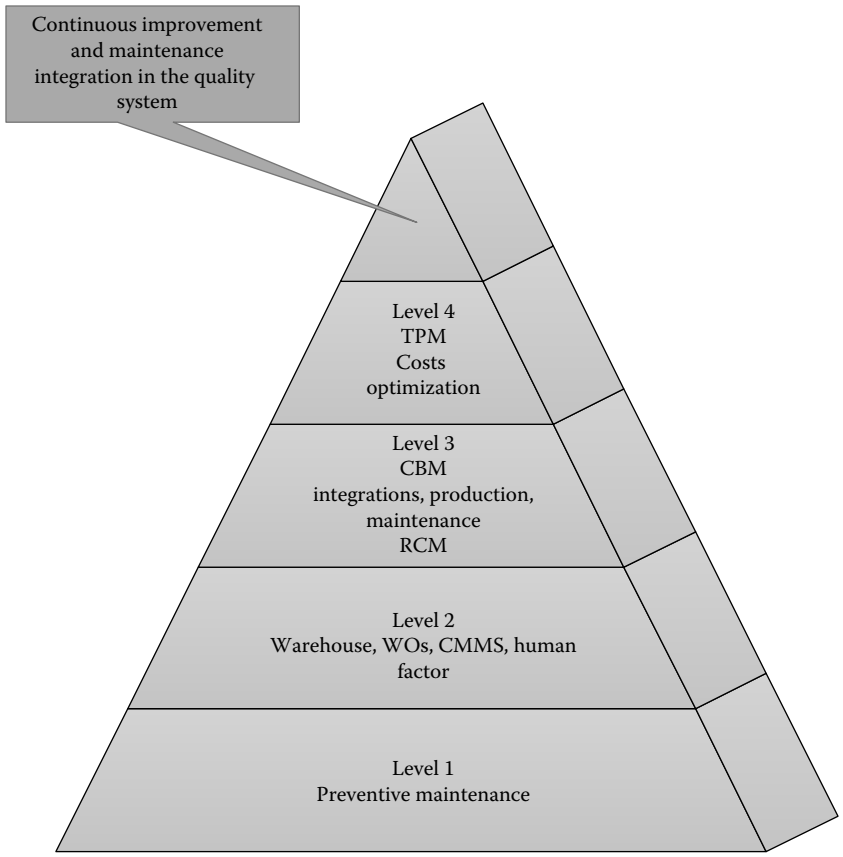


FIGURE 7.42
Level 5 in the evolution of the maintenance.

8. Are operator records and corresponding authorizations kept for work on equipment?
9. Are stoppages in production and their causes analyzed using FMEA to establish corrective actions?
10. Are the causes of a decline in production analyzed?
11. Are product rejections analyzed?
12. Are these analyses carried out by mixed production and maintenance teams?
13. Does the company get suggestions for improvement from the employees in production and maintenance?
14. Is the economic impact of these suggestions analyzed?
15. Is the maintenance plan upgraded every 1–2 years in accordance with worked hours and results?
16. Are advanced statistical techniques applied?
17. Is the department and its functioning regularly audited?
18. Is there a policy of improvement based on benchmarking?
19. Does the maintenance department have a regular process of benchmarking with other factories/departments in the group or sector?

20. Are the results of benchmarking reviewed and communicated?
21. Are these results used to implement improvement plans?
22. Are the 6 sigma philosophies used as a tool for continuous improvement?
23. Are the workplace and equipment improved through the 5S to impose order, cleanliness, standardization, organization, and integration?
24. Are there established indicators of operational and financial management?
25. Are the definitions of these indicators based on calculation methods, sources of information, frequency of occurrence, and responsibilities?
26. Are all the areas and relevant personnel related to the indicator and its particular definition known?
27. Have the objectives been established for each indicator?
28. Is the benchmarking program performed for these indicators?
29. Are these indicators used as a basis for decision-making?
30. Are communication indicators achieved periodically by the staff?
31. Is there a relationship between the management indicators and improvements?
32. Is specialized equipment used by the different departments to solve important problems?
33. Are the practices and fault analysis methods used by a multidepartmental improvement team?
34. Are there regular meetings and plans for these teams?

Relevant indicators include the dedication of staff to continuous improvement at this level, including activities such as benchmarking, 5S, improvements, or dedication to the quality management system.

$$\text{OI8} = \frac{\text{Man-hours used in continuous improvement}}{\text{Total man-hours of maintenance staff}}$$

Svantesson [314] harmonized this indicator between SMRP and EFNMS. To take into account all internal staff performing direct and indirect maintenance, it is important to calculate the hours worked. It is a key indicator to measure the effort made.

The WCM indices propose dedicating 5%–10% of the available work to improvement. Svantesson's view and the WCM agree on values of 7% or 8% as a reasonable degree of innovative maturity in an organization.

The following indicators are similar to the *IO8* and may break down the previous indicator to measure improvements made by the production team separately from the maintenance personnel.

$$\text{OII31} = \frac{\text{Improvement equipment hours by production operators}}{\text{Total operators' worked hours}}$$

$$\text{OII32} = \frac{\text{Improvement equipment hours by maintenance operators}}{\text{Total operators' worked hours}}$$

All teams are not having good politics formation and will be cumulative indices that grow the audit. However, the critical machines, considered by *TI18* parameters, are being added to the Kaizen policy.

$$\text{KAII3} = \frac{\text{Critical equipment included in continuous improvement activities}}{\text{Total number of critical equipment}}$$

$$\text{TPMI2} = \frac{\text{Critical equipment included in design improvement studies}}{\text{Total number of critical equipment}}$$

$$\text{TPMI3} = \frac{\text{Critical equipment included in 5S activities}}{\text{Total number of critical equipment}}$$

The suggested measures are easy to acquire through the records; the savings measure is more complex if there has been improvement.

These indicators should continue to increase until we reach a stable level appropriate to the organization's maturity. When assets show a constant failure rate, improvements are not necessary.

$$\text{KAII4} = \frac{\text{Number of suggestions given by maintenance employees}}{\text{Total number of maintenance employees}}$$

$$\text{KAII1} = \text{Savings achieved by employees' suggestions}$$

All these indicators can be seen in the contributions to the scorecard. Figure 7.43 shows four relevant aspects. The surveys on the four hierarchical levels extract an indicator with respect to the perception of the Kaizen culture in maintenance. The numerical indicators reflect the teams still subject to these policies, the time commitment of the actors involved, and the efficiency of the practices.

7.9 Likert Scale for Maintenance Surveys

We close this chapter with a reflection on the Likert scale used to evaluate surveys in the auditing process. The scale responds to various criteria, including ease of understanding, rapid assessment, and, of course, the removal of the negative feeling so often felt in the evaluative process.

7.9.1 Measurement of Attitude with the Likert Scale

We often use the Likert scale in research to assess attitudes and opinions. This scale, first developed in 1932 by a psychologist, is noted for its speed and simplicity of implementation.

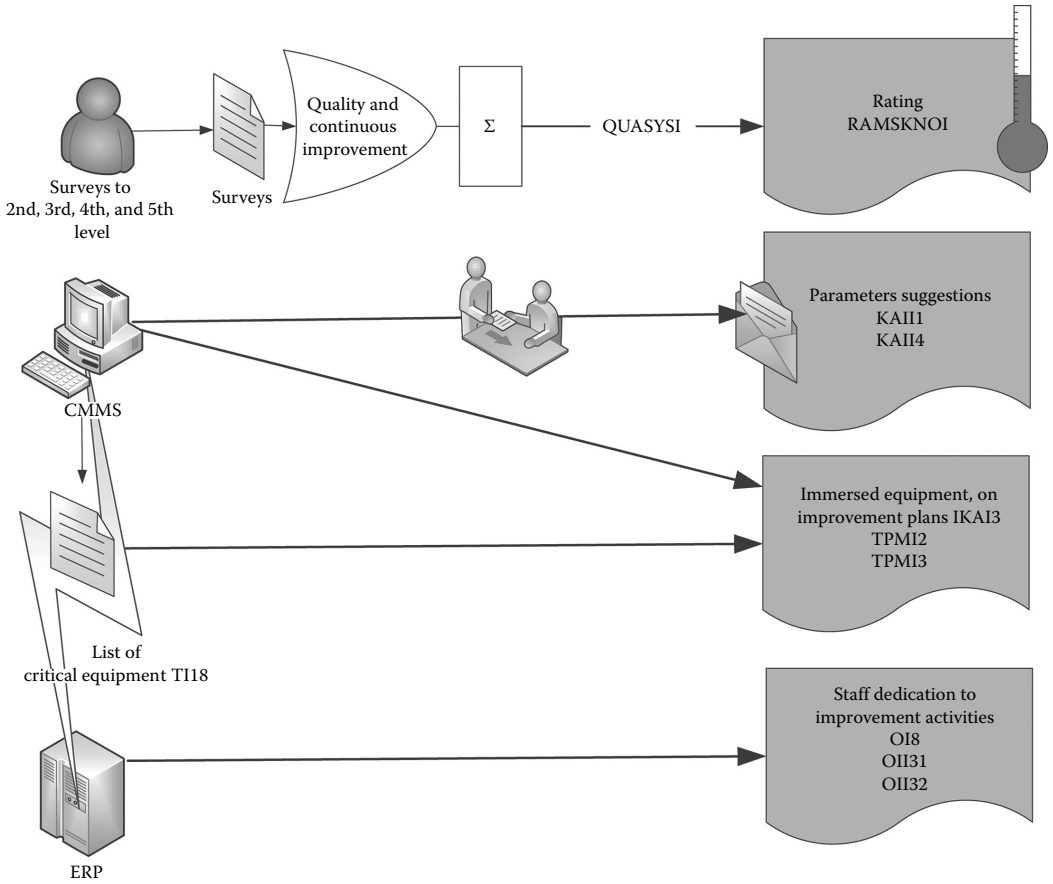


FIGURE 7.43
Audit process of integrated maintenance in terms of quality and continuous improvement.

Its implementation has grown exponentially in 77 years, and it continues to be the preferred scale for almost all researchers.

The Likert scale is an ordinal level. It is characterized by locating a series of selected phrases on a scale with degrees of agreement/disagreement. These phrases are submitted to a survey's subjects. The phrases are organized in groups and have the same reaction scheme, allowing the respondent to quickly learn how the system works. The main advantage is that all respondents share the same order of phrases. In addition, when developing it, Likert sought to make the degrees of the scale user friendly for the respondent.

This qualitative method of measuring attitudes was developed by Likert in surveys of attitudes toward international relations, race relations, economic conflict, political conflict, and religion, conducted between 1929 and 1931 in various universities in the United States [189]. The Likert scale remains one of the most frequently used ways to measure attitudes. This simple technique offers a wide choice of responses and avoids the use of judgment required in other methods to measure attitudes.

On the scale, attitudes are set on a continuum that goes from the favorable to the unfavorable. In addition, the technique puts each individual attitude at a certain point, admittedly

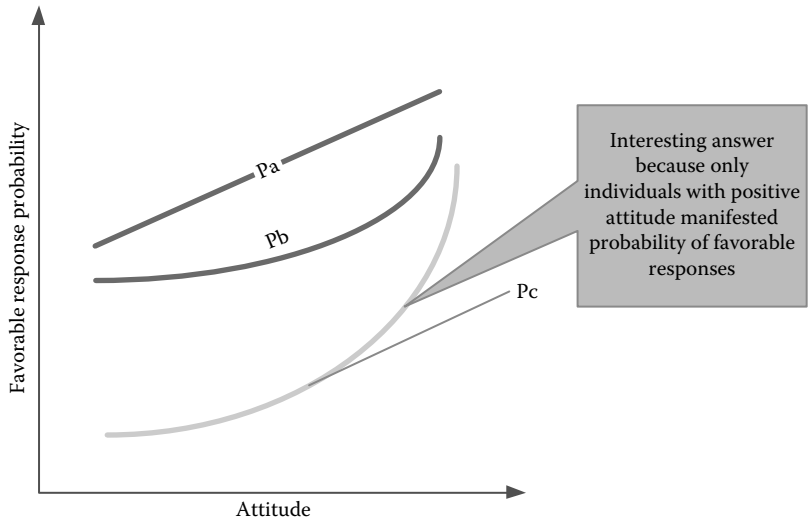


FIGURE 7.44
Probability of favorable response (Pa, Pb, and Pc).

a common feature of other scales, but in addition takes into account the amplitude and the consistency of the attitudinal responses.

Previously, it was necessary to analyze the philosophy driving the measurement, but the Likert scale uses statements or propositions, that is, statements to which respondents are asked to give an individual attitudinal response. It is assumed that the attitude exists, and respondents are sorted based on their extent of agreement or disagreement with the propositions, provided they are related to the attitude being measured. If this relationship is found, that is, if subjects have an attitude toward a particular proposition, the scale is valid (Figure 7.44).

Figure 7.44 sums up the previous discussion. The figure shows a shift in the probability of receiving a favorable response (i.e., agreement with the proposition) on the continuum of attitude; it is drawn inside the likelihood of receiving a different response. If the attitude is favorable, we should have a greater probability of receiving a favorable response. The curve corresponding to proposition A (Pa) indicates the probability of a "neutral" response; but even subjects with a less favorable attitude can have a high probability of returning a favorable response. Proposition B (Pb) is intermediate. Finally, proposition C (Pc) only receives favorable responses from people with a very favorable attitude, overall. However, these curves do not represent all possibilities associated with an attitude.

Some propositions can be corrected, as seen in Figure 7.45.

Pd offers a constant proportion of favorable responses. Regardless of the attitude, subjects will respond to the same favorable degree. Curve E is simply a coding error; if its values are reversed, it will be a suitable proposition. Curve F (Pf) is obtained by a statement aimed at an unfavorable response, rejected by the subject.

The fundamental property of the Likert scale is its ability to find a consistent relationship. This also implies the probability a person will accept or reject propositions or remain constant, as does his/her hypothetical attitude. However, responses are tied to the favorable or unfavorable inclination of the respondent. A certain number of statements must be approved for the scale's findings to be valid.

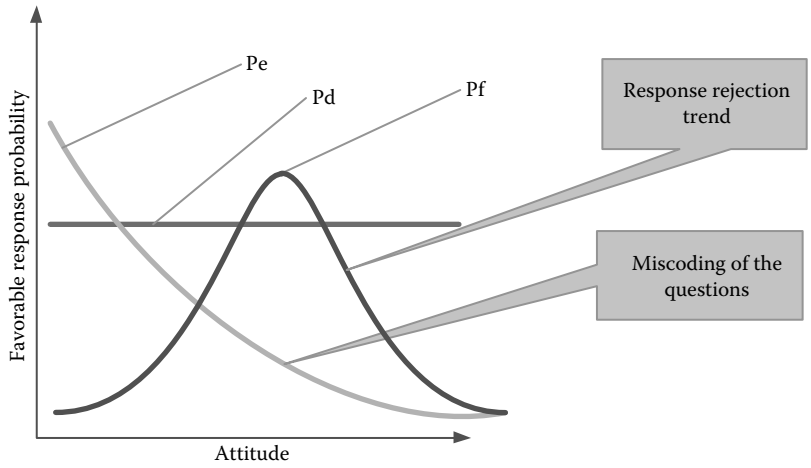


FIGURE 7.45
Probability of favorable response (Pd, Pe, and Pf).

Each element or proposition provides information on the subject's attitude. The accumulation of information and the number of responses allow us to determine the position a person occupies on a hypothetical continuum of attitude. In this sense, we can say that each element provides insufficient but necessary information.

7.9.2 Stages of Construction

To construct a scale of attitudes, we must first define the purpose of the attitude variable we need to measure. Second, we need the relevant information to build the items (propositions). A scale can be established at this point if a pilot assessment is done in a representative sample of the population. This assessment enables us to decide whether the proposed items are discriminating enough or must be modified. Finally, we set the scale into the sample we want to explore. We get the score of each individual and examine the validity and reliability of the scale. In short, the stages are the following:

1. Definition of the attitudinal object
2. Collection of preliminary set of information
3. Determination of the items/categories
4. Creation and administration of a sample
5. Analysis of the items

7.9.2.1 Definition about the Attitudinal Object

Before beginning construction of the scale, and this is for any type of scale, we must clearly specify our purpose for studying attitude. This is obviously linked to the objectives of the research. It should be clearly worded without ambiguity if we want to get a good scale that actually measures what we want. The choice of the corresponding items and, therefore, the entire scale will depend on this first step.

7.9.2.2 Collection Defined

The scale requires many items to cover the entire range from the very unfavorable to the favorable. These can be determined by various methods.

- *Literature on the subject*: This step is common to all methods of research. In the case of the scales of attitude, we need to review the specific literature on the object of study and any other scale already built that attempts to measure the same or similar objects. This procedure is an important source of items for the scale.
- *Previous interview*: This is another common stage to all surveys, namely, questionnaires or scales of attitude. Interviews can be either individual or group but should be focused on the object of our research and the attitudes expressed toward it. The interview can be conducted with any person deemed representative of the population being studied. A good way to do this is to consider some of the variables, which are then analyzed. However, we have little interest in interviews at this stage because they involve excessive work and a great loss of time.
- *The investigator's intuition*: Although the previous two stages are very useful, we should not ignore the role of intuition in building the scale and constructing the items. No items are intrinsically good or bad. For this scale, the responses must be favorable or unfavorable, always nonneutral. Although it is not strictly necessary, half of the items should be favorable and the other half unfavorable.

7.9.2.3 Selection of Items from Previous List

The selection of items has to take into account the linguistic and grammatical characteristics of the items, their logical structure, and their general characteristics.

The construction of the items should meet the following requirements:

- All statements should have some relationship with the object of study.
- Views should reflect the present attitude of the subject and not past attitudes. Statements must be expressed in the present tense.
- Assertions with a double meaning are ambiguous; each statement must express a single idea.
- Statements applicable to limited groups of people should be avoided.
- Chosen items do not have to be answered in the same way by subjects who have a positive attitude and subjects with an unfavorable attitude.
- Assertions must not have related concepts causing confusion.
- Certain vocabulary should be avoided unless it serves a particular purpose.
- To avoid phrases that may be interpreted as facts, each proposition should be debatable.
- Assertions with which the majority would agree (or disagree) should be avoided.
- Language must be clear, simple, and direct.
- Sentences should be short.
- Words that imply universality should be avoided (all, always, none, ever, etc.).
- Sentences should use adverbs with care (simply, usually, etc.).
- Sentences should be simple, without dependent clauses.
- Complex negative forms should be avoided (e.g., sentences with double negation).

- Each proposition should have only one possible interpretation.
- Each statement must allow responses throughout the range of intensity of the attitude measure.

7.9.2.4 Determine Items/Categories

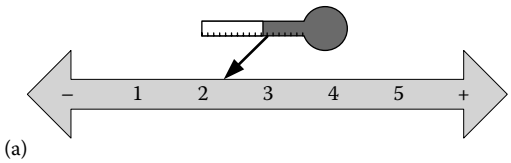
Each statement is followed by an estimate scale (rating scale) that consists of a graduation from "strongly agree" to "strongly disagree" and includes intermediate grades. It should be noted that, while Turnstone's scale asks subjects to respond to only those items they consider relevant, in a Likert-type scale the subjects must express their opinion on all items

The forms to submit the graduation are varied:

A. The estimate scale includes a numerical value assigned to each gradual interval.

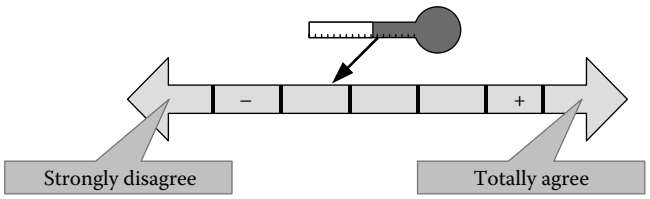
Score	Assessment
–2	Strongly disagree
–1	Disagree
0	Indifferent or neutral
1	Agree
2	Totally agree

Or, with another numerical assignment



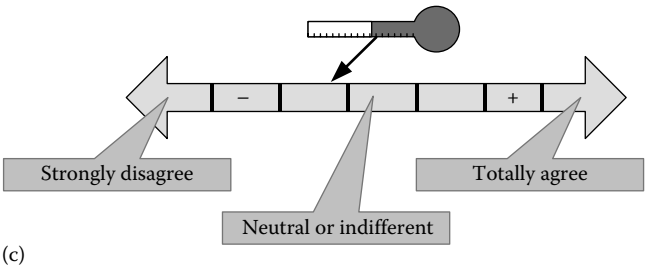
(a)

B. A statement is followed by an evaluation scale that indicates the meaning of the intervals and how responses should be noted.



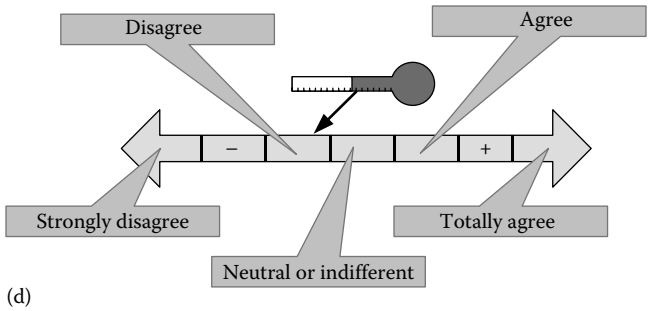
(b)

Or



(c)

Or finally



(d)

C. The scale gives respondents letters or numbers indicating meaning and how to respond.

Score	Assessment
A	Totally agree
B	Agree
C	Indifferent or neutral
D	Disagree
E	Strongly disagree

A Likert scale has many varieties; this, in principle, does not affect the results if the scale retains its philosophy. The cumulative gradation of the intervals must not be altered. It is common to have assessment scales with six or seven intervals, but the standard is five, with widespread agreement not to pass seven. It is very usual to encrypt this gradation from 1 to 5, where 1 means total agreement and 5 total disagreement.

We must bear in mind, however, whether the item is rated as favorable or unfavorable. We must assign inverse scores to the unfavorable items. An entirely unfavorable response to the first item should be assimilated with a completely unfavorable response in the second.

We usually give negative scores to unfavorable items in the categories.

In this case, the questionnaires' evaluation of the measurement system includes five levels, from 1 to 5, where 1 is the most unfavorable and 5 is most positive.

It is important to mention that the auditor will not follow up on all allegations made in the survey. For example, the auditor will not check the years of technological expertise of each supplier or the certification, even though these are essential indicators in the maintenance management associated with a contract. However, we can request a random check of the certificate of one supplier or the safety manuals associated with certain work.

Each item is scored according to the formula shown in Table 7.1.

7.9.2.5 Pilot Test of Scale

This stage will provide the information necessary to decide which items can stay in the scale and which cannot. An overall score will be obtained for each subject in the pilot test. This overall score enables us to estimate the position the subject holds in the hypothetical continuum of attitude.

TABLE 7.1

Likert Scale Evaluations Depending on the Score

Score	Assessment
5	Defines an optimal situation. The maximum degree assumed that 100% of the time the activity is performed as defined in the question referred.
4	Defines a good situation but with caveats. Most of the time it acts as the question raised, but sometimes voluntarily or involuntarily it is obviated.
3	Average situation. Compliance with the question is random. We can find similar rates of compliance and noncompliance.
2	Poor situation. Almost never complies with the statement made.
1	The statement made is never satisfied. Ignorance, not being implemented the system, or voluntarily on any occasion is performed as indicated.

7.9.3 Analysis of Items

A person with a very favorable attitude toward the object should have a high probability of giving a large number of favorable responses. By the same token, a person who has given many favorable responses has a high probability of having a positive attitude. The number of favorable responses, or possibly a complex mixture, will, therefore, be a good indicator of the attitude. For an item to be accepted in the final scale, analysis should show that its acceptance or rejection is related to the position of each particular subject in the attitudinal continuum. That is, it should be consistent.

Those items receiving favorable responses by individuals who are part of a group that does not respond to the majority of the other items in a favorable manner (or vice versa) are discarded.

In other words, we want to validate the significance of an item by establishing the relationship between the basic answers that have been given and the corresponding global ones. The global answers validate the basic ones.

7.9.4 Likert Scale: Disadvantages

The main disadvantages of a Likert scale are the following:

1. Many studies indicate Likert scales have a bias if we can see the distribution of frequencies and approvals outweigh the disapprovals. In this case, the expressions of agreement/disagreement are not equidistant.
2. It has been verified empirically that to "agree" with any phrase of the Likert battery implies lower mental effort by the respondent. The neutral response "neither agree nor disagree," which is the central position of the scale, is associated with "moderate agreement," and not with the response "undecided" (as many believe). Many respondents perceive that declaring themselves "undecided" is negative; therefore, they tend to move closer to positions of agreement.
3. An ordinal scale does not allow knowing with precision the "quantity" of agreement or disagreement. This prevents adding internal values because ordinal numbers cannot be used. This is often misdiagnosed; it causes distortion because it adds the natural numbers to get five degrees of agreement/disagreement and assigns a total score that expresses a (presumed) state.

4. The Likert scale has a problem understanding the respondent's evaluation: an assertion may be disapproved for various reasons, so an open question should be included to determine the causes. Generally, to reduce costs of research, we assign the same scores to two different opinions, but these may be in opposition.
5. In general, respondents tend to react to a single term of the sentence. This phenomenon has been named "the object reaction."
6. Finally, we tend to reduce the fidelity/level of confidence of the answers when we arrange phrases in long groups (e.g., one below the other). This applies not only to the Likert scale but also to other techniques. To avoid this, opposite statements should be inserted in the same group.

7.10 Conclusion

The proposed model is a multidimensional integration of a series of uncontrolled aspects in the maintenance function and has been analyzed in isolation. Many factors have been considered in the proposed model of the maintenance function, including methodological tools and technologies used in other business areas but not implemented in the management of assets.

The model offers the following:

- It integrates qualitative aspects of attitudinal surveys with diverse quantifiable indicators whose fidelity lies in the nature of the data exploitation.
- It refers to the maintenance metric at different organizational levels as vertical, with each level being horizontal. This defines who owns the indicator, who brings the information, who calculates it, and who uses it.
- It proposes a way to make calculations and obtain results by evaluating the organization in accordance with its goals.
- The system is modular and progressive in that it displays the level of development achieved in the maintenance of the company.
- Finally, the audit uses a hierarchical distribution indicator, organized according to the BSC perspective. Actors in the maintenance function include customers, finances, and processes. Indicators are relocated in the BSC to give a clear measure of the degree of development and satisfaction of each perspective and the affected stakeholders.

8

Audit Model Application and Scorecard in Companies: Results and Conclusions

8.1 Introduction

This chapter discusses the tests performed with the proposed model and compares them to the results of classical models. It considers whether the proposed methodology solves problems in measuring the performance of maintenance. The scorecard model and subsequent audit were tested in three companies with very different caseloads where the maintenance function must meet divergent demands. The aim was to test the approach in companies whose vision and mission of maintenance differed. The three companies are categorized by sector:

- A paper manufacturer (continuous production)
- A newspaper press (rotary process, i.e., noncontinuous)
- A city of 700,000 (water pipelines)

8.2 Mission and Vision of Companies: Level 0

Before starting an audit, it is essential to know the vision and mission of a company, especially the conceptions of the management teams about maintenance. It is necessary to know exactly what role maintenance plays in the achievement and scope of the mission and vision of the company (Figure 8.1). Is maintenance seen as a strategic factor or a necessary evil?

8.2.1 Department Role in Organizations Audited

Broadly speaking, the differences between the three companies can be explained as the following. First a company manufacturing paper prioritizes continuous processes (i.e., nonstoppage of production). Second, a newspaper press uses noncontinuous processes (i.e., at certain time intervals). Finally, the city must ensure and maximize the availability of water service to citizens (i.e., intermittent).

Clearly, the direction of each company will value certain maintenance factors over others. It is necessary to know what is expected of the department before measuring success.

It is important at this stage that the auditor does not prejudge whether the vision mission that has been transferred to the maintenance department is correct. The audit should simply assess whether the function is aligned with organizational goals.

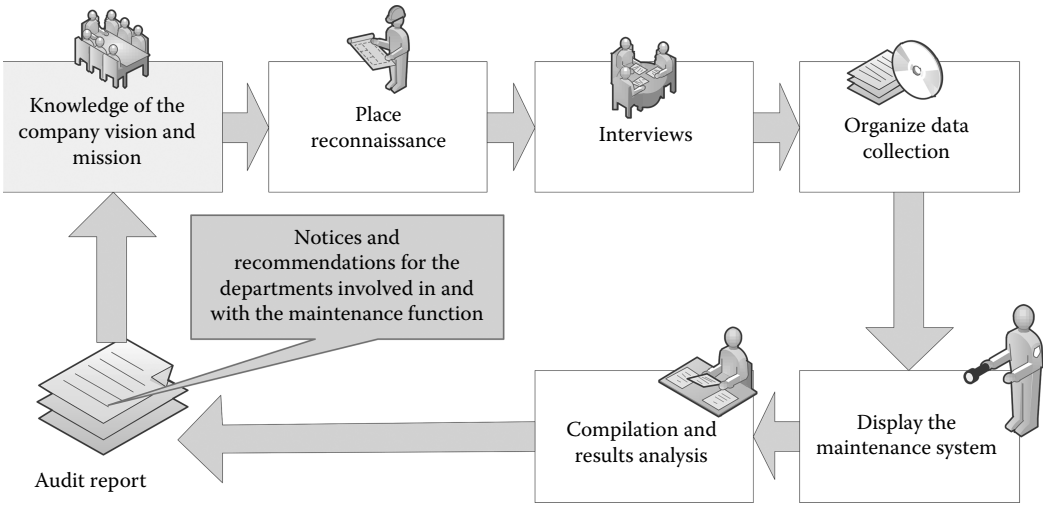


FIGURE 8.1
Knowledge phases of company mission and vision.

In the case of the city, the utilities department maintains several hundred kilometers of pipelines; these are buried under sidewalks and streets at different depths. The ages of the pipes vary from 1900 to the present. In theory, a policy of preventive or routine maintenance should allow maintenance workers to check and/or replace the pipes. Parallel resources should be allocated to repair faults as they arise. Yet, these policies are meaningless because of the high cost of access to pipelines and the uncertainty that other actions may cause breaks in the pipes. This is coupled with the decline of water supply service to residents affected by preventive inspections or scheduled substitutions, in addition to road closures arising from interventions.

In short, it is important not to prejudge what is expected of departments. In the case of the city's water policy, evaluating or auditing incorrectly, that is, without considering what is expected of the department, might lead auditors to think that a lack of preventive maintenance and appropriate programming indicate bad management when, in fact, this is not so. The first step of an audit is to define how the objectives of a maintenance department are aligned with those of the organization.

8.2.2 Company Structure

Once it is clear what the organization expects from the maintenance department and following the model of auditing, we can determine how the relationships between the different elements of the organization actually work. These relationships will affect the reliability of the data obtained in the measurement of performance.

Organizational flowcharts are useful to situate the maintenance department within the company, to establish hierarchical relationships and note what figures are of more or less weight. These dependencies will establish the basis for policies on purchasing, interventions, and so on.

Careful observation of the chart allows us to see the allocation of roles at different hierarchical levels. We can draw conclusions about the company and gather information necessary for the measurement process (Figure 8.2).

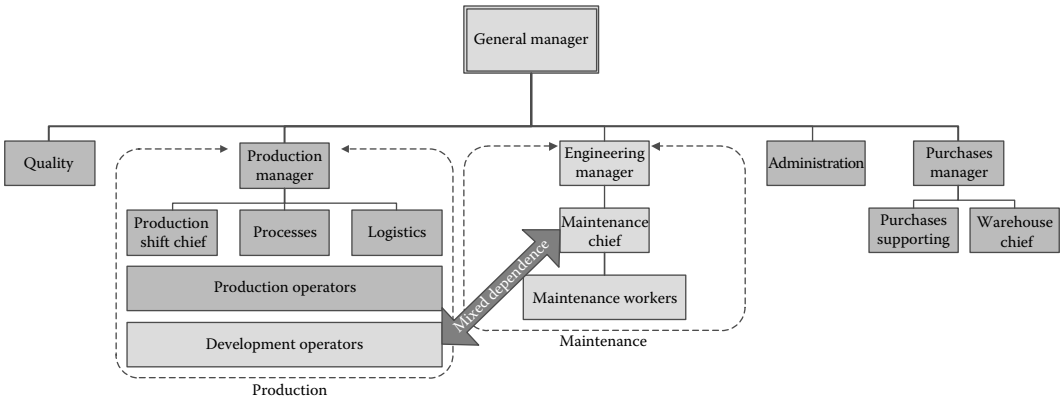


FIGURE 8.2
Flowchart of newspaper press using rotating processes.

The organizational chart in the previous figure corresponds to a traditional structure in which the head of maintenance occupies level 3. In this case, higher levels are assigned to the production manager and his immediate superior, the director of engineering. The existence of an engineering director at the management level and placing production over maintenance suggests precision machinery, high technology of high value where knowledge and maintenance are values in themselves. The commitment of the company to technological innovation stems from a need for effectiveness and productive efficiency.

However, this structure puts the head of maintenance hierarchically lower than production manager, without direct dialogue with the general direction of the company. This will be reflected in a possible loss of authority, with higher production criteria leading to marginal maintenance.

Level 1 corresponds with the CEO. Level 2 is not occupied by an operations manager or plant manager; rather, this responsibility is shared by the director of engineering (head of assets) and production manager (head of the function for which the plant is intended). Level 3 corresponds with the chief of maintenance, making the hierarchy asymmetrical.

Under the head of maintenance, the structure is minimal, with a middle manager at level 4 and the corresponding operators at level 5. Due to the reliability of the facilities and existence of redundant equipment, the maintenance staff is reduced and operators tune the equipment. These operators belong to production but make small adjustments, for example, cleaning, substitutions of certain elements, and even small takedowns in accordance with the maintenance function. At first glance, we see the integration of production and maintenance in a policy of total productive maintenance.

The audit model must fit the structures and reflect the channels of power and decision-making. In the case of the press, given the small size of the structure of maintenance, that is, 8 or 9 people, the roles are slightly offset. Thus, for example, the maintenance manager plans warehouse supplies, assuming the role of middle management at level 4 as stated in the audit model. He is a supervisor but does not make decisions on how to develop maintenance programs, either planned or unplanned.

8.2.3 Visit to the Company

Once the mission and vision is known, as well as what the organization expects of maintenance and who comprises maintenance, we must visit the facilities (Figure 8.3). Despite

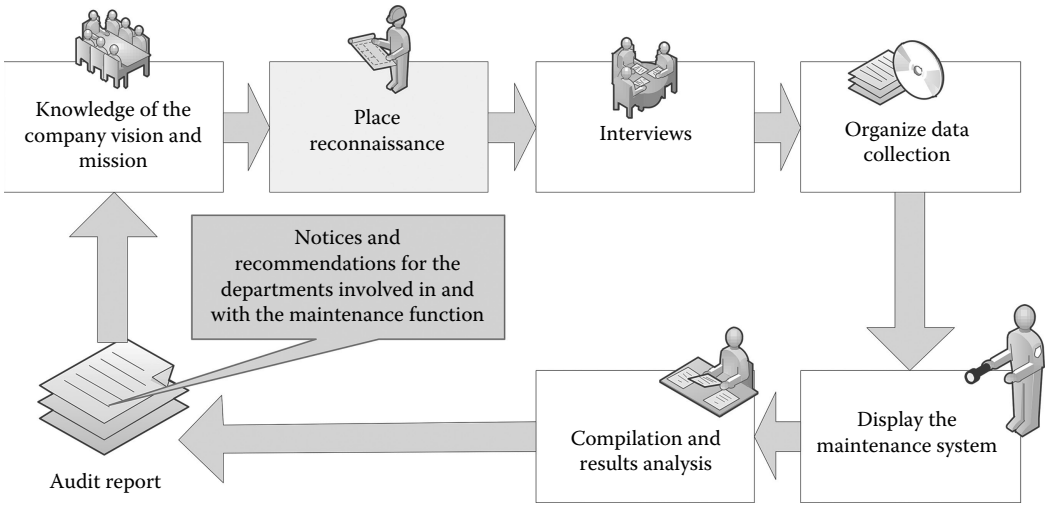


FIGURE 8.3
Reconnaissance phase.

having all the numerical data and access to individuals to be interviewed, valuable information is obtained from visits and seemingly inconsequential comments made during the visits. With these visits, we can position the department within the plant and observe the distribution of offices, documentation flow, warmth in relations, computer equipment, condition and cleanliness of workshops and warehouses, and the everyday discourse of workers performing tasks, etc.

In these preliminary visits, usually the audit process is not yet known, so we can observe attitudes and facilities without influencing the later audit system. In the case of the rotating schedule at the press, because of the nonexistence of administrative staff linked to maintenance, the department head enters all data into the system, directly manages the warehouse, and devotes much of his time to administration, not management.

The paper industry and the city's utilities department have higher administrative support in planning, contracting, and procuring maintenance. In these centers, a strong middle-management team under the head of maintenance executes the strategy set in level 3. In other words, there is a well-developed level 4.

Another relevant aspect is the spare parts warehouse where all three companies have features to consider for proper analysis of associated indicators. The city's utilities department has little criticality in spare parts because the pipe sections are economical, have high availability, and are large; they can be accessed through suppliers and contracts quickly and at a good price. In addition, stocking such large products requires large well-staffed stores able to transport large volumes with adequate logistics.

The other two companies have radically different warehouse systems. The paper industry uses outsourced spare parts, seeking to optimize the availability of parts and associated costs through the company's purchasing department. The plant uses complex machinery, with costly, foreign-made components. This generates a plant of great economic value and low turnover. In addition, spare parts take years to be used; thus, stocked spares may be out of date before they are required. Purchasing decisions are not made by the maintenance department; the department simply looks for the most appropriate providers when required.

The press has a warehouse managed by the head of maintenance. The spare parts information is entered into the CMMS.

8.2.4 Level 0 or Management Commitment

Level 0 is associated with management commitment to and knowledge of the maintenance function. It has a dual perspective. First, surveys of knowledge of the maintenance function and performance are conducted among senior management; second, macro values are extracted with respect to availability, quality, and/or budgets. Although these macro values are segmented and divided, this level provides information on the budget of the department, the amount of product rejection, uptime, and availability. From this, we can establish a functional reference framework for the production model and logistical support of maintenance (Figure 8.4).

As a result of this analysis, we can obtain the context in which the maintenance function is developed, observing its relations with those making decisions and noting the opinions of the company directors.

The structure in which we are conducting the surveys covered by level 0 is shown in Figure 8.5.

Answers to the questionnaires use the five-point Likert scale, with 1 being most negative and 5 most positive. In our evaluations, we must remember that respondents tend toward positive answers or at least "nonnegative" ones. The surveys presented later on show management understanding of and commitment to maintenance; note that responses from production managers are included (Table 8.1).

Level 0 surveys conducted among top managers involved in the maintenance function create an initial scenario of the current situation of the department and the organizational support available for development. Equally important is the first impression of the function performed by maintenance and its influence on the company.

Figure 8.6 shows the surveys given to level 1, level 2, and level 3 managers in the press. As seen in the flowchart, a director of engineering is above both the production manager and the maintenance manager, and the production manager is above the maintenance department. The general manager is at the head of the company.

The results lead to some quick conclusions to address the audit process. None of the responses is below 3, so there is some degree of overlap and correlation between the

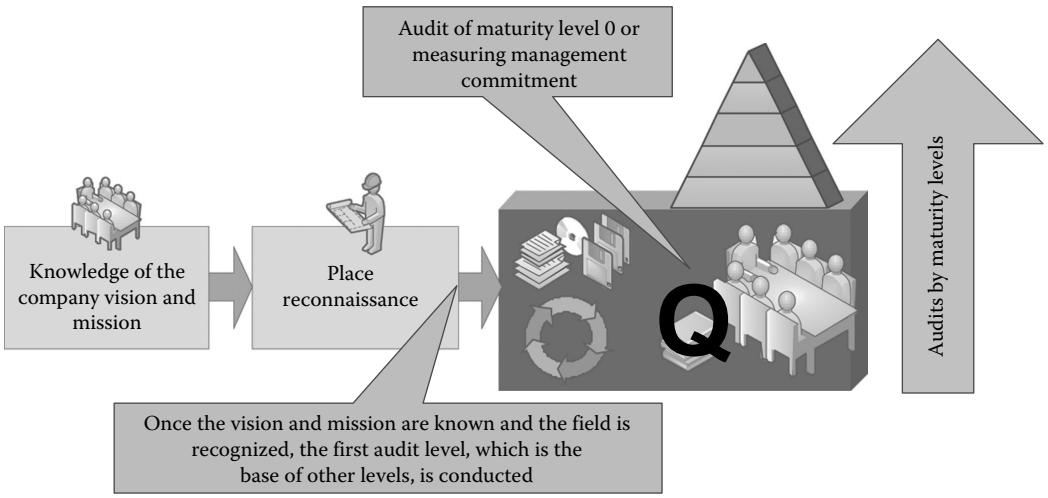


FIGURE 8.4
Conducting the audit of level 0.

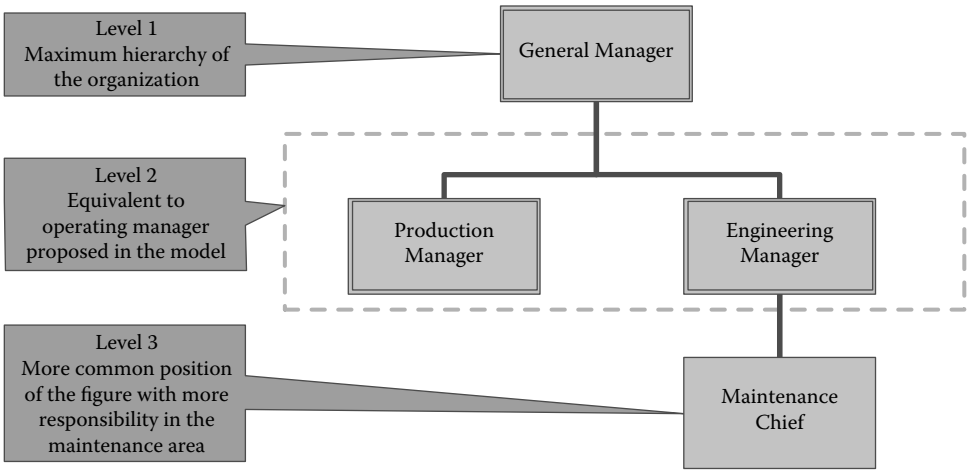


FIGURE 8.5
Levels 1, 2, and 3 of the newspaper press.

TABLE 8.1

Management Commitment Surveys for the Press

	Management Commitment to Maintenance Function			
Answer Number	**Level 1 General Manager**	**Level 2 Engineering Manager**	**Level 2 Production Manager**	**Level 3 Maintenance Chief**
1	5	5	5	5
2	5	5	3	4
3	5	5	3	5
4	5	5	5	5
5	4	5	3	4
6	4	4	3	4
7	4	5	3	5
8	3	5	4	4
9	3	5	3	4
10		4	3	5

impressions of the different executives surveyed. Interestingly, production most penalizes the maintenance activity with scores typically around 3, while maintenance has a perception of itself close to 5. The levels agree on the knowledge of site maintenance in the business plan of the company (i.e., knowledge of the vision/mission of the department) and the present maintenance structure.

The most severe differences arise when respondents are questioned about the existence of metrics for maintenance and performance measurement of the department; these are partially unknown or do not agree with the production direction. As is common in organizations, there is no culture of performance measurement. This suggests difficulty in collecting data as production areas are not used to measuring performance. Problematically, values obtained from the indicator of commitment to maintenance reveal extremely low commitment in production, principal client of the maintenance function (Figure 8.7 and Table 8.2).

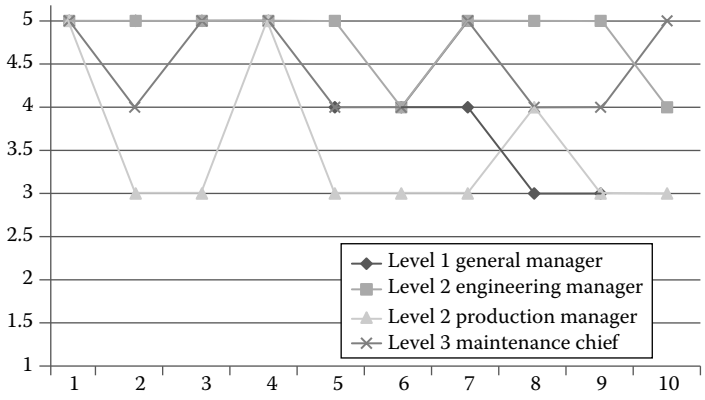


FIGURE 8.6
Level 0 surveys in the press.

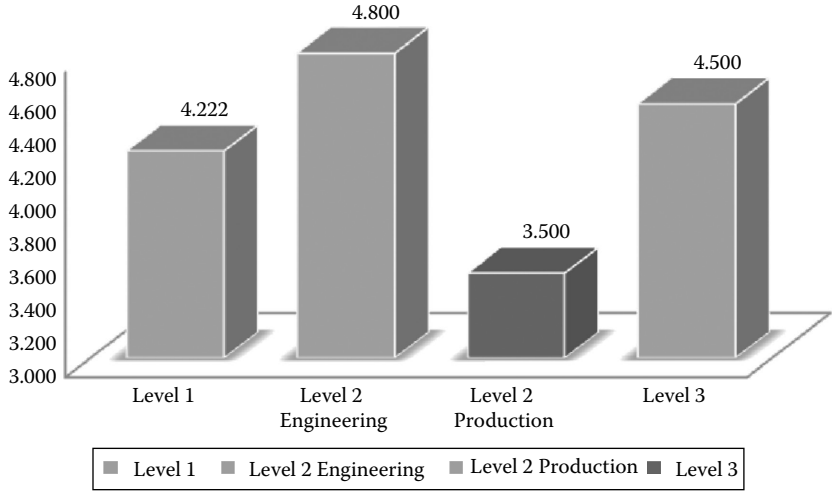


FIGURE 8.7
Management commitment indicators based on surveys: level 0.

TABLE 8.2
MAINTCOMPI Indicator Hierarchy

MAINCOMPI	**Management Commitment to and Knowledge of Maintenance**	
	Level 1	4.222
	Level 2 Engineering	4.800
	Level 2 Production	3.500
	Level 3	4.500
MANCOMPI Average		**4.256**

The indicators that should be analyzed at this level correspond to large production figures, quality, and finance related to maintenance.
The first indicator available for the press is the EI1, expressed as

$$\text{EI1} = \frac{\text{Total maintenance costs}}{\text{Assets replacement value}}$$

That is, the relationship between the maintenance costs and the value of asset replacement. We derive a value of 1.72%. This indicator is slightly low but close to Weber and Thomas's [331] scales relating to world-class levels (between 2% and 3%).

It is important to note that the press does not calculate production rates mixed with maintenance; hence, we see a low correlation between surveys of its directors and those of other respondents. Maintenance is not working with EI3 data on maintenance costs of each unit produced or reductions in these unit costs resulting from the various improvements implemented. Nonetheless, we can calculate the EI3 indicator as follows:

$$\text{EI3} = \frac{\text{Total maintenance costs}}{\text{Quantity produced}}$$

This indicator turns out to be €0.005 (i.e., 0.5 US cents) per unit produced, representing an increase over the previous year when it was €0.00043 (0.43 cents US) per manufactured unit. We might initially think this represents an abnormal increase in maintenance costs; however, a reduction in the quantity of units produced has generated the rather stable maintenance costs with an increase for each unit. This is a typical example of indicator that requires exchanging information between two departments and whose rapid and out-of-context reading can be confusing.

To avoid the dissociation of indicators that combine maintenance and production information, we might opt for the OEE, a blend of indicators of the two business areas, if this option is viable. Exploiting historic data can provide an approximate calculation of the benchmark. The OEE is expressed as

$$\text{OEE} = \text{OEEI}\,1 \times \text{OEEI}\,2 \times \text{OEEI}\,3$$

where
OEE1 is availability
OEE2 is performance efficiency
OEE3 is quality

The calculation of each is the following:

$$\text{OEEI}\,1 = \text{Availability} = \frac{\text{Total activity time}}{\text{Programmed time}}$$

Availability (OEE1) is very high because there are very few stops due to breakdown or unavailability, lack of raw material, etc. Stoppages hover around an average of

6 min/month compared to a production of 8192 min/month, which supposes availability around 99.92%.

$$\text{OEEI 2} = \text{Performance efficiency} = \frac{\text{Actual production for the programmed time}}{\text{Planned production for the programmed time}}$$

Performance efficiency (OEEI2) is around 90.35% because it requires about 5% more productive hours to meet the requirements specified in the planning.

$$\text{OEEI 3} = \text{Quality rate} = \frac{\text{Total production} - \text{Defects}}{\text{Total production}}$$

The quality rate (OEEI3) indicator reaches 93.5%, very close to previous years, with slight variations of 4% or 5% on the rate of quality, moving the OEEI indicator (availability) to 93%–94%.

These three indicators create an OEE around 83.8% very close to the minimum threshold of 85% set by world-class indices. It is configured as an indicator of overall effectiveness but has never been calculated as performance metrics or as a tool for making assessments. Other indices considered at level 0 are unavailability expressed as TI1 and TI2:

$$\text{TI 1} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Maintenance unavailability time}}$$

$$\text{TI 2} = \frac{\text{Availability time achieved during the required time}}{\text{Required time}}$$

Both TI1 and TI2 are at values higher than 95%, that is, within the most stringent thresholds of SMRP, EFNMS, and world-class standards. Therefore, the unavailability figures are difficult to improve for the press.

We can conclude that the press has adequate macro indicators budgeted correctly with overall effectiveness and good availability based on the policy of allowing production to intervene in the machines during scarce production intervals. These indicators were achieved without the use of metrics, a fact reflected in the surveys, so reduction targets are set as

$$\text{TPMI 5} = \text{Decrease the unit production cost}$$

This indicator, TPMI5 represents a "key factor" for many maintenance managers; they observe the effectiveness of their actions in the final cost per unit produced.

A culture of objectives based on mixed indicators is implanted in the paper industry with its continuous production processes, with the EI3 set around €8 maintenance cost per ton produced of paper. The direction of maintenance strictly observes the reductions resulting from the various actions performed.

These indicators are not calculated in the city's utilities department either. Here, exploitation or production with respect to supply is disconnected from the repair of assets; this ignores the amount of maintenance that goes into each liter of water served to the public.

To sum up, it useful to begin by observing the flowchart of a company and perform an audit survey in the lower levels. In the case of the press and its rotating schedule, this preliminary information reveals an ignorance of macro indicators, especially those integrating production data and quality data. This lack of knowledge is indicated in the management surveys. In other words, there is no policy with clear objectives for the maintenance function.

This first basic level yields information relevant to the subsequent audit. A first impression of maintenance management, particularly management's knowledge of the metrics associated with this function, tells us a great deal. We learn, for example, if maintenance is actually integrated into the company strategy through fast access to the indicators proposed for level 0. The absence of indicators such as OEE in everyday use and unfamiliarity with their use suggests the need to include communication and awareness of metrics in the resulting reports of the current process.

8.3 Audit Level *n*: Study Case, Level 1 of Evolution

8.3.1 Obtaining Data at Different Levels

Once we have surveyed the management team and perceived the team's views of the metric of maintenance and its role within the organization and determined the ease of obtaining data, we can start the audit process with the completion of surveys and collection of data necessary to prepare indicators (Figure 8.8).

Some data, especially at lower levels, are easy to obtain directly from the CMMS. The most easily removable data are those relating to the effectiveness of the system, including records of the working parts and the cost of production. It will be more difficult to extract parameters for efficiency.

The full audit of level 1 for the paper industry is presented later. In level 1, we look for planning and scheduling of work, or the existence of a culture of preventive maintenance

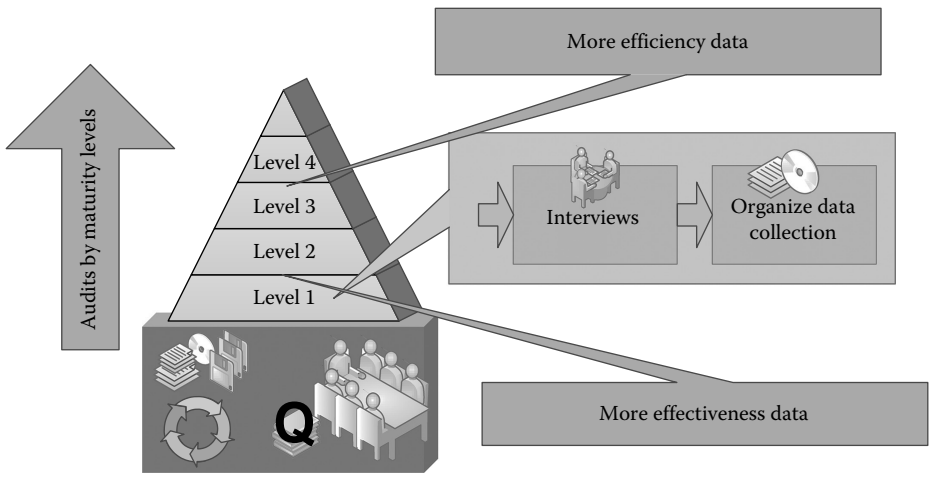


FIGURE 8.8
Audit process, once past level 0.

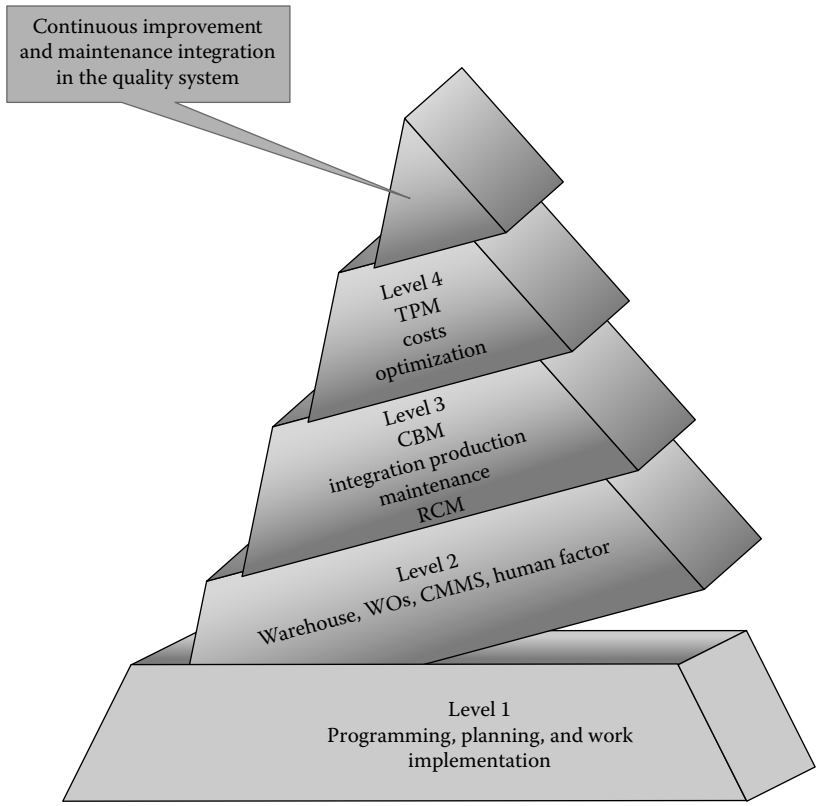


FIGURE 8.9
Level 1 of maintenance evolution: preventive maintenance.

rather than corrective maintenance. Commitment to efficient planning and scheduling allows the company to move to the next phase. Few companies reach higher levels, however. Sometimes, they have not opted for the implementation of certain methodologies or have not extended them to their customers. Sometimes, they rely on RCM, TPM, or CBM, even though data indicators show contradictory results in the effectiveness versus efficiency of these methodologies. Finally, companies frequently use methodologies and technologies simply because they are found useful in other companies (Figure 8.9).

8.3.2 Audit of Evolutionary Level of Maintenance

For the audit of level 1, we use the following sources of information:

- Surveys of hierarchical levels
- WOs extracted from CMMS
- Financial and human resources data extracted from ERP

The audit process is shown in Figure 8.10. In this case, the maintenance management software is MAXIMUM, a commercial software with wide national and international deployment. The software was implemented in 1998 and in the first 2 years, the guidelines for reliability were established. The extracted and analyzed records consist of more than

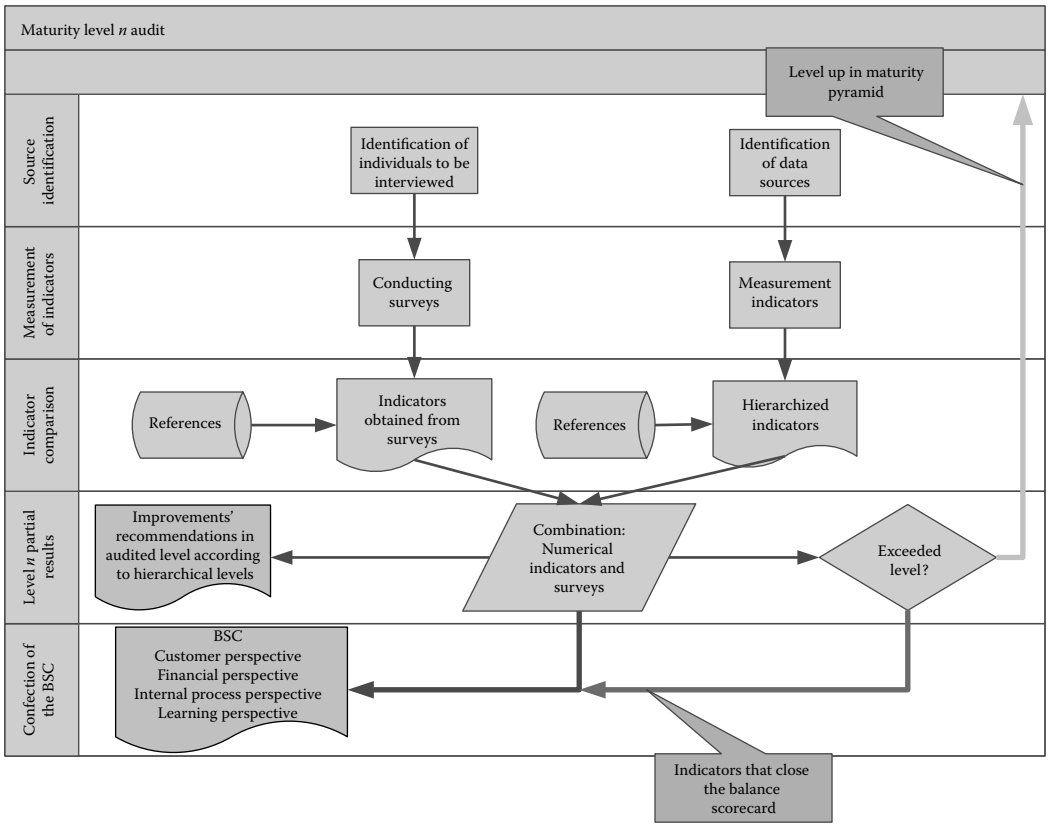


FIGURE 8.10
Audit process.

320,000 work orders (WOs) from 2000 to mid-2009. These data were entered by production and maintenance. From them, we can extract all relevant indicators of the maturity of level 1, except for a few from finance and human resources. The integrated management system that brings together these latter two departments is SAP; it is not connected to CMMS, so data must be removed manually.

Once we have the data, we can prepare the indicators, but this takes time. Data on machine downtime, hours spent, forecasts, actual hours, etc. must be filtered from the records. Access to data and procedures to extract the proposed indicators can be expensive depending on the available storage and processing capacity. At this time, we conduct surveys of certain levels, in this case, levels 3, 4, and 5. The maintenance manager is on level 3; level 4 has two controllers, and level 5 has three mechanical department officials.

The surveys and proposed indicators must be compared with international standards and manufacturers' suggested maximum or minimum acceptable limits. The surveys must be analyzed and the averages calculated per profile. We also need to note discrepancies.

By comparing these indicators with their references and combining them with the results of the surveys for validation, we can derive a framework of standards indicating pass or fail for the factors we are auditing. We can also make recommendations based on the deficiencies.

A level should have a number of indicators within the permissible references, and there should be coherence between these values and the results of the surveys conducted at

different hierarchical levels. A level is successfully completed when the evolution of the indicators is clearly converging toward permissible values, provided the surveys also show elevated values indicating genuine commitment and knowledge on that level.

Finally, the indicators move to the balanced scorecard. The indicators are associated with different strategies to comply with the predetermined objectives. All targets are classified according to the four perspectives mentioned before and the aim is to improve how they are perceived by their respective users. In the event that the indicator is positive, that is, inside the marked reference values or its trend is clearly and unequivocally converging toward these values, we can conclude the strategy related to that measure is fulfilled and the target is met. When this indicator is negative, we can conclude there has been a partial failure of the strategy with which it is associated. If all or most indicators of a strategy are within the allowed values, we can conclude the strategy has been successful, with some nonconformities associated with negative indicators. If there are several negative indicators, however, the strategy has clearly failed, with a consequent negative impact on the objective and vision.

Once these indicators are transferred to the scorecard, they are related to the strategies; a company passes to the next level of developmental maturity, if the audited level has no significant problems in this respect.

If the indicators are transferred to the scorecard and a negative contribution of these different perspectives is revealed, the audit process is stopped. It is meaningless to build levels based on a poorly implemented or nonexistent strategy.

The scorecard scenario has a third possible aspect: along with positive or successful indicators and negative or failed indicators, there may be neutral or missing indicators. This simply means the company never considered addressing the strategies associated with the underlying objectives. The absence of these indicators on the scorecard does not imply a failure in the strategies; the company simply did not take them into consideration to achieve certain goals depending on them.

As discussed in the previous chapter, performing a complete audit of all indicators will detect the levels of immaturity. Respondents may enter consistently negative values, with responses revealing ignorance or inaction; or they may simply dread an audit of any kind. If the audit is detained at level n, this does not imply negative aspects of the audited maintenance model. Some perspectives are simply developed more than others in different organizations. The vision and mission of the company changes at times or is modified. At times, productive capacity may be required or financial and customer perspectives may be developed over others. When the company undertakes a comprehensive plan of quality and process improvement, the internal process perspective is developed; the learning and growth perspective is developed when the company perceives the importance of human capital. These developments relate to different time stages and are associated with different points of maturity of the maintenance function.

8.3.3 Surveys Level 1: Implementation and Validation

As discussed, the traditional audit models of maintenance collect aspects through surveys and in-depth interviews. The methods proposed by authors like Tavares or standards such as Venezuelan COVENIN advocate for measuring maintenance performance through surveys of different aspects related to maintenance function.

The model proposed here considers the information collected from those involved in the maintenance function to be important. But this is validated by numerical indicators and targets that consider the human factor in the survey.

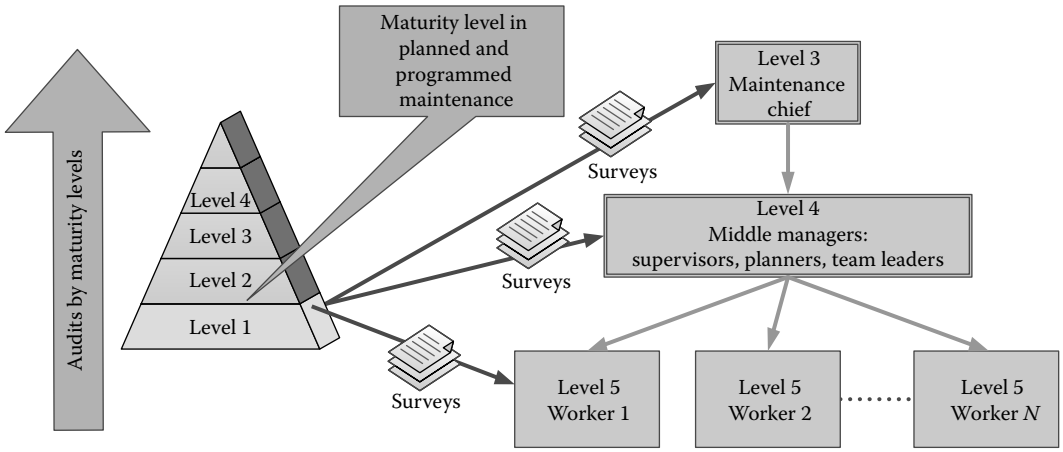


FIGURE 8.11
Audit level 1: surveys of stakeholders.

Later, the surveys of the paper and the newspaper press industries are presented to show the different results obtained by the traditional method and the method proposed here. At this level, indicators drawn from surveys and further validation come from levels 3, 4, and 5 as seen in Figure 8.11; these levels are selected because the director of maintenance and middle managers or planners are more interested in such indicators.

8.3.3.1 Survey: Job Scheduling: The WORKPLANI Indicator

Figure 8.12 shows the answers of the three groups of respondents at this level: the head of maintenance, managers, and technical officers. Two surveys are given to middle managers and three officers; Figure 8.12 indicates the average values by level (Table 8.3).

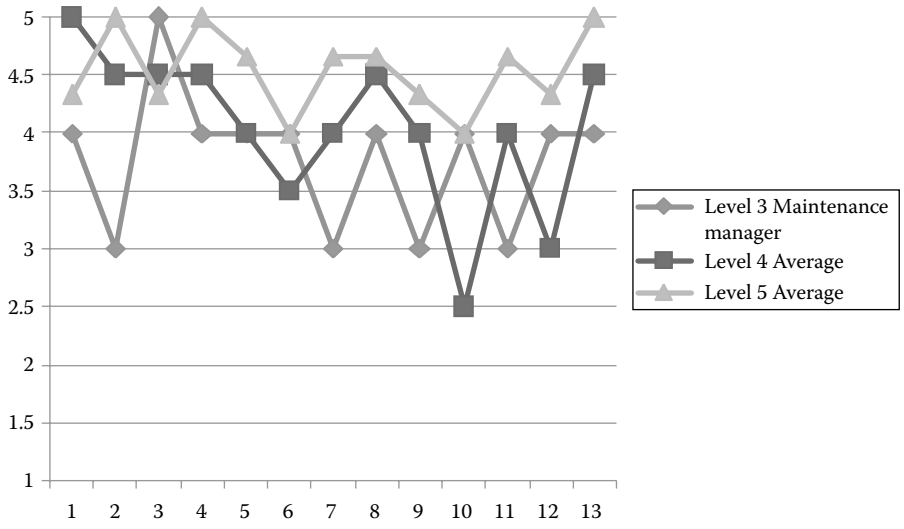


FIGURE 8.12
Work planning survey results for the paper industry.

TABLE 8.3

Work Planning Survey Results for the Paper Industry

	Work Planning							
	Level 3 Maintenance Manager	**Level 4 Operator 1**	**Level 4 Operator 2**	**Level 4 Average**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**
1	**4**	**5**	**5**	**5**	**4**	**5**	**4**	4.333
2	**3**	**5**	**4**	**4.5**	**5**	**5**	**5**	5.000
3	**5**	**5**	**4**	**4.5**	**5**	**5**	**3**	4.333
4	**4**	**5**	**4**	**4.5**	**5**	**5**	**5**	5.000
5	**4**	**4**	**4**	**4**	**5**	**5**	**4**	4.667
6	**4**	**4**	**3**	**3.5**	**4**	**5**	**3**	4.000
7	**3**	**4**	**4**	**4**	**5**	**5**	**4**	4.667
8	**4**	**5**	**4**	**4.5**	**5**	**5**	**4**	4.667
9	**3**	**4**	**4**	**4**	**4**	**5**	**4**	4.333
10	**4**	**3**	**2**	**2.5**	**4**	**4**	**4**	4.000
11	**3**	**4**	**4**	**4**	**5**	**5**	**4**	4.667
12	**4**	**3**	**3**	**3**	**5**	**5**	**3**	4.333
13	**4**	**5**	**4**	**4.5**	**5**	**5**	**5**	5.000

The results show all values above 3, very close to 4, with one exception (there is one 2). This suggests a positive opinion and uniform perception of the maintenance team as a whole. Responses differ somewhat for those below middle managers or the director of maintenance. This logical effect of the scale used is a trend to positive answers at levels with objections to the audit process, where employees may see it as having a punitive intent. However, there are no large distances between the scores. That is, surveys of the three levels indicate the collective impression is of proper planning; there are areas for improvement but, overall, expectations are met. The subsequent numerical indicators will validate whether the impression given by the surveys is true.

Similarly, we can see the results of the surveys of the hierarchical levels in the newspaper press. In this case, the surveys carried out to maturity level 1 were completed by level 3, the head of maintenance, and by level 4, the maintenance crew chief and middle manager in charge of level 3 and three officers of the department.

The two blocks of surveys are reflected in Figure 8.13.

In the first block on job scheduling, we see the matching response; it indicates ignorance of the bulk of the tasks for the next day as well as a lack of tools and spare parts. This response to a key question alerts us to the possibility of failed planning which should be monitored.

The figures in the following compare the responses on the same level in the two companies. Surveys on the same questions at different levels often differ by only one point; any significant differences reflect weaknesses that will surface in numerical indicators.

At the level of the head of maintenance, Figure 8.14 shows a differential jump in job knowledge; findings for the press suggest poor planning or execution of scheduled jobs.

At the middle-management level, shown in Figure 8.15, the most important difference arises in tools, safety or parts necessary to perform the tasks, that is, details on the type of work and necessary accessories. Logically, this concern arises on the level of planners and team leaders. At the level of officials, as we see in Figure 8.16, respondents at the press are

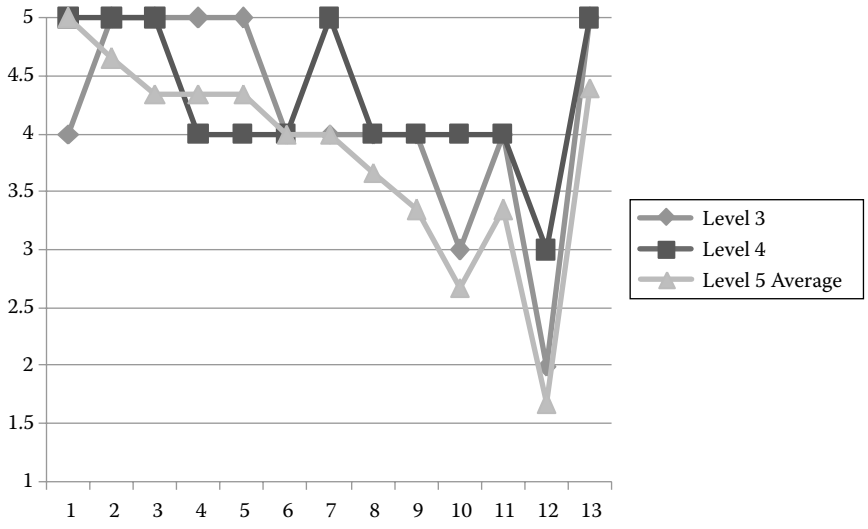


FIGURE 8.13
Maturity level 1 surveys: work planning for newspaper press.

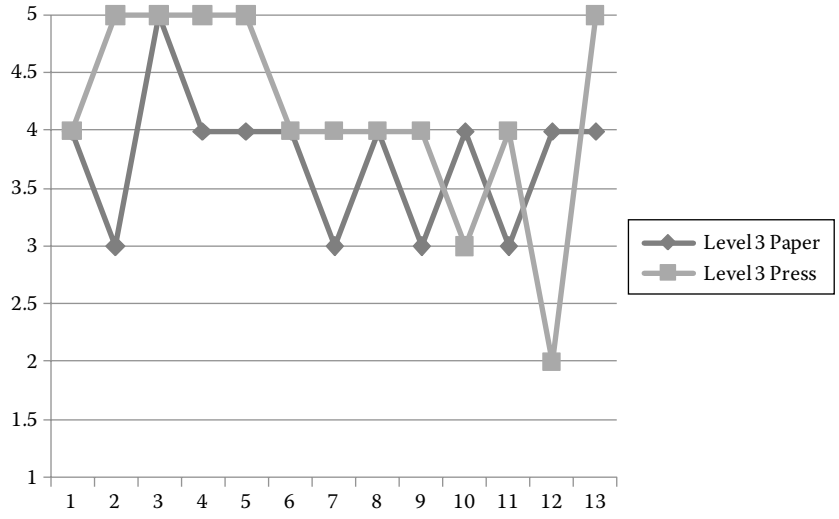


FIGURE 8.14
Work planning surveys: press versus paper industry, hierarchical level 3.

unclear; there is increasing divergence when they are asked about planning and scheduling of maintenance tasks.

The differences lead to concern about scheduling maintenance jobs for the newspaper press, but the concern is tempered by very positive responses in other aspects.

The final values for indicators obtained from the surveys are summarized in Table 8.4.

As the table shows, indicators for work planning obtain high values in three hierarchical levels and in the two audited plants; the asset indicators resulting from these surveys show two values above four, indicating planning is accurate (Figure 8.17).

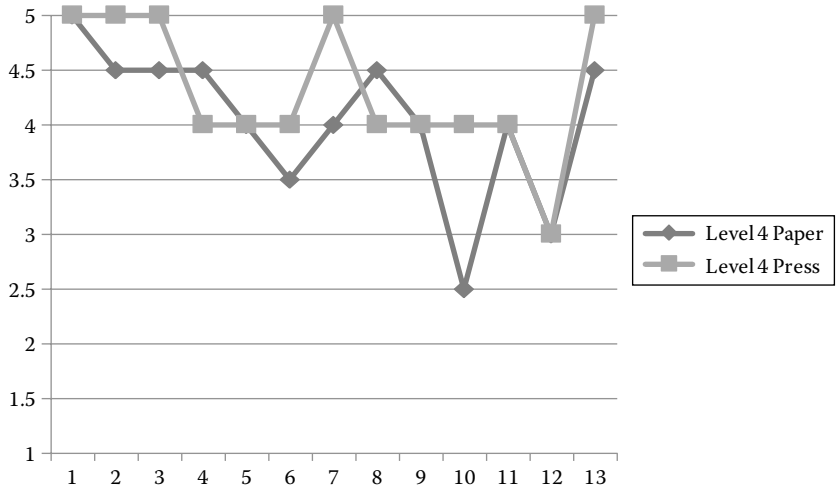


FIGURE 8.15
Work planning surveys: press versus paper industry, hierarchical level 4.

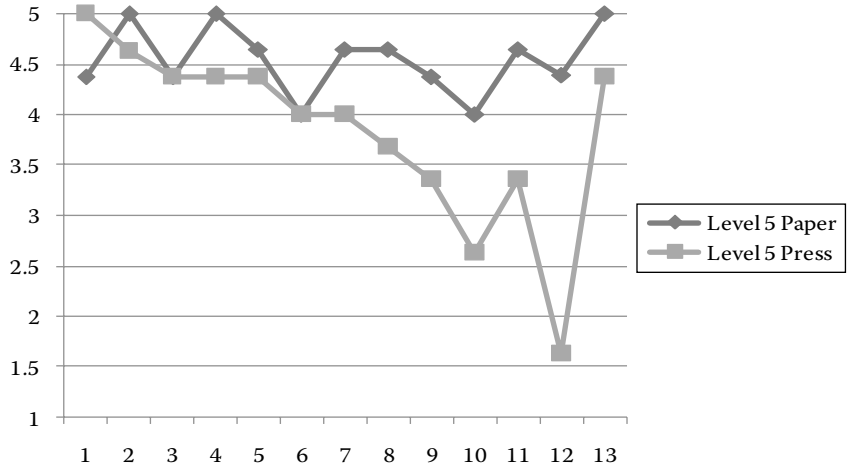


FIGURE 8.16
Work planning surveys: press versus paper industry, hierarchical level 5.

TABLE 8.4

Hierarchical WPLANI of Evaluated Industries

WPLANI Press	Work Planning	WPLANI Paper	Work Planning
Level 3	4.154	Level 3	3.769
Level 4	4.308	Level 4	4.038
Level 5	3.821	Level 5	4.536
WPLANI Average	**4.094**	**WPLANI Average**	**4.115**

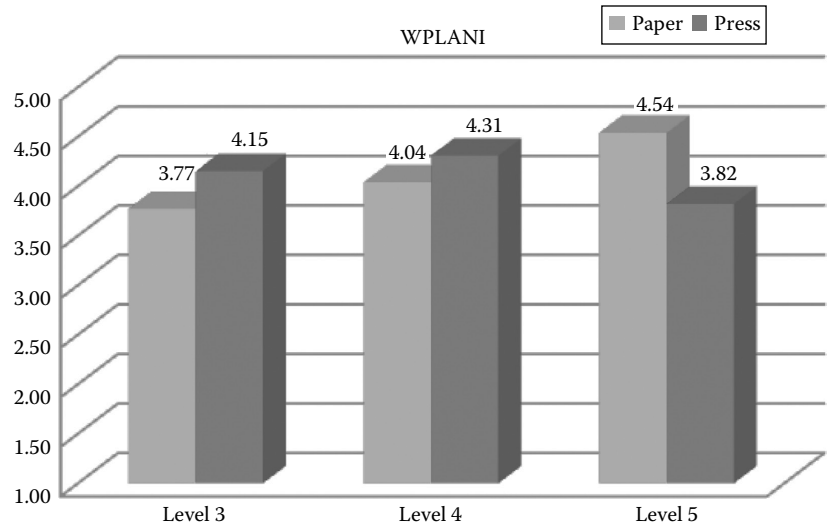


FIGURE 8.17
WPLANI indicator extracted from planning work surveys: press versus paper industry.

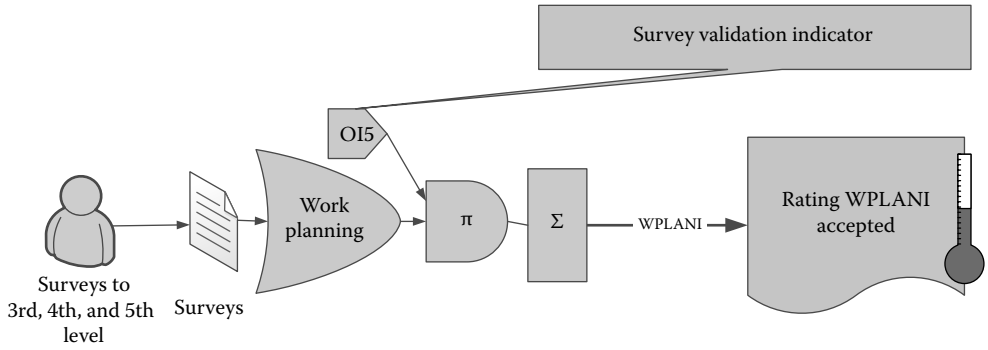


FIGURE 8.18
WPLANI validated with indicators: method of calculation.

These values must be validated by indicators. In the case of surveys on job scheduling, the numerical indicator to verify the accuracy of the impressions the maintenance team is OI5; WPLANI parameter extraction is shown in Figure 8.18 and expressed as

$$\text{OI5} = \text{WOI12} = \frac{\text{Planned and scheduled maintenance man-hours}}{\text{Total number of maintenance man-hours available}}$$

The OI5 indicator represents the volume relative to the total planning. There are many theories about adopting this indicator. The "world-class" perspective suggests around 95% of the maintenance hours should be for planned maintenance; this solves the problem of a possible lack of labor force in emergencies, leading to the overtime hours commonly associated with external companies.

This strategy comes from an aversion to waste because of idle resources and requires comprehensive planning and control, that is, an indicator close to unity. In the past 3 years,

TABLE 8.5

WPLANI Indicator Validated

PLANT	Surveys and Results WPLANI	OI5 (%)	WPLANI Accepted
Paper	4.115	96.96	3.9899
Press	4.094	28.32	1.159

many companies have come closer to reaching 95%. In this case, the paper company OI5 has a value of 96.96%, close to world class, while the press is 28.32%, a very low value (Table 8.5).

When the values derived from the surveys are very high, around 4 out of 5 on the Likert scale, this implies that the findings of the surveys are reliable and we can use the proposed model.

For the press, there is a significant decline between the indicator and the survey values, reflecting a lack of knowledge of the activity. This case demonstrates a failure of the traditional model of surveys where this aspect would have gone unnoticed.

8.3.3.2 Questionnaire: Execution of Work: The WEXECI Indicator

The second parameter to obtain from the surveys relates to the perception of the execution of scheduled jobs. Surveys are conducted at the same levels. The answers from the paper industry follow.

The responses of the three groups associated with the execution of the work are shown in Figure 8.19. The trend is positive except for three valleys marked by responses 9, 11, 14, and 15. Answer 9 refers to knowledge of scheduled times, etc. This indicator can be validated by numerical indicators. In general, the department is skeptical about work execution, ignoring much of the data when they are available in the system or easily retrievable. Numerical indicators validate the pessimistic views of some equipment maintenance (Table 8.6).

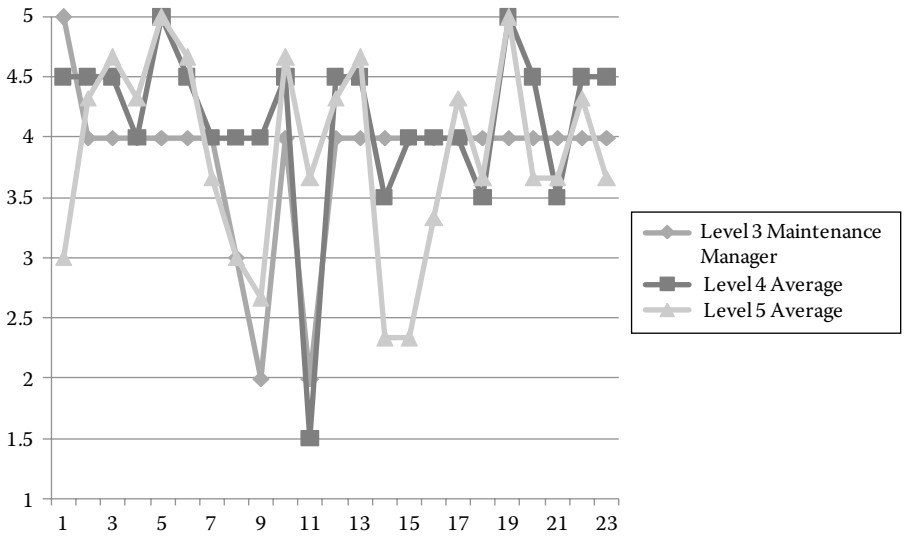


FIGURE 8.19
Work execution survey results: paper industry.

TABLE 8.6

Work Execution Survey Results: Paper Industry

	Work Execution							
	Level 3 Maintenance Chief	**Level 4 Operator 1**	**Level 4 Operator 2**	**Level 4 Average**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**
1	5	5	4	4.5	4	3	2	3.0000
2	4	5	4	4.5	5	5	3	4.3333
3	4	4	5	4.5	5	5	4	4.6667
4	4	4	4	4	5	5	3	4.3333
5	4	5	5	5	5	5	5	5.0000
6	4	5	4	4.5	5	5	4	4.6667
7	4	5	3	4	4	5	2	3.6667
8	3	5	3	4	4	3	2	3.0000
9	2	5	3	4	3	3	2	2.6667
10	4	5	4	4.5	5	5	4	4.6667
11	2	1	2	1.5	5	4	2	3.6667
12	4	5	4	4.5	5	5	3	4.3333
13	4	5	4	4.5	5	5	4	4.6667
14	4	5	2	3.5	4	1	2	2.3333
15	4	5	3	4	5	1	1	2.3333
16	4	5	3	4	4	5	1	3.3333
17	4	4	4	4	5	5	3	4.3333
18	4	5	2	3.5	5	5	1	3.6667
19	4	5	5	5	5	5	5	5.0000
20	4	5	4	4.5	5	5	1	3.6667
21	4	5	2	3.5	5	5	1	3.6667
22	4	5	4	4.5	5	5	3	4.3333
23	4	5	4	4.5	5	5	1	3.6667

Answer 11 is before the asset review of each production shift. This does not indicate a decline in the performance of work, so it is not a negative indicator.

Finally, responses 14 and 15 indicate backlog, which is worrying because this is the job of the scheduler.

We now turn to the press (Figure 8.20).

This second set of answers on the execution of the work represents significantly lower values; the degree of knowledge and satisfaction is lower but more uniform.

When we compare the two companies, the paper industry and the press, we observe the following at the various hierarchical levels:

In the graph shown in Figure 8.21, in two questions on job scheduling, knowledge and how to carry jobs out, the director of maintenance of the paper industry seems to have a more pessimistic view than his comparator in the press.

At the level of middle managers, we see the biggest differences in the questions concerning knowledge of downtime, rates of applied maintenance, and comparison of estimates with actual execution. Despite subtle differences, values are high and the score in the two organizations is positive (Figure 8.22).

As for maintenance managers, the most important differences are observed in the first questions. In these questions, the managers from the paper industry prove to have

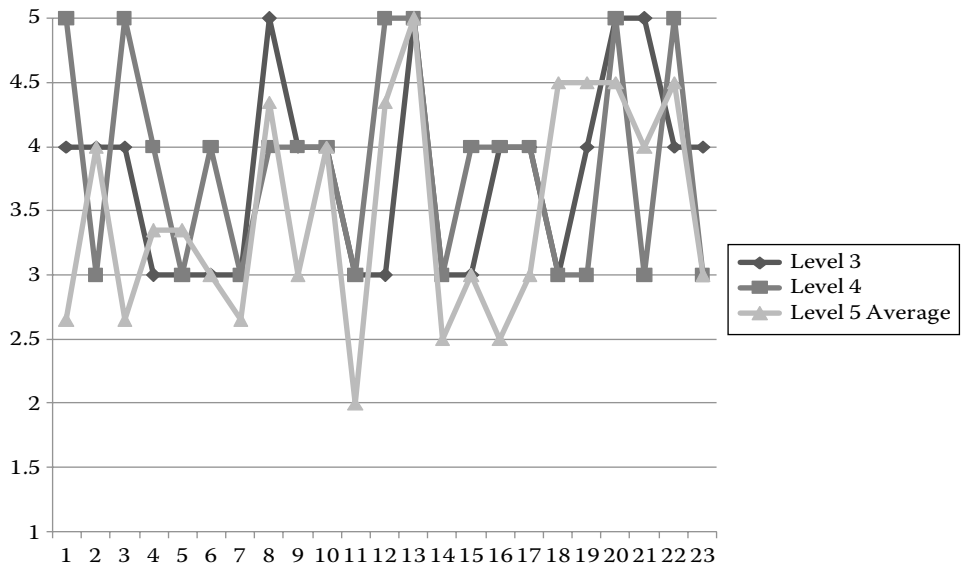


FIGURE 8.20
Surveys of maturity level 1: work execution, press.

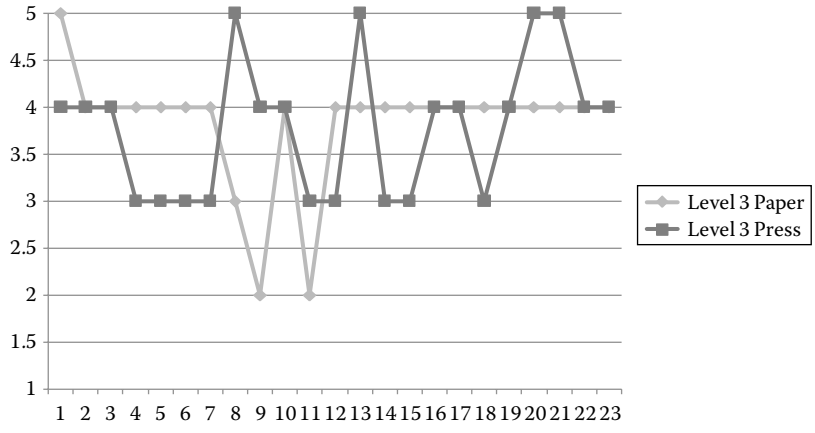


FIGURE 8.21
Surveys of work execution: paper industry versus press, hierarchical level 3.

knowledge of established maintenance procedures, resulting in a noticeable gap with the knowledge of the employees of the press (Figure 8.23).

Once surveys are analyzed according to the questions asked on indicators, they are validated using the associated numerical measures. The following values are derived (Table 8.7):

Figure 8.24 shows the high correlation of values between different hierarchical levels, with special emphasis on the more realistic perception at lower levels. We also see a greater understanding of planning and its execution. The managers rely on the planning but think the execution (for which they are responsible) does not meet the parameters. The use of numerical indicators suggests this differential perception is encouraged by two indicators that blur the customer perspective and internal processes.

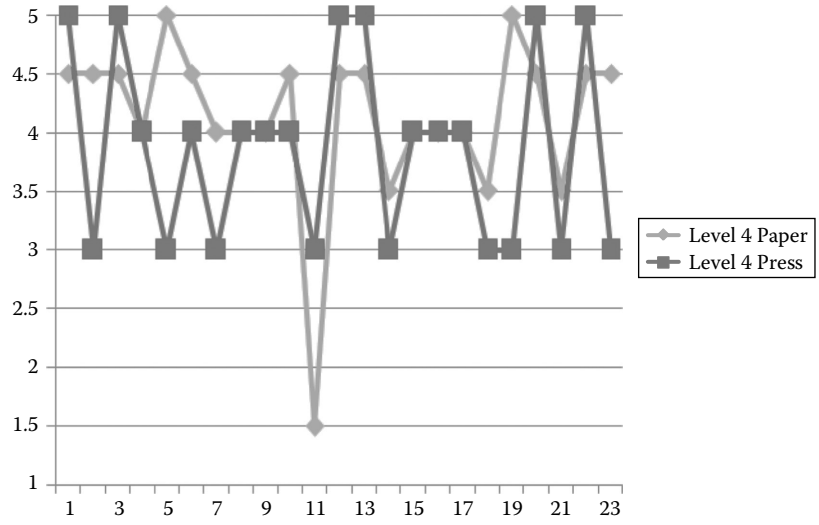


FIGURE 8.22
Surveys of work execution: press versus paper industry, hierarchical level 4.

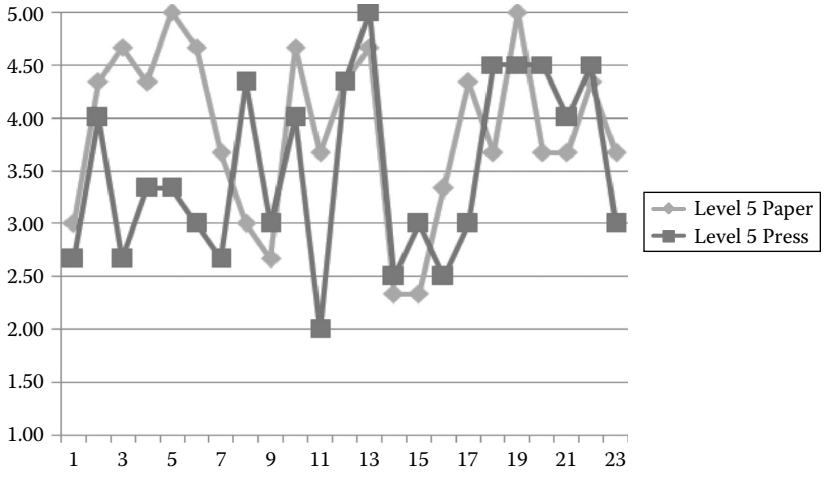


FIGURE 8.23
Surveys of work execution: press versus paper industry, hierarchical level 5.

TABLE 8.7
WEXECI Hierarchy in Evaluated Industries

WEXECI Paper	Work Execution	WEXECI Press	Work Execution
Level 3	3.826	Level 3	3.783
Level 4	4.130	Level 4	3.870
Level 5	3.870	Level 5	3.493
WEXECI Average	**3.942**	**WEXECI Average**	**3.715**

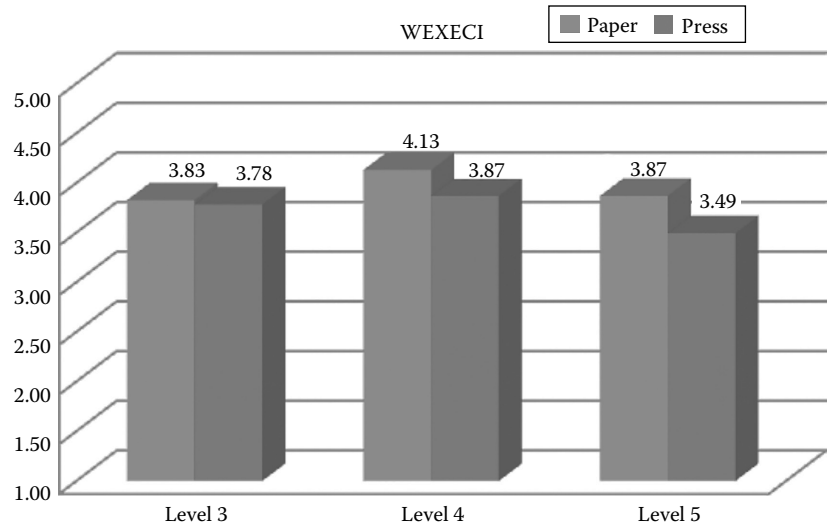


FIGURE 8.24
WEXECI index by hierarchical levels in the press and paper industry.

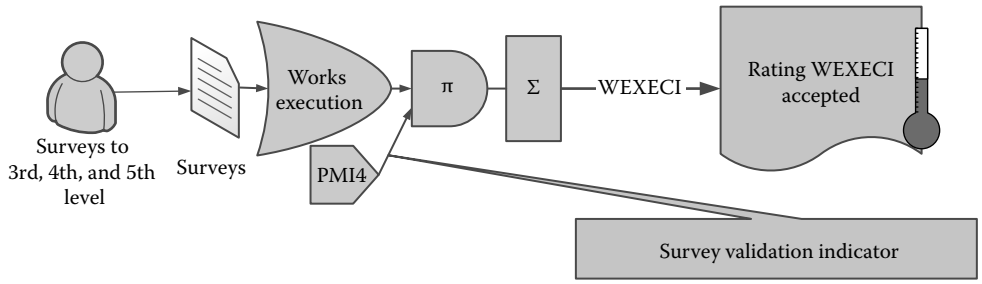


FIGURE 8.25
WEXECI validated with indicators using numerical calculation.

The average values at the two plants are close to four and uniform across hierarchical levels, with some nuances. While the classical audit perspective using surveys would show the execution of work as successful, the proposed model requires validation or confirmation of the survey results through a series of associated numerical indicators, as shown in Figure 8.25.

The indicator with which the surveys are validated is PMI4. As discussed in the previous chapter, it is expressed in the following ratio:

$$\text{PMI 4} = \frac{\text{Preventive maintenance tasks performed}}{\text{Preventive maintenance tasks scheduled}}$$

Preventive maintenance requires a program tailored to the plant. To measure the execution of preventative maintenance, it is important that a large number of the planned activities are not cancelled. The WCM perspective suggests a compliance rate of 95%; the paper company is close to this, at 97.49% and 99.49% for the past 2 years.

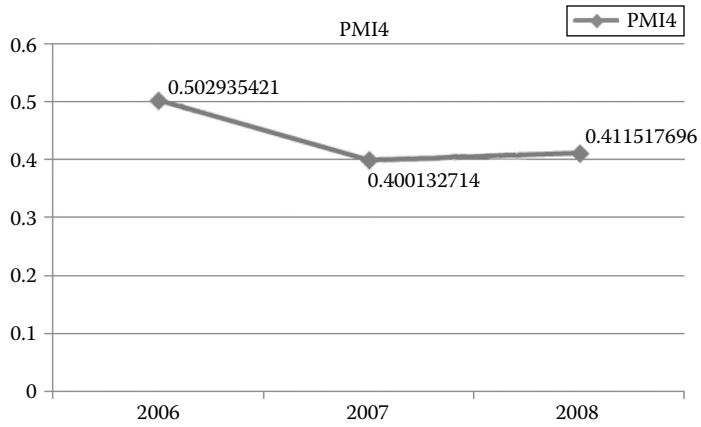


FIGURE 8.26
Evolution of PMI4 in the press.

In the press, the PMI4 indicator is troubling because it presents a rate of task completion for preventive maintenance of 40%, indicating a high failure rate in planning. Problematically, this indicator validates the results of the surveys.

The evolution of the past 3 years shows similar values, indicating a large number of preventive tasks are not carried out. It is not a onetime occurrence, but shows a common dynamic in the maintenance department (Figure 8.26).

The results validated with their respective indicators are in Table 8.8.

The WEXECI indicator for the press is validated at levels of 1.5, below acceptable levels; after validating surveys with PMI4, the paper industry shows successful values, endorsing the impressions of the maintenance team.

If the survey results are plotted and further validated by the indicators, we obtain the graph in Figure 8.27. This graph shows the results of the surveys, that is, the audit by the traditional method, and next to them, the values validated or certified by associated numerical indicators.

The traditional method and the validated method agree in qualifying one of the two companies. In the paper industry, values and positive responses are matched to successful planning and execution of work in the maintenance department. However, in the press, the traditional method is still successful, with both planning and execution keeping high values close to four. This is where the proposed method and the mixture of targets and numerical indicators provide relevant information; in the case of the press, the WPLANI and WEXECI rate drop substantially and are unacceptable. This method demonstrates the need to combine data from ERP and CMMS with the results of surveys and interviews, as the latter do not always provide reliable data; Tavares maintenance radars or the results of

TABLE 8.8
WEXECI Validated

PLANT	Survey Results WEXECI	PMI4 (%)	WEXECI Accepted
Paper	3.942	99.49	3.9218
Press	3.715	41.15	1.528

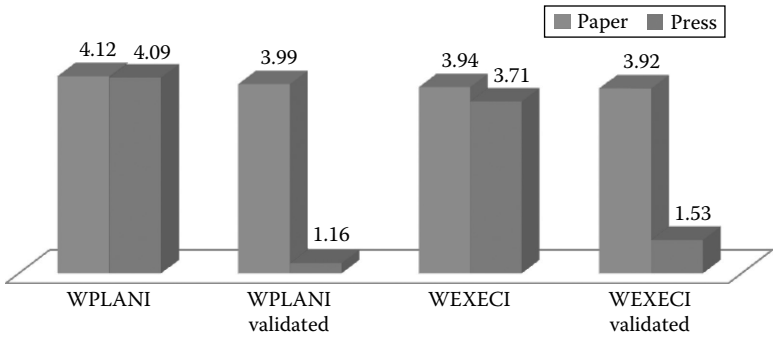


FIGURE 8.27
Indicators from surveys with and without validation by associated indices.

COVENIN standards may be wildly inaccurate and subjective, representing the projection of a desire not a reality.

The model does not stop at validating the maturity level. It calculates a series of nested numerical indicators accompanying the validated surveys, using either the world-class values of SMRP/EFNMS or the company's values, marking the maturity level and showing the results of improvements or making recommendations based on variations in the benchmarks.

8.3.4 Indicators Relating to Hours of Human Resources in Planning and Execution

The existence of an information system for human resources has been discussed since 1998; the possibility of exchanging (manually in many cases) information with other departments allows the paper industry to include all indicators proposed at this maturity level. Most data are taken from CMMS; some are from ERP.
The following are analyzed for this level:

- 333,183 WOs
- Direct costs of €113,807,806 in the years audited
- Approximately 2,634,531 work hours for maintenance workers

Given the amount of data, we can assume some degree of reliability.

The press also has CMMS and ERP, allowing the exploitation of the data required to compile the indicators. However, it does not have certain records required for integrating the production process, and concepts such as scheduled shutdowns and downtime for maintenance do not make sense.

8.3.4.1 Indicator OI25

In addition to the expertise of planners, OI25 can determine the degree of commitment to planning and compliance. In-house and external personnel are included in calculations, as well as all scheduled maintenance activities, whether preventive, predictive, or corrective. Figure 8.28 graphically plots the convergence of the schedule with what was executed in the paper company; this is the result of knowledge based on experience and information

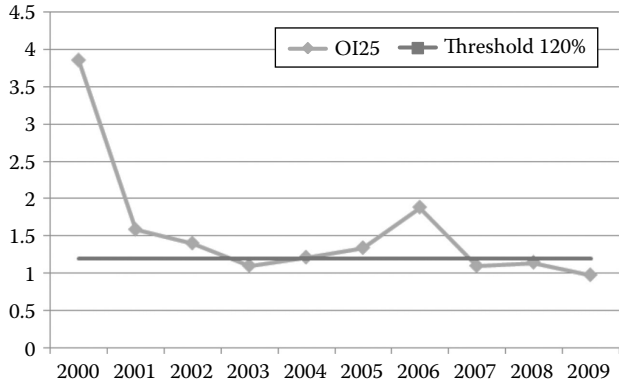


FIGURE 8.28
OI25 index for 2000–2009.

TABLE 8.9

OI25 Index for 2000–2009

Year	Estimated Hours	Executed Hours	OI25
2000	46,056	177,421	3.85228852
2001	146,092	231,193	1.5825165
2002	133,124	186,098	1.39792975
2003	146,983	161,210	1.09679351
2004	150,353	181,849	1.20948036
2005	227,174	303,597	1.33640734
2006	223,029	419,287	1.87996628
2007	237,664	260,060	1.09423388
2008	226,975	258,897	1.14064104
2009	123,563	120,194	0.97273456

on the duration of the tasks. The final values for the past 3 years in this industry are close to unity and below the threshold of 20% for excess hours (Table 8.9).

$$\text{OI}25 = \frac{\text{Direct maintenance man-hours in scheduled activities}}{\text{Total planned man-hours for direct staff}}$$

In contrast, the indicator for the press has a value around 70%. To calculate it, we estimate the number of planned hours that were not used. A low value outside the established references requires a review of planning.

8.3.4.2 Indicator OI5 WOI12

$$\text{OI}5 = \text{WOI}12 = \frac{\text{Planned and scheduled maintenance man-hours}}{\text{Total number of maintenance man-hours available}}$$

The importance of this indicator as an evaluator of the surveys has already been mentioned. It is crucial to know the proportion of time spent on scheduled activities versus time spent

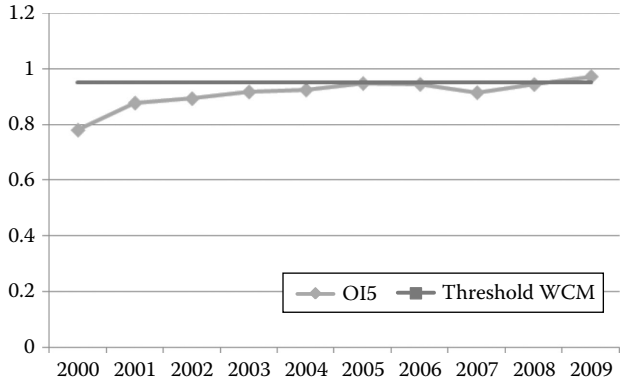


FIGURE 8.29
OI5-WOI12 index for 2000–2009.

TABLE 8.10
OI5-WOI12 Index for 2000–2009

Year	Available Hours	Maintenance Plan Hours	OI5
2000	228,072	177,421	0.77791662
2001	264,220	231,193	0.87500189
2002	208,932	186,098	0.89071085
2003	176,226	161,210	0.91479123
2004	197,228	181,849	0.92202426
2005	321,242	303,597	0.94507256
2006	445,110	419,287	0.94198513
2007	285,098	260,060	0.91217757
2008	274,985	258,897	0.94149499
2009	123,951	120,194	0.96968964

on unplanned ones, that is, a high level of improvisation based on null planning. Values in the paper industry are within expected limits, close to unity and WCM limits (Figure 8.29 and Table 8.10).

In the press, however, the indicator OI5 WOI12 has a value of around 28%.This value is low because of poor planning of the work; in this case, staff assigned to the maintenance of productive assets are more involved in other tasks of higher importance and urgency.

8.3.4.3 Indicator WOI13 OI21 PMI10

$$\mathrm{IOT}13 = \mathrm{IO}21 = \mathrm{IMP}10 = \frac{\text{Maintenance overtime}}{\text{Total number of maintenance worked hours}}$$

In the paper industry, the percentage of overtime including subcontractors is a mere 4.5%; this value is maintained in all calculations. To Hawkins [113], normal overtime should be around 6% of the total number of hours worked, so the company is within the suggested

limits. In contrast, in the last year, the press has increased the amount of overtime to 8.45%, outside the suggested limits; this increase is associated with failure to perform scheduled preventive maintenance.

8.3.4.4 Indicator PMI2

$$\text{PMI}\,2 = \frac{\text{Man-hours spent on emergency works}}{\text{Total worked man-hours}}$$

In the paper industry, the downward trend in emergency work has been accompanied by an increase in planning, arriving close to "world-class" values; only 5% of jobs are urgent ones, and the company has achieved values lower than 10% in the past 5 years (Figure 8.30 and Table 8.11).

In the press, the PMI2 indicator reaches an extremely small value of 0.5%. The indicator of hours of emergency work with respect to the total is very small. The rate is 10 times lower than the threshold of world class, so it is perfectly located within the suggested references. This low value is obviously the result of using machinery that does not require continuous intensive production.

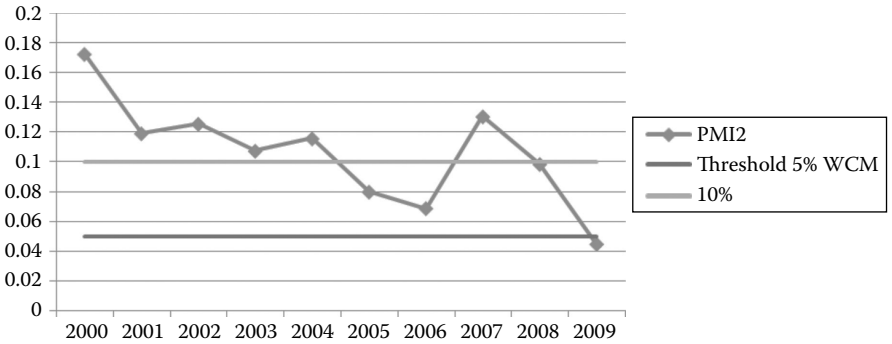


FIGURE 8.30
PMI2 index for 2000–2009.

TABLE 8.11

PMI2 for 2000–2009

Year	Emergency Hours	Total Hours	PMI2
2000	38,938	226,147	0.17218004
2001	29,409	247,348	0.11889726
2002	20,987	167,541	0.12526486
2003	13,467	125,659	0.10717099
2004	11,836	102,476	0.11550021
2005	11,957	150,077	0.07967243
2006	14,797	215,629	0.0686225
2007	13,840	106,261	0.13024534
2008	9,782	99,563	0.09824935
2009	2,303	51,639	0.04459808

8.3.5 Indicators Relating to the Fulfillment of Tasks

8.3.5.1 Indicator PMI4

$$\text{PMI}\,4 = \frac{\text{Preventive maintenance tasks performed}}{\text{Preventive maintenance tasks scheduled}}$$

The need for a preventive program adapted to the real needs of the plant as well as scrupulous monitoring have already been noted. The relevant indicator assumes the need for the execution of those tasks and penalizes their absence. The WCM perspective suggests a compliance rate of 95%; the paper company is very close to this (Table 8.12).

The PMI4 indicator for the press is worrisome as it shows scheduled preventative maintenance is carried out at a rate of 41.15% with a high failure in planning (Figure 8.31). Especially troubling is that this indicator validates the results of the surveys, so its low value invalidates positive results of the tests performed. Although there is no value found for the current year, the indicator responds to a common dynamic in the department, so planning must be one of their objectives.

TABLE 8.12

PMI4 for 2000–2009

Year	WOs Number of PM Planning	WOs Number of PM Execution	PMI4
2000	5,202	5,167	0.99327182
2001	8,212	8,140	0.99123234
2002	8,966	8,856	0.98773143
2003	8,420	8,301	0.98586698
2004	8,291	8,137	0.98142564
2005	10,914	10,877	0.99660986
2006	13,599	13,454	0.98933745
2007	16,080	15,160	0.94278607
2008	15,904	15,505	0.97491197
2009	9,056	9,010	0.99492049

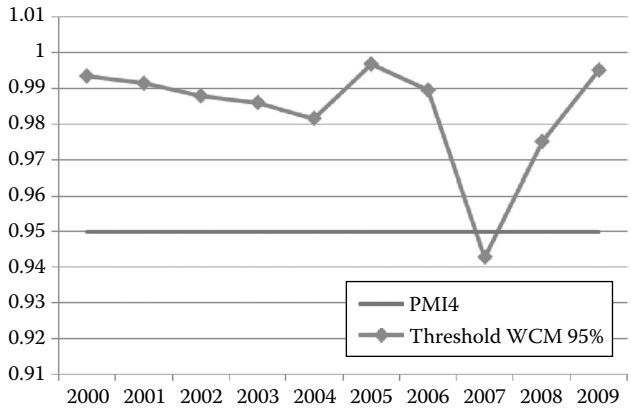


FIGURE 8.31
PMI4 index for 2000–2009.

8.3.5.2 Indicator PMI9

The PMI9 indicator represents a distortion in the system: the percentage of total delayed orders. The WCM says compliance must be at least 90%, but the paper company has a delay between the planned closure of the WOs and the actual closing. This dysfunction does not affect the existence of a culture of foresight and maintenance scheduling, that is, it affects efficiency but not effectiveness. The high value of delayed orders found for the paper company (around 90%) is an incorrect estimate probably due to the need for a correction factor, coupled with a review of the documentary circuit that runs from the completion of the task until the closing of the order lapse to find the delay (Figure 8.32 and Table 8.13).

$$\text{PMI9} = \frac{\text{Number of PM delayed tasks}}{\text{Number of PM pending tasks}}$$

We see a slight decline of tasks delayed, but the correction factors should be introduced to optimize future resources based on realistic forecasts. These forecasts should lower the rate to a maximum of 10%, or more an ambitious rate of 5% if we take the WCM perspective. Note that the dates must match (completion and closure) so that there are no misunderstandings. In some cases, the WO is complete but not closed; this is the date that

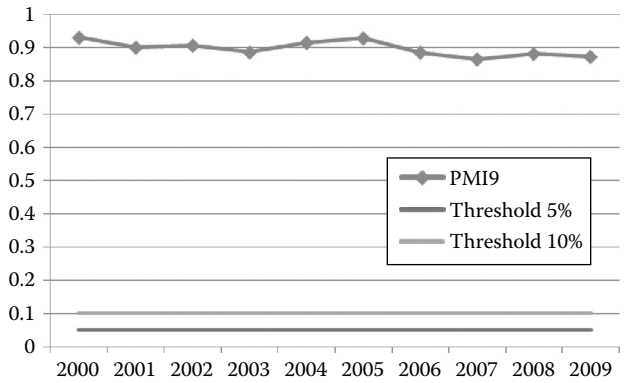


FIGURE 8.32
PMI9 index for 2000–2009 in the paper industry.

TABLE 8.13

PMI9 for 2000–2009 in the Paper Industry

Year	WOs Number PM	Delayed WOs PM	PMI9
2000	5,167	4,803	0.92955293
2001	8,140	7,323	0.89963145
2002	8,856	8,020	0.90560072
2003	8,301	7,347	0.88507409
2004	8,131	7,431	0.91390973
2005	10,867	10,081	0.92767093
2006	13,422	11,873	0.88459246
2007	15,111	13,060	0.86427106
2008	15,399	13,561	0.8806416
2009	7,319	6,381	0.87184042

appears on the estimate even if it differs from the closing date because of an administrative delay. That is why we must keep in mind the necessary overlap between the official closing of the order and the estimate.

In the press, this PMI9 indicator represents 100%.This indicator confirms the fears of the previous indicator, showing 100% of the delayed orders as pending, generating WOs that are not met or pending in excessive volume.

8.3.6 Economic Indicators

8.3.6.1 Indicator PMI5

$$\text{PMI}\,5 = \frac{\text{Tasks estimated costs PM}}{\text{Tasks real costs PM}}$$

The PMI5 development in the paper industry is clearly positive with progressive success in the estimated cost, placing it at the rate proposed by Stegimelle and Olver [306] of 86% (Figure 8.33). This success in the cost estimate indicates the need to transfer orders closures; there is an adequate estimate in time and materials that, after reaching heights of 86%, must be maintained over time (Table 8.14).

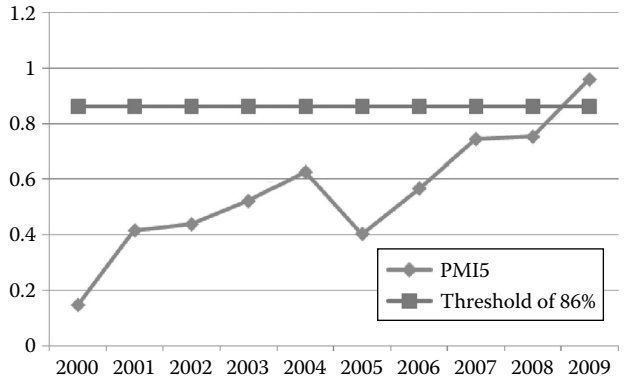


FIGURE 8.33
PMI5 index for 2000–2009 in the paper industry.

TABLE 8.14

PMI5 Index for 2000–2009 in the Paper Industry

Year	Estimated Cost PM	Real Cost PM	PMI5
2000	107,590	736,886	0.1460063
2001	589,879	1,419,977	0.41541448
2002	412,779	943,377	0.43755466
2003	509,834	977,547	0.52154423
2004	717,312	1,146,086	0.62587973
2005	864,702	2,146,930	0.40276208
2006	1,232,523	2,174,634	0.56677262
2007	1,709,426	2,299,764	0.74330497
2008	1,697,396	2,258,225	0.75165052
2009	915,441	954,888	0.9586894

The PMI5 indicator in the press has a value of 75.89%, 10 points lower than that recommended by international organizations.

8.3.6.2 Indicator PMI11

$$\text{PMI11} = \frac{\text{Preventive maintenance total costs}}{\text{Preventive maintenance total costs} + \text{Corrective maintenance total costs}}$$

Table 8.15 and Figure 8.34 represent the evolution of the costs of preventive maintenance and urgent corrective maintenance. There is an upward trend, with many values higher than 80%. In most cases, in fact, they are between 85% and 90%, showing the commitment of the organization to scheduled maintenance based on effective preventive maintenance, which reduces the percentage of urgent corrective maintenance.

The graph clearly shows a gradual rise in recent fiscal years. In the final year, the indicator is approaching 80%, practically inside suggested values. Proper containment of this indicator values above 80% involves the reduction of maintenance associated with the "firefighting" (i.e., reactive maintenance = putting out fires) traditionally linked to this department. The replacement of reactive maintenance by nondestructive inspection, among other things, significantly improves the LCC of productive assets.

TABLE 8.15

PMI11 Index for 2000–2009 in the Paper Industry

Year	Preventive Costs	Emergency Corrective Costs	PMI11
2000	736,886	1,317,432	0.35870104
2001	1,419,977	1,584,696	0.47258953
2002	943,377	1,231,605	0.43374014
2003	977,547	796,109	0.55114802
2004	1,146,086	901,982	0.55959372
2005	2,146,930	996,701	0.68294593
2006	2,174,634	141,8578	0.60520615
2007	2,299,764	151,3661	0.60307047
2008	2,258,225	1,202,338	0.65256
2009	954,888	216,289	0.81532339

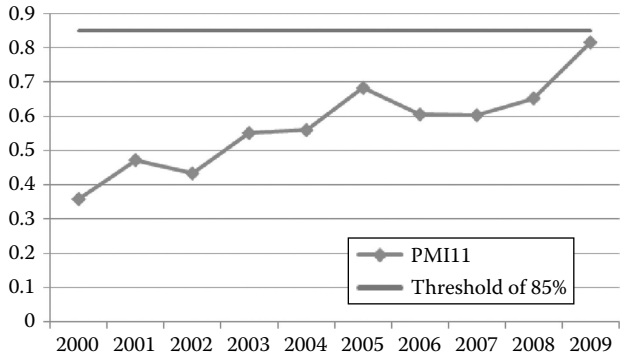


FIGURE 8.34
PMI11 index for 2000–2009 in the paper industry.

In the press, the PMI11 indicator has a value of 61.34%. Preventive costs are 20 points lower than recommended, with excessive costs of corrective maintenance. This volume of corrective maintenance may partly explain the degradation in the performance of tasks scheduled for preventive maintenance.

8.3.6.3 Indicator EI20

$$\text{EI}\,20 = \frac{\text{Cost of programmed maintenance stops}}{\text{Total maintenance costs}}$$

The EI20 indicator represents the cost of maintenance performed during scheduled stops for this purpose. In another era, it was an ideal time for machinery overhauls, major repairs, or corrective interventions that could not be rushed. The audited company, because of today's need for continuous production processes, will reduce the percentage of time budgeted for those stops with the gradual integration of preventive and predictive maintenance, which will significantly reduce the need for aggressive corrective maintenance (Table 8.16).

Figure 8.35 displays a steady downward trend; such stops are no longer needed because of the improvement in the life of the assets and the corresponding lack of major repairs

TABLE 8.16

EI20 Index for 2000–2008 in the Paper Industry

Year	Total Costs	General Stops Costs	EI20
2000	8,929,291	865,697	0.09695025
2001	10,958,492	1,124,512	0.10261558
2002	9,251,571	787,121	0.08507971
2003	9,881,008	1,773,165	0.17945183
2004	9,467,956	844,974	0.08924566
2005	12,631,135	757,286	0.05995392
2006	16,804,142	1,254,420	0.07464945
2007	12,172,379	720,179	0.05916502
2008	12,262,387	583,496	0.04758421

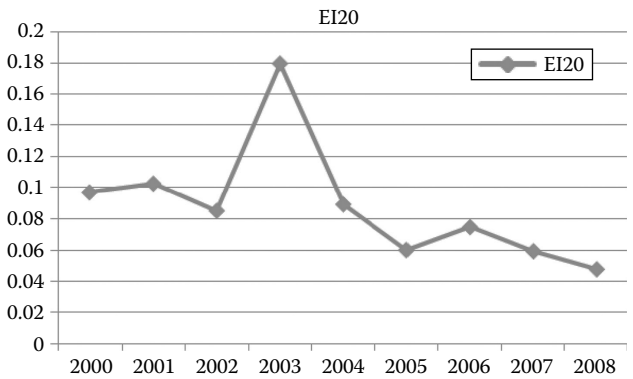


FIGURE 8.35
EI20 index for 2000–2008 in the paper industry.

required to restore machinery. Year 2009 is not included because this indicator includes annual costs that have not been evaluated for this year.

In the press, the EI20 indicator is meaningless; when an industry whose production is based on time intervals of 2 or 3 h a day, the rest of the day is available to do the necessary interventions. Even they have redundant production equipment if necessary extend the interventions for various reasons, or if an unsolvable emergency stop occurs in the time to obtain the production to be manufactured daily.

8.3.7 Technical Indicators of Effectiveness

8.3.7.1 Indicator PMI12

$$\text{PMI12} = \frac{\text{Preventive maintenance unavailability time}}{\text{Preventive unavailability time} + \text{Corrective unavailability time}}$$

Unavailability related to the planned versus unplanned maintenance is a "key factor" of the level of programming jobs. The paper company meets WCM parameters of more than 95% availability. Obviously, this implies the existence of successful planning and allocation of unavailability maintained over the years. This does not preclude a finding of excessive downtime resulting from scheduled maintenance in subsequent RCM analysis. Upgraded plans for availability could include more reactive maintenance (Table 8.17).

Figure 8.36 indicates a progressive increase toward a reduction in unplanned downtime in favor of scheduled maintenance. As discussed before, this demonstrates the existence of a preventive maintenance schedule but is not necessarily optimized in availability achieved or costs incurred.

Like the EI20, the PMI12 and TI20 indicators are meaningless in an industry with rotating unavailability caused by planned maintenance, unlike continuous process industries. Such indicators represent a special case requiring an adaptive scorecard. It is important to identify indicators that are meaningless in certain types of industries to identify and isolate falsely optimistic or pessimistic data. The balanced scorecard is flexible enough to accommodate companies with different types of production.

TABLE 8.17

PMI12 for 2000–2009

Year	Planned Stop Hours	Unplanned Stop Hours	PMI12
2000	27,233	1,281	0.9550747
2001	27,042	3,596	0.88262941
2002	22,442	2,482	0.90041727
2003	29,656	2,212	0.93058868
2004	30,691	1,493	0.95361049
2005	37,116	1,633	0.95785698
2006	67,183	3,142	0.95532172
2007	50,343	2,841	0.94658168
2008	51,671	2,089	0.96114211
2009	24,496	640	0.97453851

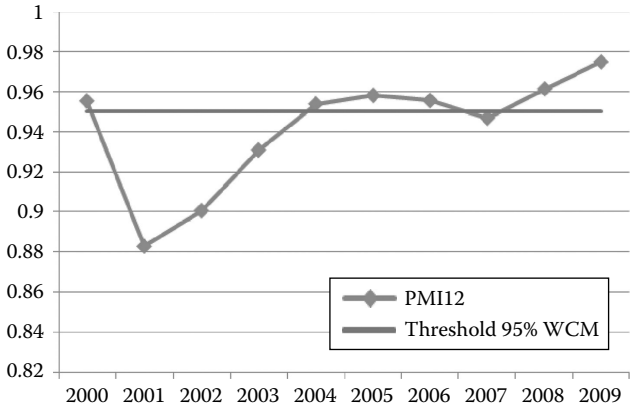


FIGURE 8.36
PMI12 index for 2000–2009.

8.3.7.2 Indicator TI20

$$\text{TI}20 = \frac{\text{Planned and scheduled maintenance time causing unavailability}}{\text{Planned and scheduled maintenance time that requires unavailability}}$$

The TI20 indicator, in accordance with UNE 15341 [356], includes all planned activities of the company. The indicator must be calculated from two different perspectives in the paper industry. The first includes the activities of preventive and predictive maintenance and outages generated from such activities. As shown in Figure 8.37, there is a clear and progressive convergence in the past 8 years toward unity, such as accuracy in forecasting undue delay. This demonstrates the achievement of targets for preventive stops (Table 8.18).

In the second, we consider all planned activities, preventive, predictive, and corrective maintenance, improvements, and extensions. The outages return to a stage similar to the previous convergence and tend asymptotically to unity. This suggests an efficient provision of nonproductive times of assets in recent years, the result of comprehensive programming and foresight. As the two variants of the TI20 indicator are strongly correlated and achieved values are close to unity in the past 3 years, we can conclude the planning of expected inactivity is accurate (Figure 8.38 and Table 8.19).

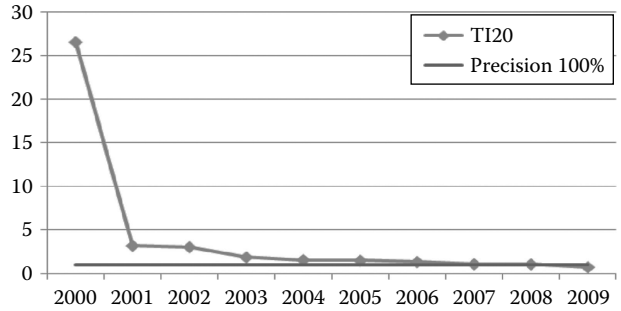


FIGURE 8.37
TI20 index for 2000–2009 in the paper industry: method 1.

TABLE 8.18

TI20 Index for 2000–2009 in the Paper Industry: Method 1

Year	Stop PM Hours	Stop PM Planned Hours	TI20
2000	9,666	365	26.4821918
2001	3,004	938	3.20255864
2002	1,812	593	3.05564924
2003	2,679	1,428	1.87605042
2004	5,620	3,560	1.57865169
2005	9,798	6,501	1.50715275
2006	15,099	11,246	1.34261071
2007	17,715	16,166	1.09581838
2008	17,767	16,582	1.07146303
2009	7,801	10,492	0.74351887

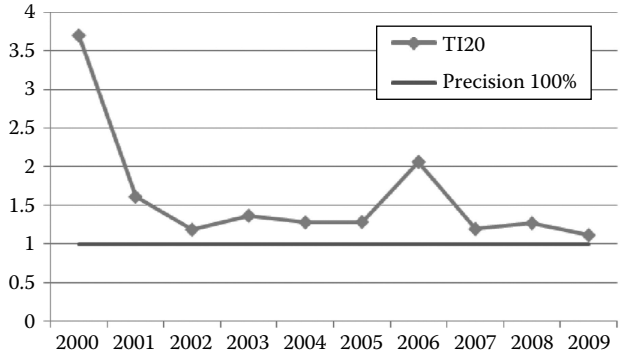


FIGURE 8.38
TI20 index for 2000–2009 in the paper industry: method 2.

TABLE 8.19

TI20 Index for 2000–2009 in the Paper Industry: Method 2

Year	Stop Plan Hours	Preventive Plan Hours	TI20
2000	28,922	7,820	3.69846547
2001	32,048	19,909	1.60972425
2002	24,568	20,733	1.18497082
2003	30,353	22,227	1.3655914
2004	31,907	24,948	1.2789402
2005	38,641	30,080	1.28460771
2006	78,004	37,831	2.0619069
2007	51,071	42,830	1.19241186
2008	52,945	41,735	1.2685995
2009	24,784	22,255	1.11363738

As indicated, the TI20 is meaningless in the press due to the rotating nature of the production process; mechanics do not need the unavailability of machines for scheduled maintenance because they have several hours to spare for it before production resumes. The group of indicators must be able to adapt to the process type to create a viable scorecard.

8.3.7.3 Indicator TI7

$$\text{TI7} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailability time due to planned maintenance}}$$

In the case of the paper industry, unavailability due to planned maintenance, that is, the complement of the TI7 indicator, complies with the value assigned by the SMRP. Olver [246] assigns a value of 6% maximum, taking into account three components of planned unavailability: scheduled tasks in preventive, corrective, and predictive maintenance. To calculate TI7 in the paper industry, we analyze these three independent lines with their outages linked to scheduled maintenance and obtain an average greater than 97%. This implies a very low level of scheduled maintenance requiring stopped machines; this, in turn, indicates increased availability, crucial data in continuous process industries. This factor, coupled with comprehensive planning resources, implies a non-negative impact of preventive maintenance on asset availability. These numbers drop significantly by introducing predictive tasks alongside RCM policies that eliminate the classical substitutions required in timetables of systematic maintenance (Figure 8.39 and Table 8.20).

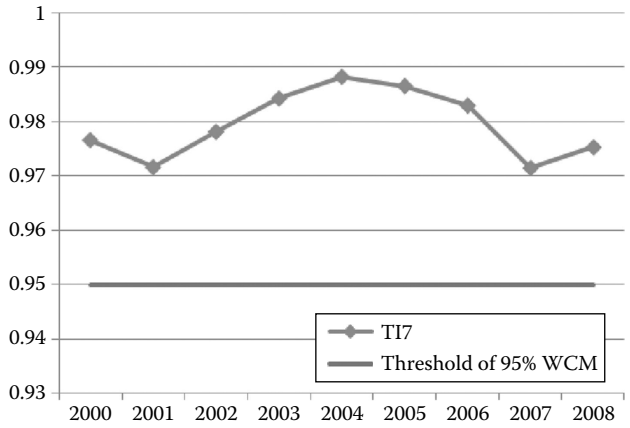


FIGURE 8.39
TI7 index for 2000–2008 in the paper industry.

TABLE 8.20

TI7 Index for 2000–2008 in the Paper Industry

Year	Unavailability Maintenance Hours	Operation Hours	TI7
2000	632	26,280	0.97651605
2001	769	26,280	0.97157011
2002	590	26,280	0.97804243
2003	424	26,280	0.98412223
2004	317	26,280	0.98808136
2005	362	26,280	0.98641243
2006	459	26,280	0.98283406
2007	773	26,280	0.97142646
2008	668	26,280	0.97521152

The absence of downtime for planned maintenance in the press means the ratio reaches 100%. On the one hand, it is a calculable indicator that yields a measurable value. On the other hand, this is not suitable for proper benchmarking; because of the peculiar nature of the rotating process, this indicator is always 100%, so any sectored comparison or comparison between plants will give rise to misunderstandings.

As for its translation to a scorecard, it will not be a positive indicator of a successful strategy. Variation is virtually impossible and it does not contribute to any corporate goal. It is, therefore, an inappropriate indicator.

8.3.7.4 Indicator OI11

$$\text{OI11} = \frac{\text{Time spent on emergency corrective maintenance}}{\text{Total unavailability time linked to maintenance}}$$

The indicator OI11 represents hour of reactive maintenance with respect to the total unavailability of maintenance. The numerator may be higher than the denominator as long as several operators are involved in each emergency (Figure 8.40 and Table 8.21).

The graphical representation of OI11 shows interesting results in the paper industry. First, an anomaly appears in 2000 with a small proportion of reactive maintenance. It is

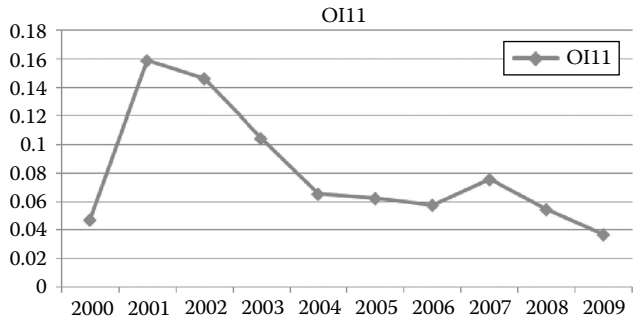


FIGURE 8.40
OI11 index for 2000–2009 in the paper industry.

TABLE 8.21

OI11 Index for 2000–2009 in the Paper Industry

Year	Stop Maintenance Hours	Reactive Hours	OI11
2000	32,900	1,548	0.04705167
2001	36,331	5,770	0.15881754
2002	27,072	3,959	0.14623966
2003	32,586	3,401	0.10436997
2004	33,477	2,186	0.06529856
2005	40,295	2,508	0.06224097
2006	81,256	4,673	0.0575096
2007	54,049	4,086	0.07559807
2008	55,128	2,996	0.05438253
2009	25,429	935	0.03676904

possible that in the early stages of CMMS there was an inadequate allocation of hours from reactive to corrective maintenance, eliminating the ability to discern emergency corrective maintenance tasks from other maintenance tasks. From that point, the trend is clearly downward to lower thresholds around 5%. This decline involves reducing unavailability due to maintenance emergencies. This reduction is, therefore, an important indicator of how the idea of "fighting fires" fades toward a planned and controlled unavailability.

The OI11 in the press, with its rotating processes, has a value of 100%. This implies an overall correlation between time dedicated to emergencies and outages resulting from them. It is logical as a high value as there is no other maintenance causing unavailability.

8.3.7.5 Indicators TI8, TI9 E, and TI10

$$\text{TI8} = \frac{\text{Preventive maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{TI9} = \frac{\text{Systematic maintenance time that generates unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{TI10} = \frac{\text{CBM time which causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

Continuing with the paper industry, in Table 8.22, the first column represents the total hours of unavailability for maintenance; the second and third represent CBM and PM unavailability for predictive and preventive maintenance, respectively.

In this case, routine maintenance comprises of improvements and preventive maintenance, so the paper company has no real interest in indicator TI9. The behavior of indicators TI8 and TI10 shown in Figure 8.41 is expected in a company requiring strong planning of the work associated with the continuous process. TI10 produces hardly any unavailability because the company uses vibration analysis, a technique that does not require stopping the machine.

TABLE 8.22

IT8 and IT10 Indices for 2000–2009

Year	Stop Maintenance Hours	CBM Machine Stop	PM Machine Stop	TI8	TI10
2000	32,900	242	9,428	0.2866	0.0074
2001	36,331	92	2,934	0.0808	0.0025
2002	27,072	41	1,790	0.0661	0.0015
2003	32,586	13	2,673	0.0820	0.0004
2004	33,477	38	5,590	0.1670	0.0011
2005	40,295	8	9,793	0.2430	0.0002
2006	81,256	27	15,083	0.1856	0.0003
2007	54,049	18	17,706	0.3276	0.0003
2008	55,128	150	17,688	0.3209	0.0027
2009	25,429	1	7,800	0.3067364	3.9325E−05

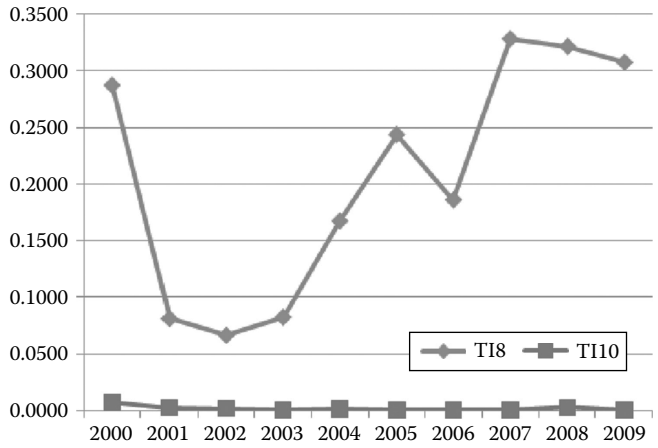


FIGURE 8.41
TI8 and TI10 indices for 2000–2009.

Unavailability because of preventive maintenance shows some ups and downs (around 2000, where data are not totally reliable); there is sustained growth from 7% to 30%, thereby attributing a third of the unavailability to preventive maintenance.

The result is consistent with a reduction in reactive maintenance and its associated unavailability and also with planned corrective maintenance, which will generate much of the rest of the unavailability. It is an appropriate balance, as excessive preventive maintenance taking nearly 100% of the unavailability may incur a waste of resources, both in maintenance and in production. Remember that RCM policies use a balanced application of preventive maintenance, leaving room to perform planned and reactive/corrective maintenance to optimize costs and availability. Calculating the complement of the sum of these three components will give the unavailability caused by unplanned maintenance, as noted by Olver [247]; SMRP places great importance on this.

In the press, these indicators are meaningless because the absence of unavailability for maintenance. In this case, the indicators would be exactly zero because there are no referenced unavailability. Again, these zeros could create misunderstandings for benchmarking; they may seem to correspond to the success of a conservation policy but are actually the result of the special type of process.

8.3.7.6 Indicators OI12, OI13, and OI14

These indicators show the union allocation of total maintenance hours (Figures 8.42, 8.43 and Table 8.23).

$$\text{OI12} = \frac{\text{Man-hours of mechanical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI13} = \frac{\text{Man-hours of electrical maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI14} = \frac{\text{Man-hours of instrumentation maintenance by internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

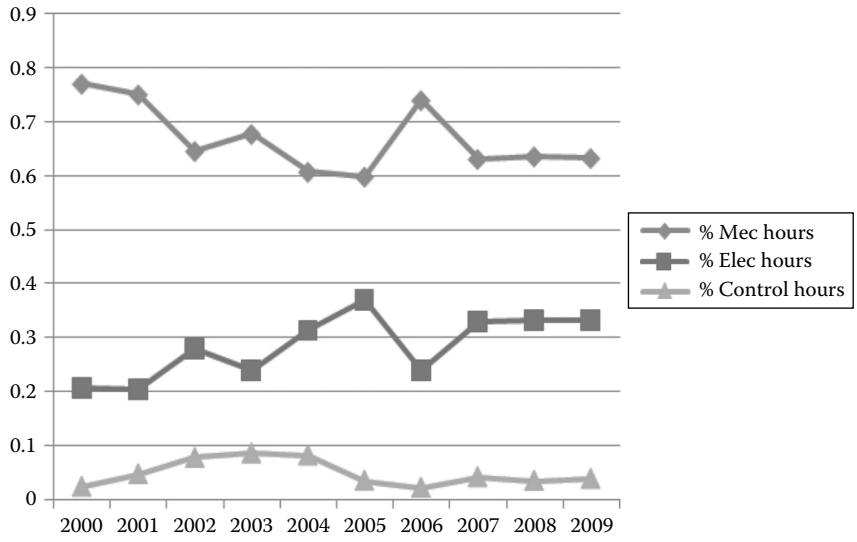


FIGURE 8.42
OI12, OI13, and OI14 for 2000–2009.

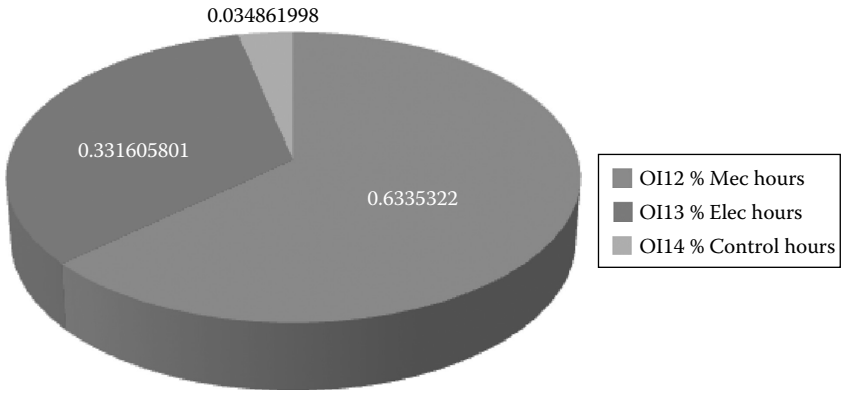


FIGURE 8.43
OI12, OI13, and OI14 indices in 2009 in the paper industry.

Indicators for the various types of maintenance show little change except for a slight decrease in mechanical maintenance in favor of electrical and electronic technological developments in all sectors. This distribution largely sets the maintenance staff as mechanical workers and, to a lesser extent, electrical workers. The little dedication to instrumentation and control tasks, as well as the rapidly changing and necessary specialization of these tasks, lead to a policy of subcontracting. It is usual to outsource this type of maintenance; not doing so risks idle resources and high educational investments.

The OI12, OI13, and OI14 indicators relating to trade union classification of the operators in the press are meaningless in the template because of the nature of the machinery; staff must have multifaceted skills to deal with problems.

TABLE 8.23

OI12, OI13, and OI14 Indices for 2000–2009

Year	Total Hours	Mech Hours	Electric Hours	Control Hours	OI12 %Mech Hours	OI13 %Elec Hours	OI14 %Control Hours
2000	226,147	173,937	46,800	5,410	0.76913	0.2069	0.0239
2001	247,359	185,302	50,373	11,684	0.74912	0.2036	0.0472
2002	167,541	107,818	46,673	13,050	0.64353	0.2786	0.0779
2003	125,660	84,866	29,973	10,820	0.67536	0.2385	0.0861
2004	102,477	61,995	32,071	8,411	0.60497	0.3130	0.0821
2005	150,078	89,432	55,447	5,289	0.59590	0.3695	0.0352
2006	215,630	159,213	51,683	4,733	0.73836	0.2397	0.0219
2007	106,261	66,811	34,990	4,460	0.62874	0.3293	0.0420
2008	99,564	63,077	33,016	3,471	0.63353	0.3316	0.0349
2009	51,639	32,558	17,093	1,988	0.63049	0.3310	0.0385

8.3.7.7 Indicators OI16, OI17, OI18, OI19, and OI20

Distribution of hours according to types of maintenance

$$\text{OI16} = \frac{\text{Corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI17} = \frac{\text{Emergency corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI18} = \frac{\text{Preventive maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI19} = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{OI20} = \frac{\text{Systematic maintenance man-hours}}{\text{Total maintenance man-hours}}$$

The WCM perspective, as Mather [206] notes, proposes a division of worker hours as follows:

- Preventive Maintenance, 50%
- Predictive maintenance, 30%
- Corrective Maintenance, 15%
- Emergency maintenance, 5%

The values achieved are

- Preventive Maintenance, 30%
- Predictive maintenance, 2%

- Corrective Maintenance, 62%
- Emergency maintenance, 3%

These values require some thought as they are quite far from world-class indices or SMRP. The SMRP values for reactive maintenance should always be below 10%, below 5 in WCM. The rates set here are suggested guidelines:

- Downward trend OI17
- Downward trend OI16
- Upward trend OI18
- Upward trend OI19

Obviously, the percentages suggested by the standard are applicable in some industrial sectors (e.g., pharmacy or food). However, there are areas where predictive maintenance does not occur to any great extent. The automotive industry is very different from the paper industry, for example, as there is no widespread implementation of CBM. Table 8.24 shows the values of indicators in the absence of a systematic maintenance plan.

Looking at indicators OI17, OI18, and OI19, we see that reactive maintenance decreases on par with yearly increases in preventive and predictive maintenance (Figures 8.44 and 8.45).

The percentage of corrective maintenance is very stable at around 60%; according to SMRP-EFNMS if it should decrease but does not. However, a more detailed analysis of this parameter indicates a substantial variation in composition importance and suggests the need for revision (Figure 8.46).

One reason the percentages of corrective maintenance will vary substantially is the cataloging done in the WOs and the data in the CMMS. If an alignment result of vibration analysis is imputed as predictive rather than corrective maintenance, or if a grease result of a visual inspection is considered preventive rather than corrective, percentages will change to the detriment of corrective maintenance, bringing values in line with SMRP and EFNMS. Table 8.25 and Figure 8.47 show the evolution of corrective maintenance with respect to the origin of the reasons for the maintenance. With slight variations, we can conclude the percentages are fairly stable; this suggests we need to review the documentation of the work.

For example, 14% of corrective maintenance originating in preventive maintenance can be coded as preventive maintenance, as can predictive maintenance caused by CBM

TABLE 8.24

OI17, OI18, and OI19 Indices for 2000–2009

Year	OI17 %Reactive	OI16 %Corrective	OI18 %Preventive	OI19 %CBM
2000	0.1707	0.3021	0.1159	0.0059
2001	0.1113	0.5274	0.1694	0.0112
2002	0.1093	0.6376	0.1664	0.0106
2003	0.0852	0.6182	0.2044	0.0129
2004	0.0780	0.6383	0.2064	0.0139
2005	0.0549	0.6427	0.2562	0.0079
2006	0.0580	0.6974	0.1936	0.0001
2007	0.0878	0.5422	0.3200	0.0001
2008	0.0580	0.5749	0.3258	0.0009
2009	0.0297	0.6253	0.2902	0.0177

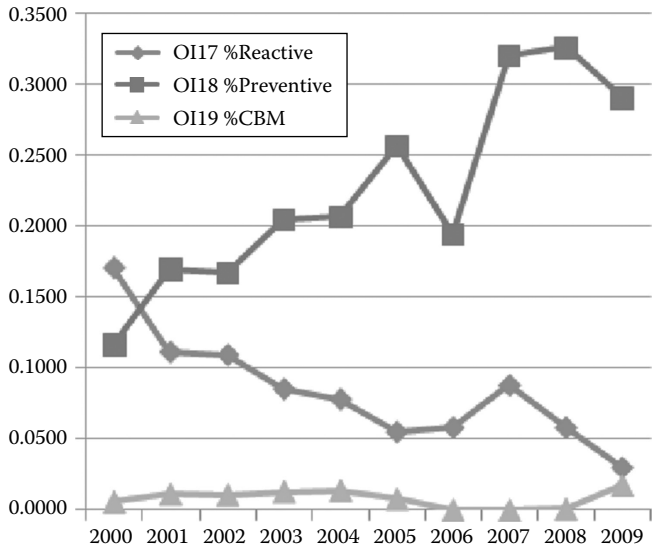


FIGURE 8.44
OI17, OI18, and OI19 indices for 2000–2009.

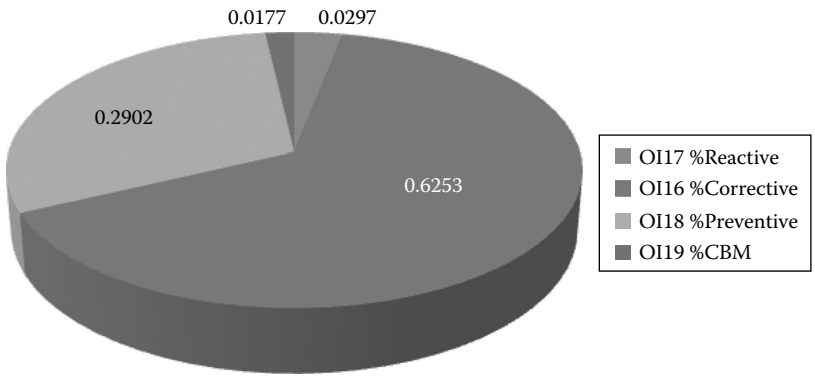


FIGURE 8.45
OI16, OI17, OI18, and OI19 indices in 2009.

actions. Spontaneous maintenance requires analysis, that is, whether it is related to a specific inspection route. A review is recommended to differentiate inspections motivated by corrective actions. These measures will balance the percentages of the four types of maintenance with trends and thresholds proposed by SMRP and EFNMS.

Analysis of the distribution of time taken for the various types of maintenance in the printing industry should highlight the lack of systematic and predictive maintenance. The distribution of times include large volumes of hours devoted to assembly and engineering improvements by the maintenance staff, with the OI16, OI17, and OI18 percentages calculated according to the time spent at the machine. If the time at the machine is not considered, the percentages may vary considerably.

The actual proportion of times presents a scenario in which the percentage of corrective maintenance is too great compared with preventive maintenance. The correction of this

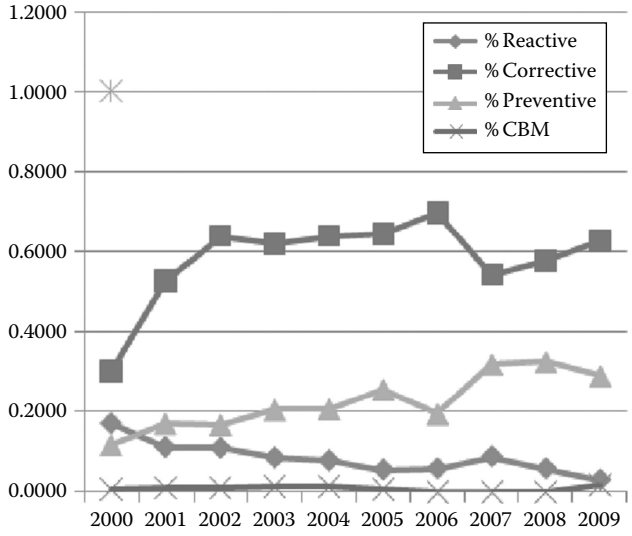
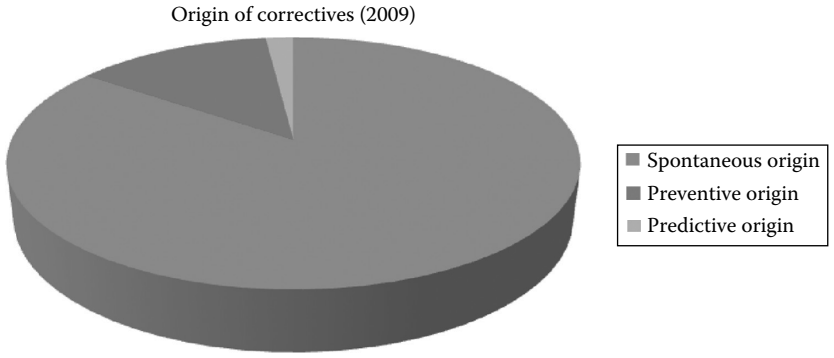


FIGURE 8.46
OI16, OI17, OI18, and OI19 indices for 2000–2009.

TABLE 8.25

Origins of Corrective Maintenance for 2000–2009



Year	Spontaneous Origin	Preventive Origin	Predictive Origin
2000	0.8066	0.1381	0.0184
2001	0.8673	0.1096	0.0147
2002	0.8376	0.1448	0.0173
2003	0.8427	0.1317	0.0254
2004	0.8670	0.0983	0.0347
2005	0.9205	0.0644	0.0151
2006	0.9385	0.0508	0.0107
2007	0.8751	0.1070	0.0178
2008	0.8710	0.1030	0.0264
2009	0.8490	0.1319	0.0187

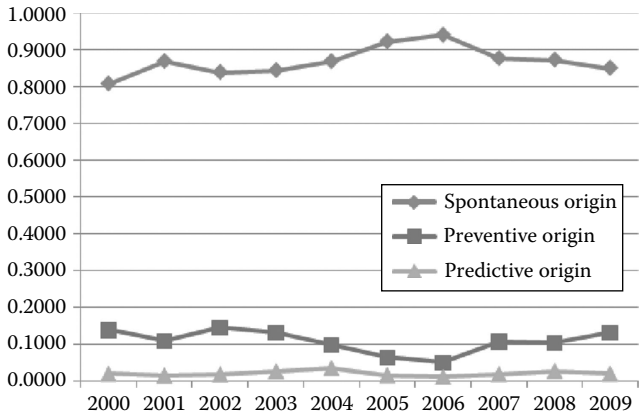


FIGURE 8.47
Origins of correctives maintenance for 2000–2009.

index, in principle, should not affect the maintenance policies; rather, it will affect the codification of the WOs and redistribute the percentages according to EFNMS and SMRP.

For the printing press, the OI16, OI17, and OI18 indices are appropriate when we consider only interventions in machines and overlook the large volume of work on improvements and modifications:

- *OI16* 38.5%: The indicator of the percentage of corrective maintenance is between 15 and 25 points above the benchmarks.
- *OI17* 0.5%: Urgent or reactive maintenance, at 10% of the threshold, has low incidence.
- *OI18* 59.9%: Preventive maintenance is at very acceptable values, below what is proposed by Mather, but when we consider the nonexistence of predictive maintenance, this percentage should increase. There is a large volume of various nonscheduled activities. The percentages of total times given in the upper diagram show preventive maintenance at 22%, corrective maintenance at 15%, and medications and improvements comprising the remaining 62%.

8.3.8 Summary of Indicators and Assessment

According to the proposed model, once the level of maturity has been determined, two tasks must be performed. The first involves finding preliminary results corresponding to the audited level to learn the state of maturity and security in dealing with the next level. These preliminary results will be derived from the survey data with their respective validations, that is, the indicators WEXECI and WPLANI previously calculated for level 1. Other data are associated with the various surveys and indices. Numerical indicators will be calculated and compared to the references values, to determine whether they are world class or internal to the organization (Figure 8.48).

Figure 8.49 highlights in a big square with a long dash line the main recommendations and observations, including technical and methodological improvements. Below this box are the summary tables for indicators for the two industries discussed here. The references must be simple; there is a problem only if the indicator shows values outside the reference values. Relevant improvements should be suggested when the causes of an imbalance are very clear. But in any case, it is essential to record this imbalance so that the audited department will be able to rebuild its strategy to return the indicator to normal values.

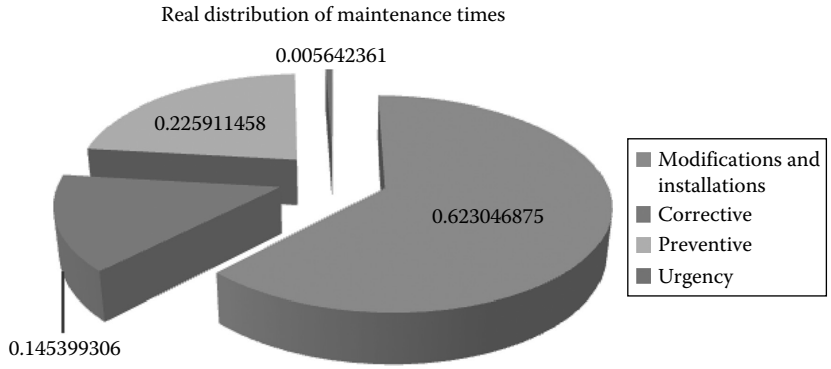


FIGURE 8.48
Distribution of service times in the press in 2008.

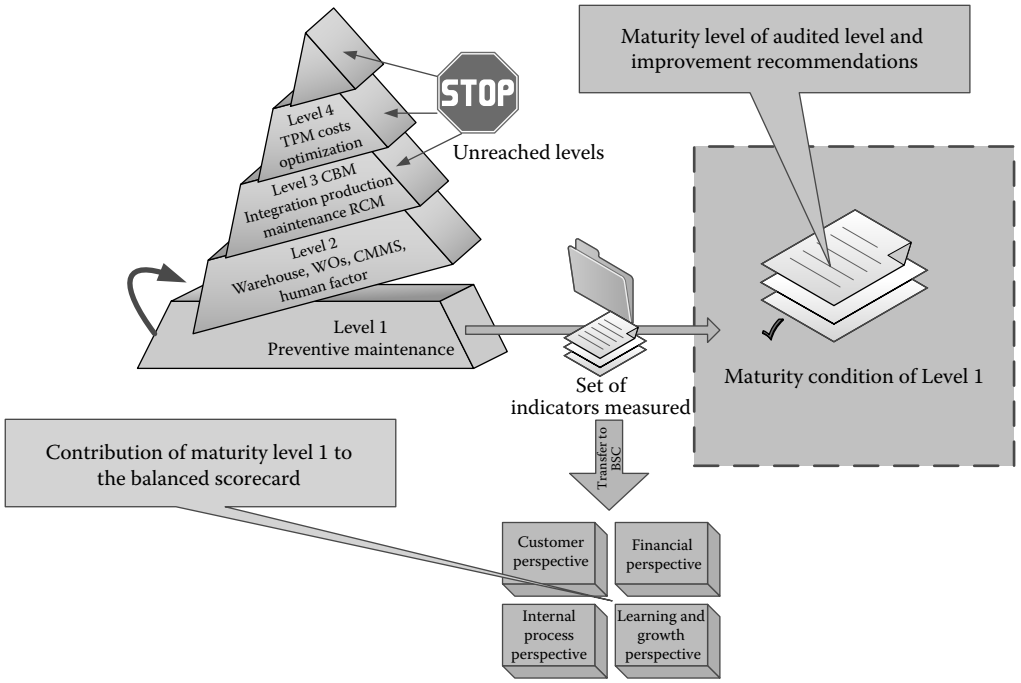


FIGURE 8.49
Output information after determining maturity level.

8.3.8.1 Scorecard Level 1 for the Paper Industry

Of the indicators present in this level, we see that only two values are out of line with the recommendations of agencies and consultants. One is shown in Figure 8.50; OI16 corresponds to the percentage of corrective maintenance; as noted earlier, it should progressively decrease and not maintained at the same level.

The correction of this index, in principle, should not affect the existing maintenance policies; changing the codifications of the WOs and a suitable classification of their origin will redistribute the percentages according to what is proposed by EFNMS and SMRP (Figure 8.50).

The second indicator out of harmony with the recommendations is PMI9. This lack of harmony is caused by delays in the implementation of the WOs. A group of similar orders

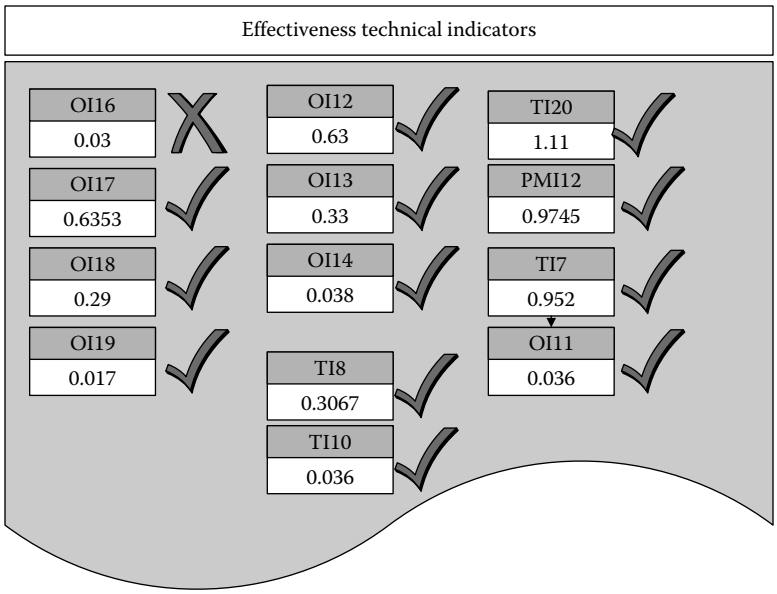


FIGURE 8.50
Summary of indicators of effectiveness within references and outside limits for the paper industry.

should be analyzed and the estimates corrected in CMMS. The resources plan can then be based on more realistic forecasts. At this point, the level is fully achieved and consolidated, and we can access the audit of level 2. This audit records two recommendations listed earlier. These recommendations do not invalidate the compliance of the level, however, because planning and work execution are tested and no modification is needed in the maintenance policy (Figure 8.51).

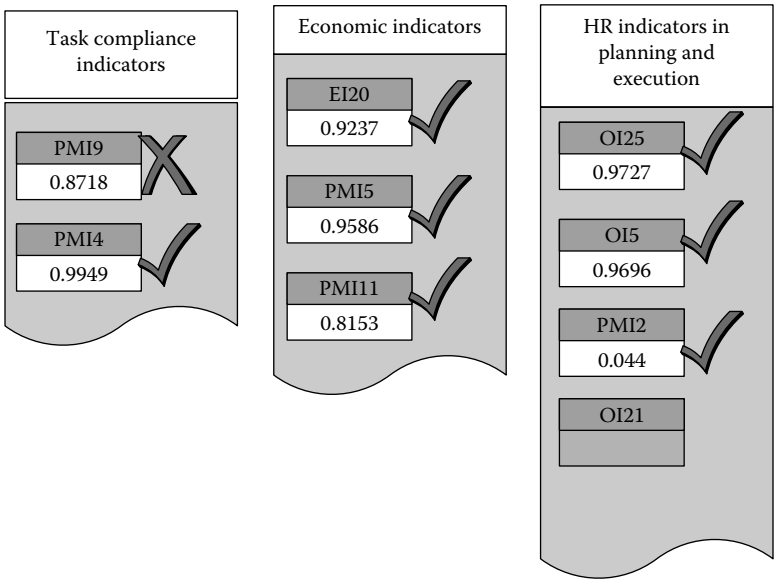


FIGURE 8.51
Summary of efficiency within references and outside limits.

8.3.8.2 Scorecard for Level 1 in the Press

These indices simply refer to the absence of outage for maintenance. The OI11 indicates all unavailability is correlated with corrective urgency, which is minimal in this case. At the same time, however, it is a negative concept given its propensity to promote the image of a maintenance department devoted to fighting fires (Figure 8.52)

In Figure 8.53, the task compliance indicator and the corresponding indicators are outside references; we also see an increase in overtime, but this is a temporary problem created by the installation of new machinery.

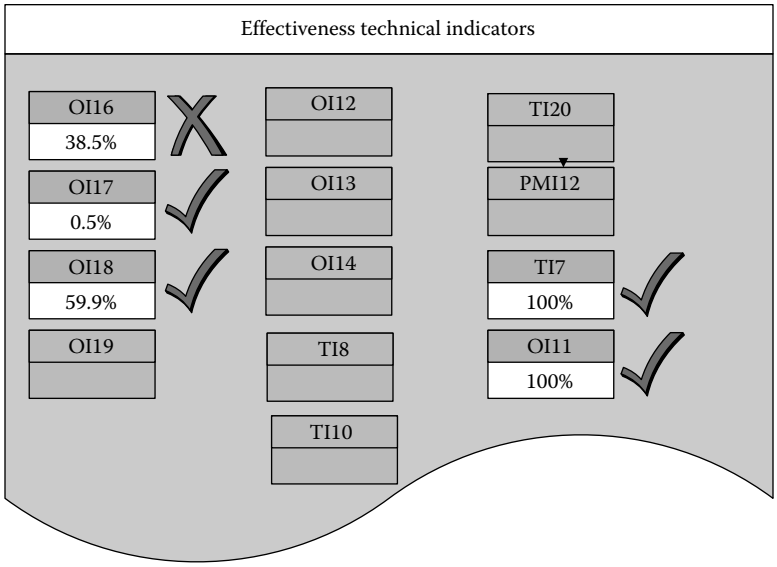


FIGURE 8.52
Summary of effectiveness within references and limits for the press.

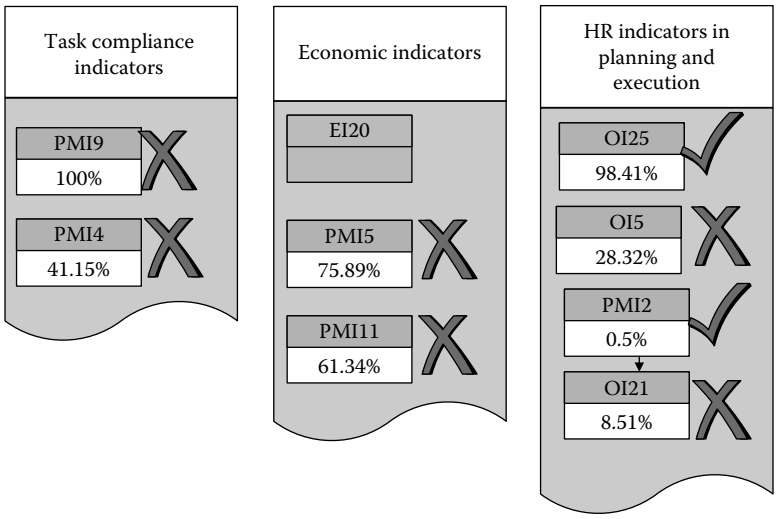


FIGURE 8.53
Summary of effectiveness within references and outside limits outside for the press.

Cost-efficiency is a cause of concern when the budget provides few resources for preventive maintenance, opting instead for corrective maintenance. The accuracy of the predictions of economic values is below that recommended by international agencies.

8.4 Level *n* Contribution to the Balanced Scorecard and Its Different Perspectives

The next task after auditing a level and obtaining the technical recommendations is moving these indicators to a scorecard based on the Kaplan & Norton's "Balanced Scorecard" [154]. The various indicators that will be audited within the different levels of evolution will help create the different perspectives of the control panel. Completing a level will improve a customer's (i.e., production) perception of maintenance and ensure the maintenance team is evolving and growing professionally. The indicators will be incorporated into the strategies designed to achieve the goals; uniting a series of objectives will show the improvement in the perspective under analysis (Figure 8.54).

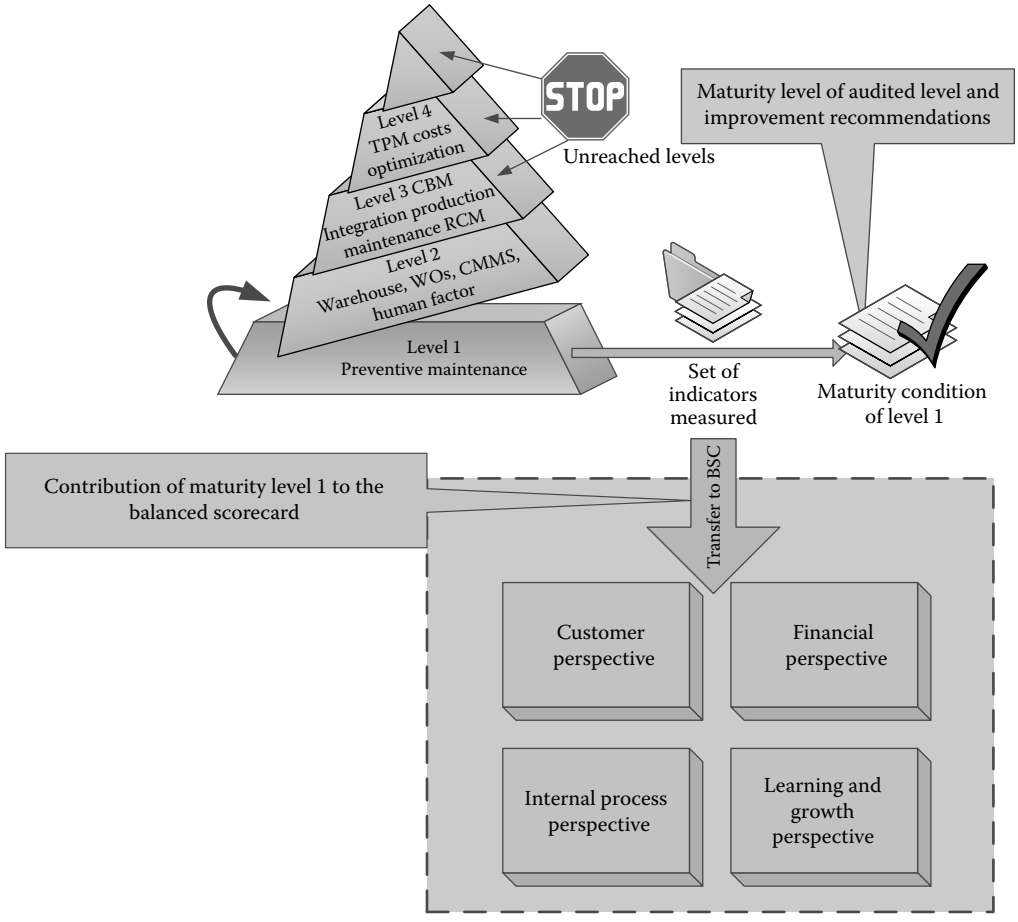


FIGURE 8.54
Contribution of level 1 to the balanced scorecard perspective.

Using Kaplan & Norton's "Balanced Scorecard" [154], the indicators are linked to their objectives and strategies. In the customer's perspective, there are four main objectives:

1. Improving maintenance policies
2. Improving quality
3. Improving maintenance response
4. Improving safety

Of these four objectives, the indicators associated with the maturity of level 1 on planning affect only the maintenance response improvement. This objective uses the strategies shown in Figure 8.55 to ensure compliance with the respective partner's indicators.

The figure shows strategies that have failed and indicates who is responsible for the failure. In this figure, the customer of planning and scheduling perceives the attempt to improve the maintenance response has failed in some of the tools used for this purpose. The evolution of these indicators is shown in the customer's perception of the department's improvement in response. It is important to emphasize the dynamic nature of the perceptions. These depend on strategies and objectives. For example, excessive delays in

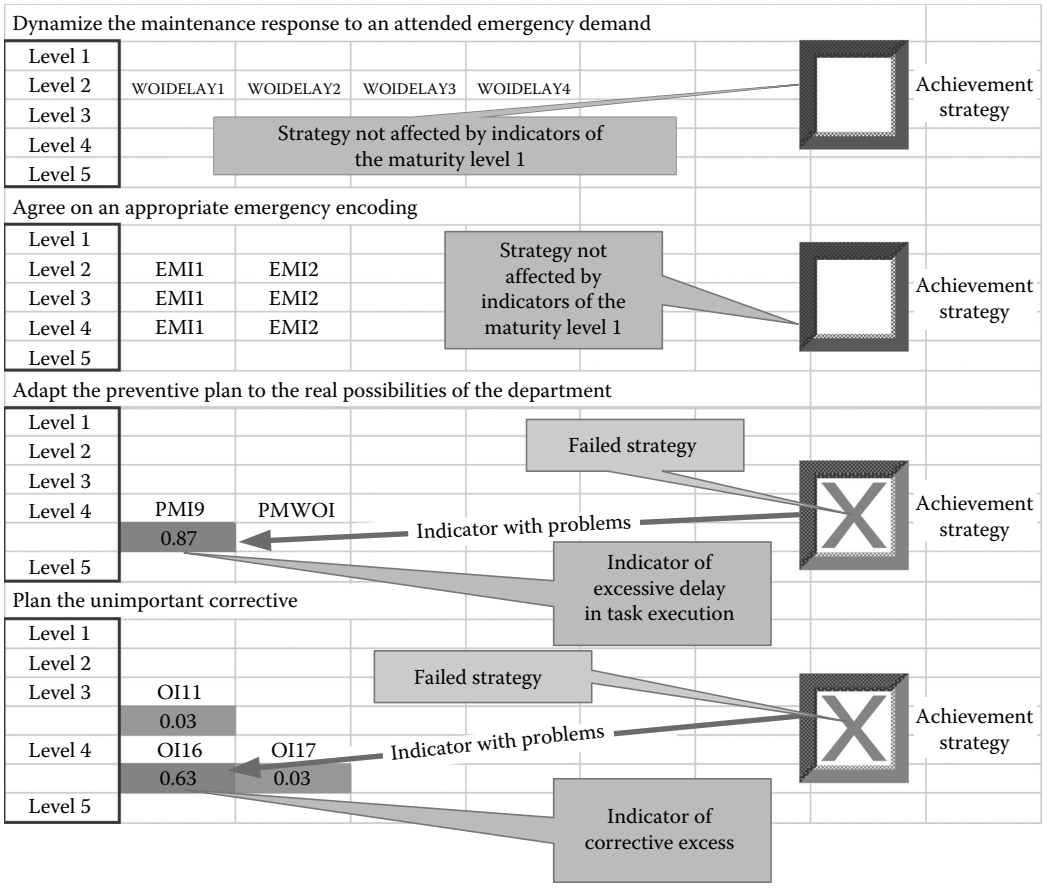


FIGURE 8.55
Customer perspective: improving maintenance response.

the implementation of planned maintenance can indicate a plan for preventive maintenance is not suitable for the department and, therefore, is not suitable to the response capacity required for corrective measures. At the same time, we see an excess number of corrective tasks, which can be the cause of this delay; this suggests the customer's perception of the maintenance department is not aligned with the plant's real needs.

It is logical that the indicator of the maturity of level 1 is planning. The distribution of prevention, the proper planning of the corrective measures scheduled, and the volume of the parameters are controlled by the planners on level 4. They can create templates or assign resources to lower levels. When maintenance is planned and scheduled, but there are some deficiencies in the goal of improving the maintenance response, the customer will perceive an excess of corrective and preventive maintenance.

The rest of the objectives are not affected by the indicators on level 1 of maturity.
In terms of the financial perspective, indicators on this level are aligned with two goals:

1. Improve availability
2. Improve costs

To improve availability, the indicators can be moved to the BSC, as shown in Figure 8.56.

All indicators involved in strategies for improving availability show positive results; the financial perspective is reinforced by the fulfillment of this objective on level 1 of maturity.

For the second objective, improving costs, Figure 8.57 shows the contribution indicators of level 1 maturity to improvement is positive with the implementation of a strategy for reaching consensus on a costs model.

All the contributions from level 1 to objectives aimed at improving the financial perspective are positive. Some strategies, such as energy consumption, are not measured by indicators of this level.

The perspective affected by indicators of this level concerns the internal processes of the department. To improve this perspective, the objectives are to

- Improve work organization
- Improve reliability
- Improve stock levels in maintenance stores
- Improve recruitment

Maturity level 1 provides indicators of two goals: to improve work organization and, to a lesser extent, to improve reliability. Figure 8.58 shows the influence of these indicators in the different strategies of the department. The failure of some indicators shows us the strategy to relocate staff properly is not achieved, but the use of the preventive and the allocation of times are within permissible values. In this aspect, then, the strategy has worked.

In the objective of improving work organization, level 1 shows positives value, except for the commitment to preventive and predictive maintenance where values are below the recommended levels. This suggests the need for a change in the allocation of tasks to operators, as was also evident in the preliminary findings at the end of the auditing process at this level.

The second objective is reliability improvement. The contribution to this objective is small but positive as seen in Figure 8.59.

The PMI2 indicator on the dedication to emergency work, that is, direct faults, presents values within those recommended by PMI2. We see positive movement toward the achievement of the ultimate goal of improved reliability.

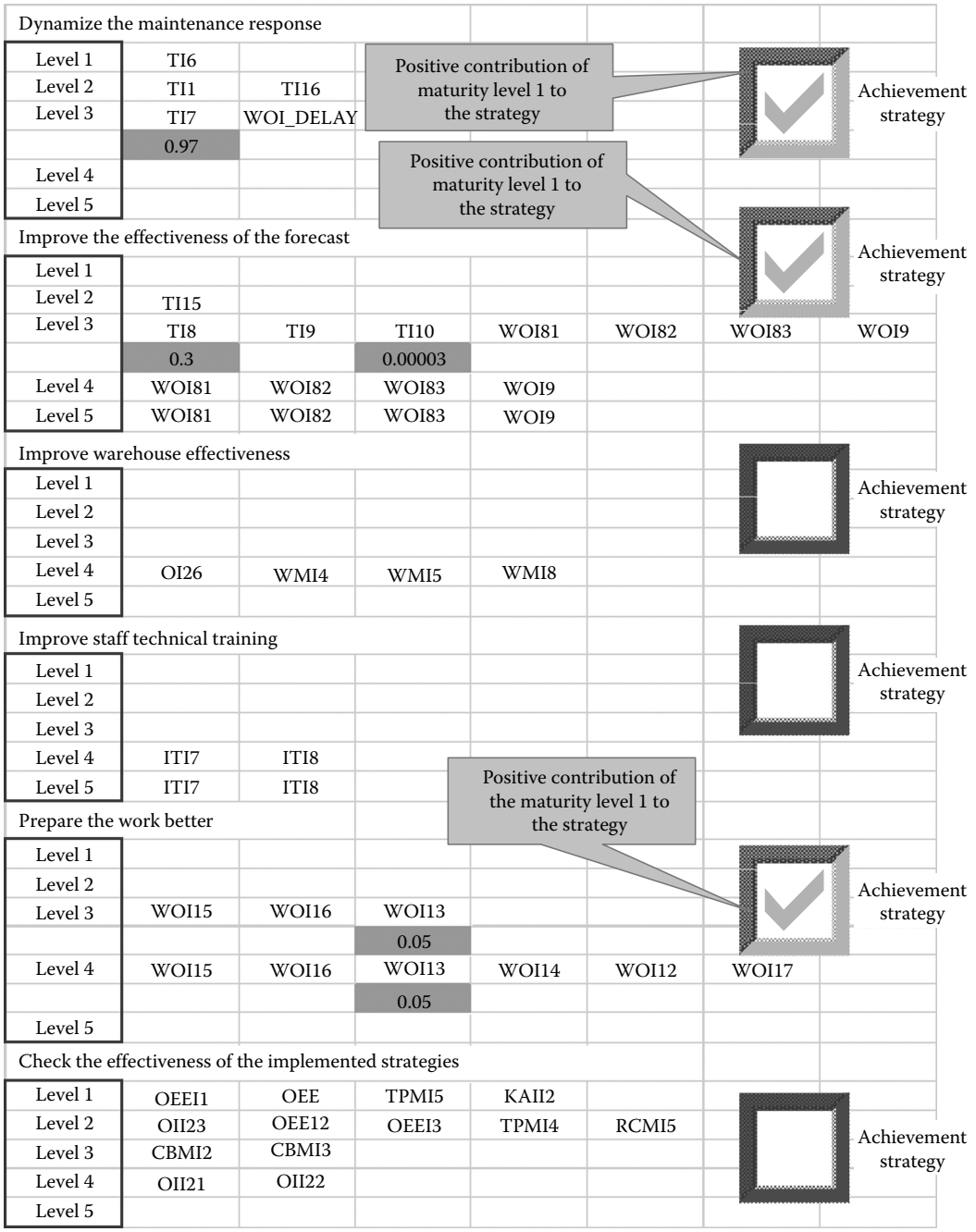


FIGURE 8.56
Financial perspective: improving availability.

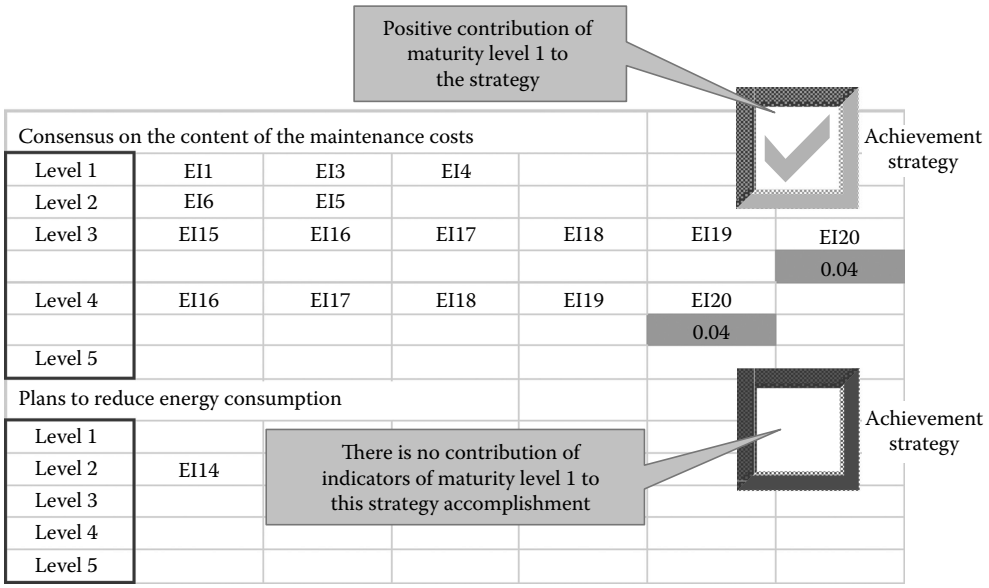


FIGURE 8.57
Financial perspective: improving costs.

The last two goals do not share any indicator with maturity level 1, or with learning and growth. This latter perspective is centered in the human factor and has no indicator on level 1. This is logical because it is a highly technical level linked to effectiveness and efficiency but without modifiable aspects by a human factor, that is, more or less formed, self-motivated, etc. (Figures 8.60 through 8.63).

The previous graphic shows the number of indicators with problems in the achievement of certain goals associated with improvement in the different perspectives. They are represented next to the indicators that are within the references or whose values can be considered admissible and positive when comparison points do not exist. It is noteworthy that in this industry of continuous process, all the indicators that appear in the control panel have been calculated for this level, that is, the model fits 100% without being deprived of indices.

8.5 Level 2 Evolution

The level 2 audit once we have passed the preventive maintenance test includes two necessary elements in maintenance management. One is proper document management including CMMS implementation of WOs and an efficient store. The other is the proper insertion of the human factor in maintenance functions, its treatment, and its growth (Figure 8.64).

The audit of the printing plant, as described before, finds different values because its production policy is radically different from the paper industry. What is required of the maintenance department will, therefore, be different as well. The closing of production generally occurs round 10 or 11 o'clock in the evening; but depending on the next day's edition of the newspaper, production may last until 1, 2, or 3 o'clock in the morning. The product

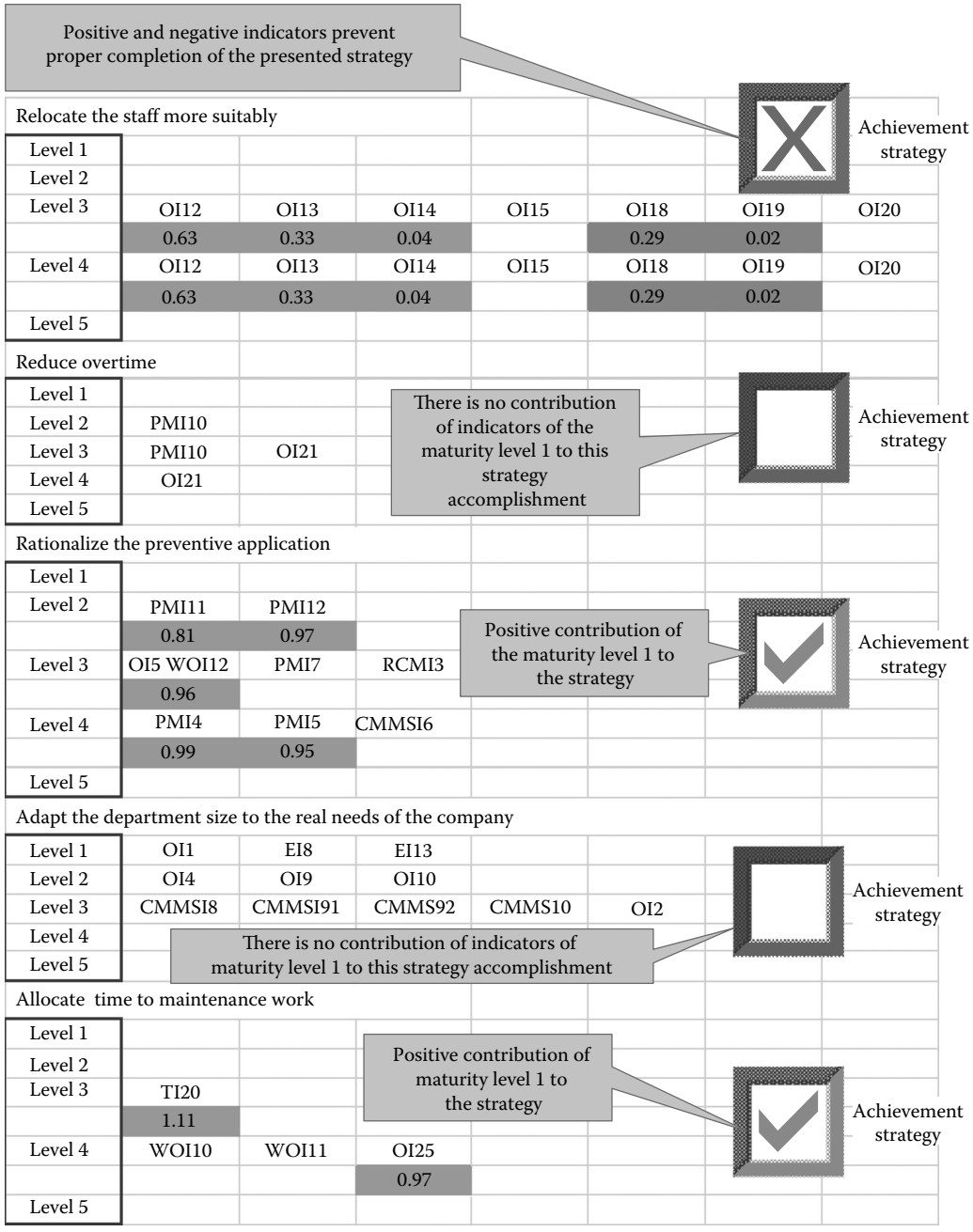


FIGURE 8.58
Perspective of internal processes: improving work organization.

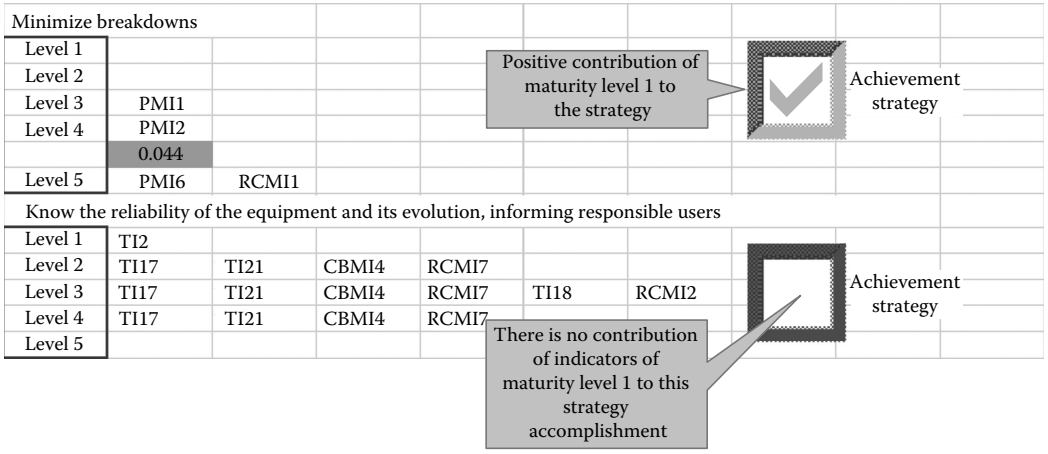
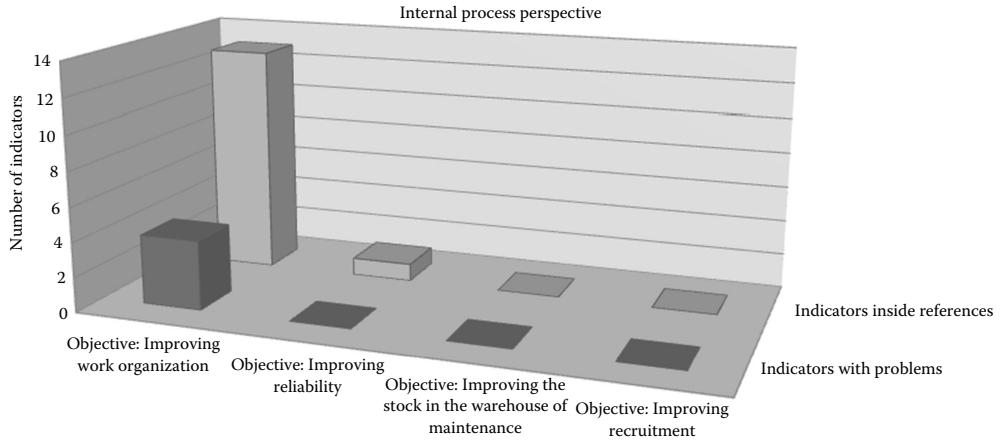


FIGURE 8.59
Perspective of internal processes: enhancing reliability.



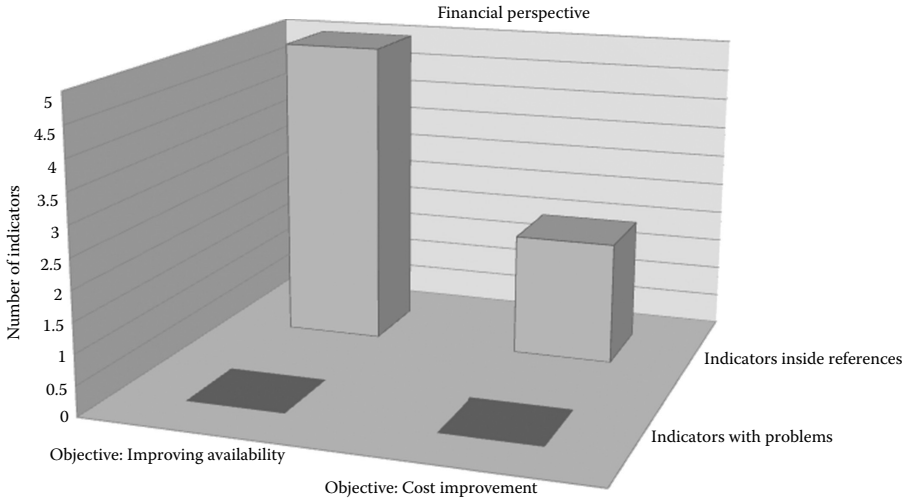
	Objective: Improving work organization	Objective: Improving reliability	Objective: Improving the stock in the warehouse of maintenance	Objective: Improving recruitment
Indicators with problems	4	0	0	0
Indicators inside references	13	1	0	0

FIGURE 8.60
Internal processes perspective: indicators related to objectives for the paper industry, maturity level 1.

is then distributed; from 6 o'clock in the morning, copies are dispersed throughout very disparate geographical locations.
The product has two characteristics inherent to its production system:

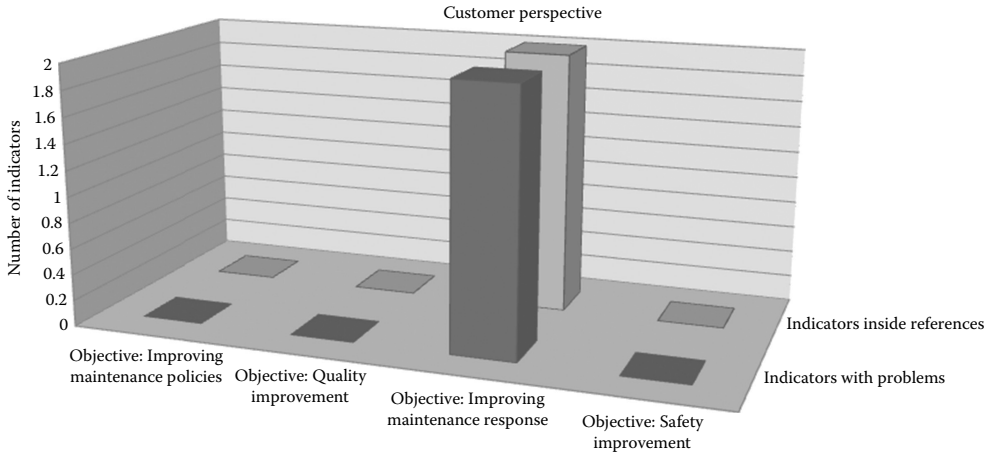
1. Its quick expiration
2. The impossibility of substitution

Of course, the newspaper automatically expires for obvious reasons. Production units lost because of faults may not be recovered because the production interval time is unrepeatable. In addition, the product cannot be replaced by any other content; stocking is



	Objective: Improving availability	Objective: Cost improvement
Indicators with problems	0	0
Indicators inside references	5	2

FIGURE 8.61
Financial perspectives: indicators related to objectives for the paper industry, maturity level 1.

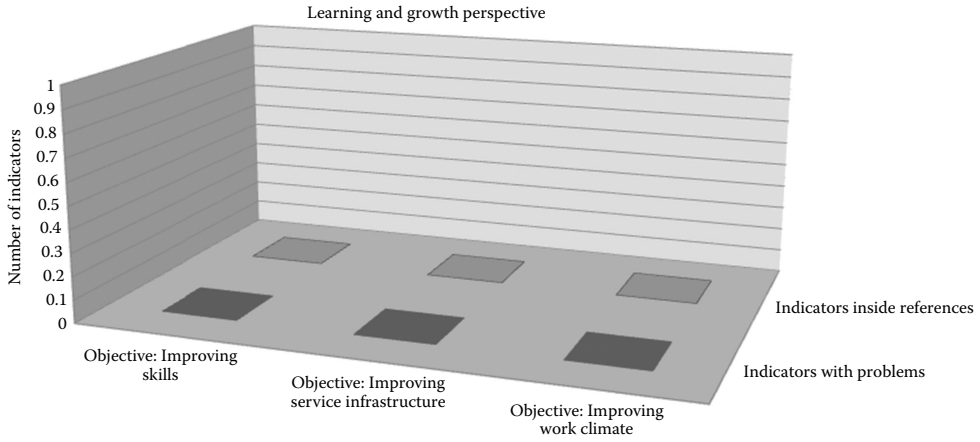


	Objective: Improving maintenance policies	Objective: Quality improvement	Objective: Improving maintenance response	Objective: Safety improvement
Indicators with problems	0	0	2	0
Indicators inside references	0	0	2	0

FIGURE 8.62
Customer perspective: indicators related to objectives for the paper industry, maturity level 1.

inapplicable, and the product must be newly manufactured and distributed without making replacements. This requires the availability of productive assets during the work interval (the highest priority), even with some redundancies, to reach the set goal.

This distinguishing feature of the production process indicates a wider development of the financial perspective by improving assets and reducing the unit cost. In addition,



	Objective: Improving skills	Objective: Improving service infrastructure	Objective: Improving work climate
Indicators with problems	0	0	0
Indicators inside references	0	0	0

FIGURE 8.63
Learning and growth perspective: indicators related to objectives for the paper industry, maturity level 1.

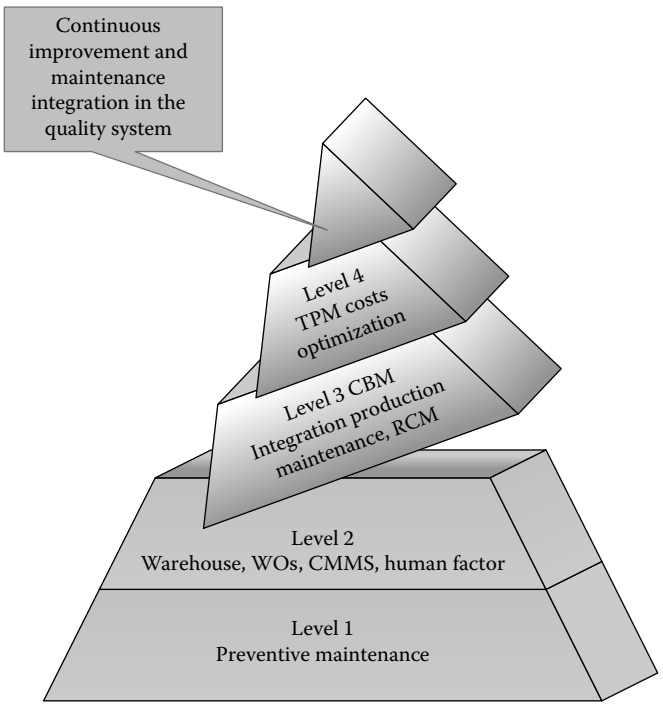


FIGURE 8.64
Level 2 of maintenance evolution.

the idiosyncrasy of the production system negates the use of indicators associated with the corresponding maturity level, so these should not be considered in certain areas. In this industry, the existence of an interval of time for production allows the company to use the rest of the day or a large part of it for repairs or preventative maintenance. Scheduled maintenance causing unavailability, scheduled stops, etc., and the indicators that depend on them are, therefore, meaningless.

A quick look at the indicators on level 1 of the press indicates that the different perspectives are severely affected by the negative indices associated with this maturity level. This also implies the need to overcome the same. The client, financial, and internal processes are adversely affected by the indicators.

The financial perspective is affected by extra hours outside reference values to improve availability; availability is achieved but with an investment of extra hours above the 6% recommended.

In terms of the client perspective, the objective of improving the maintenance response is affected by the department's use of excessive corrective maintenance. The customer perceives this as a lack of planning, suggesting the need for more preventive maintenance.

Finally, the internal processes are affected negatively by the failure of the preventive maintenance associated with low investment in this type of maintenance; this, in turn, triggers the worsening of the various perspectives.

This projection of the different BSC perspectives along with the validation of the negative indicator obtained from the surveys concerning work execution can lead to an effective and efficient program of planned maintenance, bypassing the recommendations on indicators with a negative rating.

It is important to emphasize that if the audit had been performed using the survey method as is proposed in much of the literature, highlighting the Venezuelan COVENIN standard, a successful program of preventive maintenance could have been established. If an audit had been performed using only numerical indicators, the recommendations would lack the knowledge of the users and stakeholders.

The scheduled maintenance at maturity level 1 should audit the following level 2 factors:

- Maintenance warehouse and purchasing management
  - Purchases
  - Spare Parts
- WO system
- Computerized maintenance management system (CMMS)
- Staff and subcontractor management
  - Structure of the department's staff and definition of jobs
    - Structure of the department's staff and definition of jobs
    - Labor climate
    - Motivation and training
  - Subcontracting

8.5.1 Maintenance Warehouse and Purchasing Management

Warehouse management is a first step in the search for efficiency and effectiveness because of its impact on the customer. The evaluation of the logistics system for spares is divided into four parts, with marked differences in the impact on the customer, internal

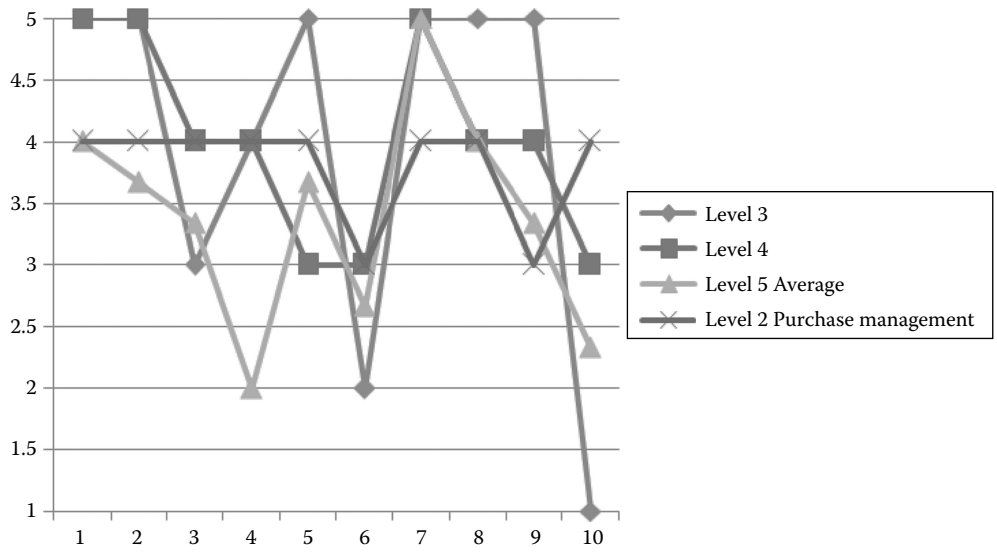


FIGURE 8.65
Surveys of maturity level 2 for the press: purchasing procedure.

TABLE 8.26

Surveys of Maturity Level 2 for the Press: Purchasing Procedure

	Purchase Procedure						
	Level 3	Level 4	Level 5 Operator 1	Level 5 Operator 2	Level 5 Operator 3	Level 5 Average	Level 2 Purchase Management
1	5	5	5	2	5	4.000	4
2	5	5	5	2	4	3.667	4
3	3	4	5	2	3	3.333	4
4	4	4	1	2	3	2.000	4
5	5	3	5	2	4	3.667	4
6	2	3	3	2	3	2.667	3
7	5	5	5	5	5	5.000	4
8	5	4	5	3	4	4.000	4
9	5	4	5	2	3	3.333	3
10	1	3	2	2	3	2.333	4

processes, and finance. For example, the translation of procedures into actions responds to the internal processes perspective (Figure 8.65 and Table 8.26).

The survey questions about the purchasing policy are on four levels, ranging from the direction of purchases up to the top level of the maintenance hierarchy. Despite being a multilevel survey, the answers show small differences; no more than a point separates respondents. There is a small discrepancy in the perception of spare parts; question four asks for respondents' perception of the purchasing procedure. There is a similarly small difference in question five, which asks about purchase orders, that is, whether they are of concern for maintenance or are simply focused on good prices, payment terms, etc. Finally, in question 10, there is a significant difference between the four responses; this is simply the product of a lack of understanding of the role of the purchasing department

TABLE 8.27

PURPROI Indicator before Hierarchical Numerical Validation

PURPROI	Purchase Procedure	
	Level 2	3.800
	Level 3	4.000
	Level 4	4.000
	Level 5	3.400
PURPROI Average		**3.800**

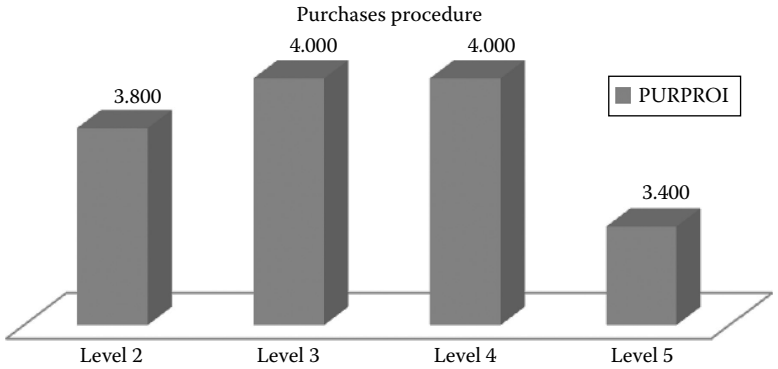


FIGURE 8.66
PURPROI indicators before hierarchical numerical validation.

in specifying the products to be purchased. This difference reflects economic concerns versus the technical efficiency sought by maintenance.

In Table 8.27, we see the average value for each hierarchical level. Individual values of 3.5 or higher and an overall value of 3.8 suggest incorrect perception (Figure 8.66).

To audit this level in the proposed model, the survey validation must use a series of numerical indicators proving the PURPROI indicator:

$$\text{PURPROI} = \text{Survey results (Purchases procedure)} \cdot \overline{\text{WMI6}} \cdot \overline{\text{WMI7}} \cdot \overline{\text{WMI9}} =$$

$$= \text{Survey results (Purchases procedure)} \cdot (1 - \text{WMI6})(1 - \text{WMI7})(1 - \text{WMI9})$$

Figure 8.67 shows the validation process; the indicators are used to validate the complementary WMI6, WMI7, and WMI9.

8.5.1.1 Indicator WMI6

The WMI6 indicator gives the proportion of urgent purchase orders:

$$\text{WMI6} = \frac{\text{Total number of urgent purchase orders}}{\text{Total number of purchase orders}}$$

This index has a value of 10.67%, very close to WCM references that suggest only 10% of the purchases should be made on an urgent basis.

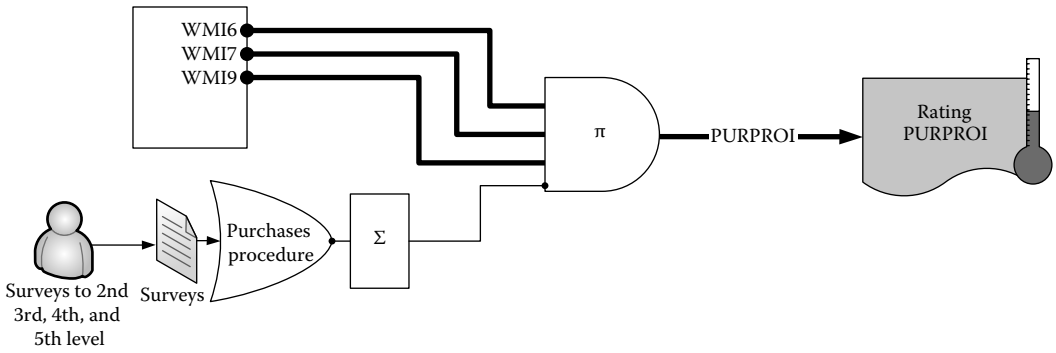


FIGURE 8.67
IPROCCOMP validation process.

8.5.1.2 Indicator WMI7

$$\text{WMI7} = \frac{\text{Total number of one article purchase orders}}{\text{Total number of purchase orders}}$$

Expenses generated by the issuance of a purchase order are fixed quantities that sometimes exceed the cost of the ordered part. The indicator displays values of 51.12%. This is too high. It indicates more than half the purchases are only a single article; this creates a high proportion of costs.

8.5.1.3 Indicator WMI9

It makes no sense for the head of maintenance to not be able to make purchases outside of the regulatory circuit of authorized purchases and suppliers.

Once we have calculated the validation indicators, we can calculate the PURPROI validated index. The value of this is 1.659. Again according to the conventional method, the surveys with the value of 3.8 pass the audit; the current purchasing procedure is endorsed by the four hierarchical levels involved (Table 8.28).

However, the validation indicators indicate a significant decrease in the indicator and, therefore, in the result of that aspect at the end of the audit; the perspective associated with that indicator will be severely affected by the value.

The second aspect to consider is supply management, or the fundamental knowledge of and correlation between maintenance data and purchasing (Table 8.29).

By observing the detailed responses in Figure 8.68, we see important differences in the knowledge of the supply policy as it is applied by the maintenance and purchasing department. The graph shows an almost permanent difference of two points in the perception of some aspects of the supply process. Table 8.30 shows the average values of the surveys according to hierarchical levels, as well as the final value of the index.

TABLE 8.28
PURPROI Validated

PLANT	Survey Results PURPROI	WMI6	WMI7	WMI9	PURPROI Validated
Press	3.8	10.67%	51.12%	X	1,659

TABLE 8.29

Surveys of Maturity Level 2 in the Press: Supply Management

	Supplier Management						
	Level 3	**Level 4**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**	**Level 2 Purchasing Management**
11	4	4	4	2	4	3.333	4
12	2	3	4	2	3	3.000	4
13	5	3	5	2	3	3.333	4
14	5	3	4	2	3	3.000	4
15	1	2	3	3	3	3.000	3
16	2	3	4	3	4	3.667	4

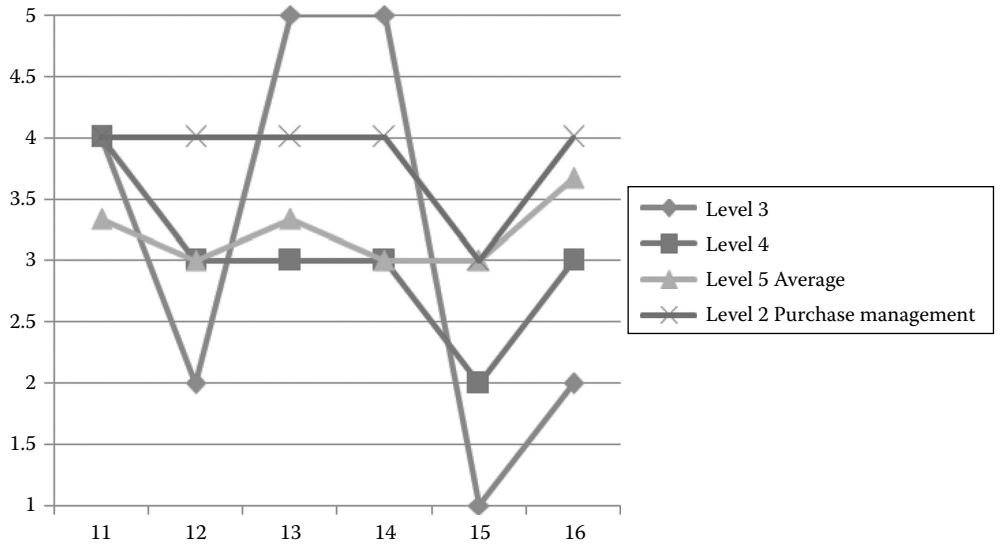


FIGURE 8.68
Surveys of maturity level 2 in the press: supply management.

TABLE 8.30

SUPMANI Hierarchical Indicator

SUPMANI	**Supplier Management**	
	Level 2	3.833
	Level 3	3.167
	Level 4	3.000
	Level 5	3.222
SUPMANI Average		**3.130**

The 3.130 value suggests the need for better internal communication and the clarification of procedures (Figure 8.69).

Another relevant aspect is the treatment of the materials upon arrival; answers in this section match much more closely, especially between two decision levels, such as purchasing and maintenance management (Figure 8.70 and Table 8.31).

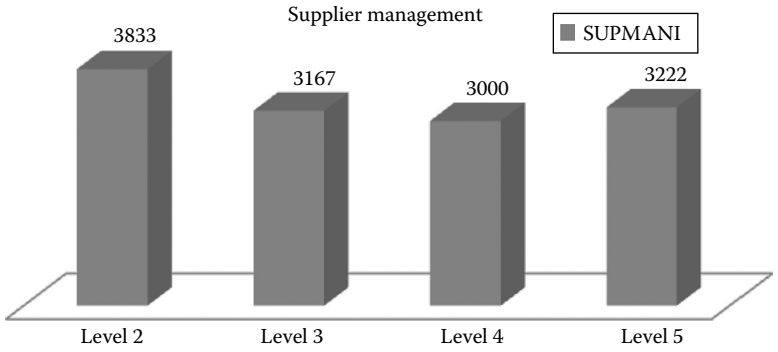


FIGURE 8.69
SUPMANI indicator before hierarchical numerical validation.

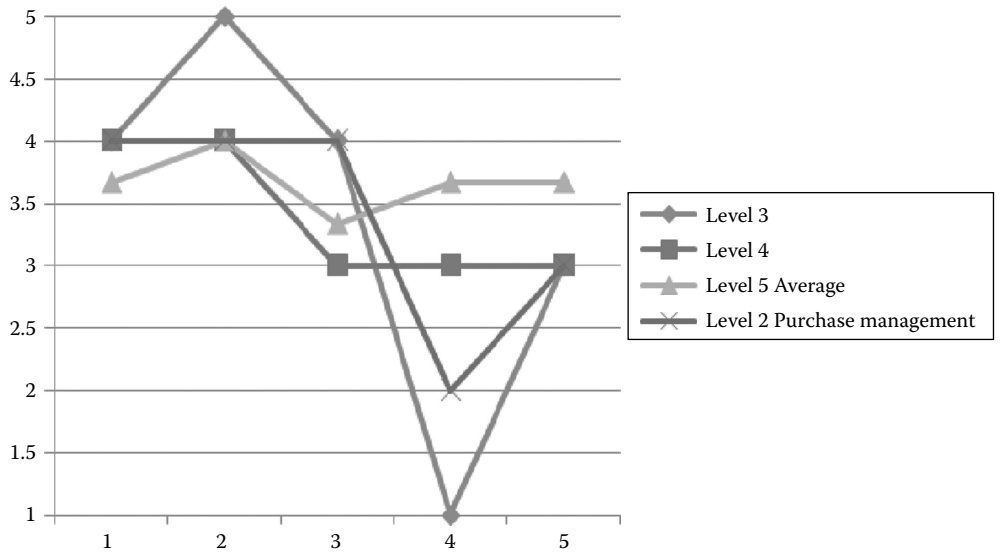


FIGURE 8.70
Surveys of maturity level 2 in the press: reception of materials.

In spite of the better matching, we will still need to make a recommendation for improvement in the receipt, handling, and storage of materials, given the dissatisfaction unanimously expressed in some responses (Figure 8.71 and Table 8.32).

Finally, and most importantly, along with the acquisition of spare parts, we need to consider the warehouse operation which stores parts and other material necessary to the maintenance equipment. Its effectiveness and efficiency are key in repair times, especially in emergency shutdowns when the appropriate sizing of the stock and accurate forecasting can prove invaluable (Figure 8.72 and Table 8.33).

Numerical indicators reflect if the impressions of the warehouse correspond among the different levels. There is a high correlation in the responses except for questions 13 and 14, in which maintenance is distant from purchasing when discussing success or failure. These differences are translated into the following indicators (Figure 8.73 and Table 8.34):

TABLE 8.31

Surveys of Maturity Level 2 in the Press: Reception of Materials

	Materials Reception						
	Level 3	**Level 4**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**	**Level 2 Purchase Management**
1	4	4	5	2	4	3.667	4
2	5	4	5	4	3	4.000	4
3	4	3	5	2	3	3.333	4
4	1	3	5	3	3	3.667	2
5	3	3	5	3	3	3.667	3

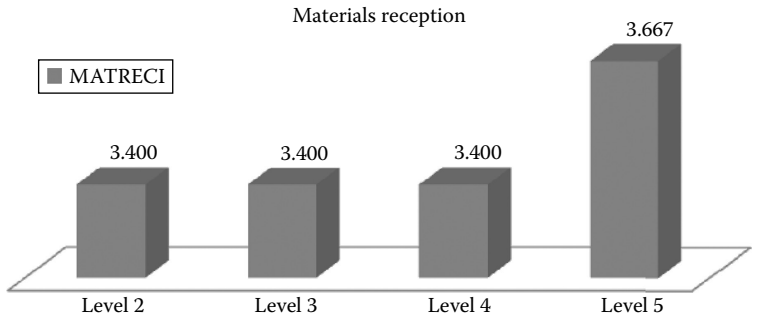


FIGURE 8.71
MATRECI hierarchy indicators before the numerical validation.

TABLE 8.32

MATRECI Indicator before Hierarchical Numerical Validation

MATRECI	**Materials Reception**	
	Level 2	3.400
	Level 3	3.400
	Level 4	3.400
	Level 5	3.667
MATRECI Average		**3.489**

Therefore, to validate the warehouse management, surveys use efficiency indicators (Figure 8.74). These indicators are WMI1, WMI3, WMI4, and WMI8 on inactive parts or jobs waiting for spare parts.

$$\text{WMANI} = \text{Survey results (Warehouse management)} \cdot \overline{\text{WMI1}} \cdot \text{WMI3} \cdot \text{WMI4} \cdot \overline{\text{WMI8}} =$$

$$= \text{Survey results (Warehouse management)} \cdot (1 - \text{WMI1}) \cdot \text{WMI3} \cdot \text{WMI4} \cdot (1 - \text{WMI8})$$

For the press, these indicators give the following results:

8.5.1.4 Indicator WMI1

$$\text{WMI1} = \frac{\text{Line articles in the inactive stock}}{\text{Total line articles in stock}}$$

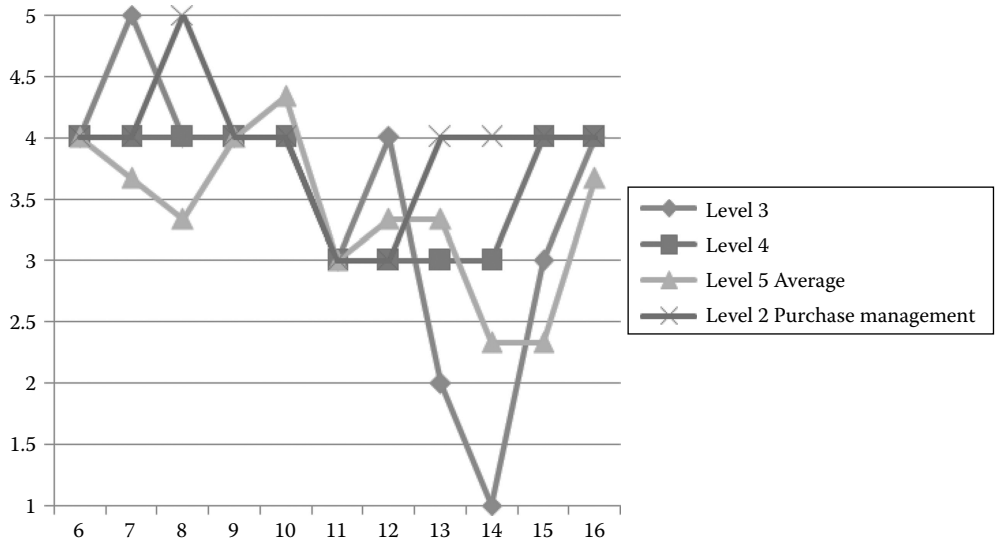


FIGURE 8.72
Surveys of maturity level 2 in the press: warehouse management.

TABLE 8.33

Surveys of Maturity Level 2 in the Press: Warehouse Management

	Warehouse Management						
	Level 3	Level 4	Level 5 Operator 1	Level 5 Operator 2	Level 5 Operator 3	Level 5 Average	Level 2 Purchase Management
6	4	4	4	4	4	4.000	4
7	5	4	5	3	3	3.667	4
8	4	4	4	3	3	3.333	5
9	4	4	5	3	4	4.000	4
10	4	4	5	4	4	4.333	4
11	3	3	5	3	4	3.000	3
12	4	3	5	2	3	3.333	3
13	2	3	5	2	3	3.333	4
14	1	3	2	2	3	2.333	4
15	3	4	4	1	2	2.333	4
16	4	4	3	4	4	3.667	4

The indicator displays values within WCM; specifically, the value is 9.27%, below the 10% value for inactive articles suggested by WCM.

8.5.1.5 Indicator WMI3

$$\text{WMI3} = \frac{\text{Total controlled spare parts in the warehouse}}{\text{Total available inventory (controlled + uncontrolled)}}$$

This indicator is 84.14%, well below the 98% proposed by the world-class indicators. These 14 points of difference represent a significant loss of efficiency.

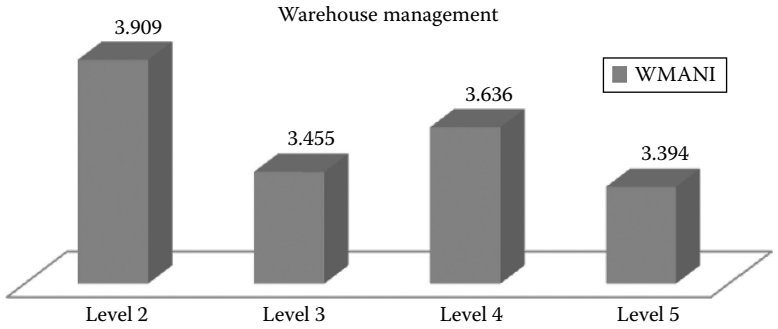


FIGURE 8.73
WMANI indicator before hierarchical numerical validation.

TABLE 8.34

WMANI Indicator before Hierarchical Numerical Validation

WMANI	**Warehouse Management**	
	Level 2	3.909
	Level 3	3.455
	Level 4	3.636
	Level 5	3.394
WMANI Average		**3.495**

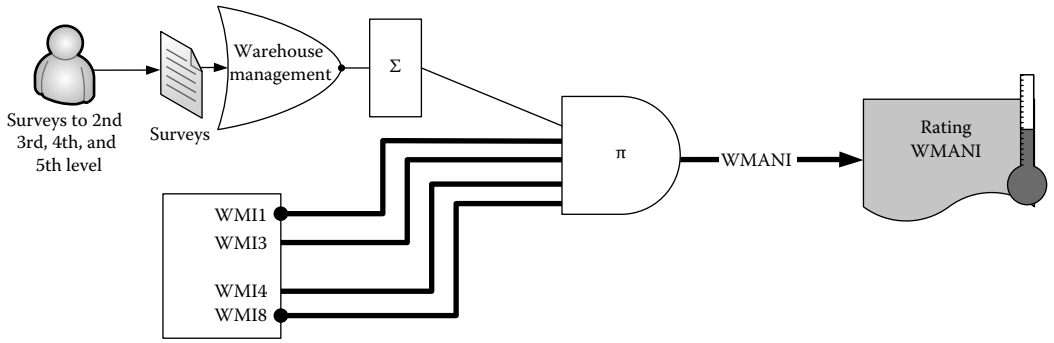


FIGURE 8.74
WMANI validation process.

8.5.1.6 Indicator WMI4 OI26

$$\text{WMI}\,4 = \text{OI}\,26 = \frac{\text{Total number of spare parts fulfilled by order}}{\text{Total number of spare parts requested}}$$

The stock is managed by maintenance, and the purchasing is associated with a request or need due to a fault; this is visible in the WOs awaiting parts. We can surmise that the percentage will be similar to that of the WOs awaiting parts, but as has been argued, this value is not conclusive.

8.5.1.7 Indicator WMI8

$$\text{WMI8} = \frac{\text{Maintenance work orders awaiting spare parts}}{\text{Total number of work orders}}$$

The world-class suggested value for this indicator is 2%; the indicator is very close to the number of WOs awaiting parts in the periods considered since the index has a value of 3%. This value has remained stable over the past 3 years, indicating the store has almost always had the spares required.

The WMANI validated indicator acquires the value of 2.583 when we combine the survey's results with the associated numerical indicators (Table 8.35).

Again, the survey and its results are framed by the numerical indicators. In this case, the differences are not as pronounced as in the purchasing procedure; the inefficiencies are less and the results of the surveys are more similar to the objective indicators.

In Figure 8.75, the survey's values, that is, obtained by classical methods, are far from the values after they are corrected and modulated by the associated indicators. When the two indicators are placed after the correction, we see that the procurement efficiency and the store would have been classified as good or satisfactory by traditional methods, while the proposed method refines and corrects these results presenting them as unsatisfactory.

In addition to the numerical indicators included in the survey validation, the control panel includes the following indices whose values in the press respond to the previous points:

TABLE 8.35

WMANI Validated

PLANT	Survey Results WMANI	WMI1	WMI3	WMI4	WMI8	WMANI Validated
Press	3.495	9.27%	84.14%	X	3%	2.583

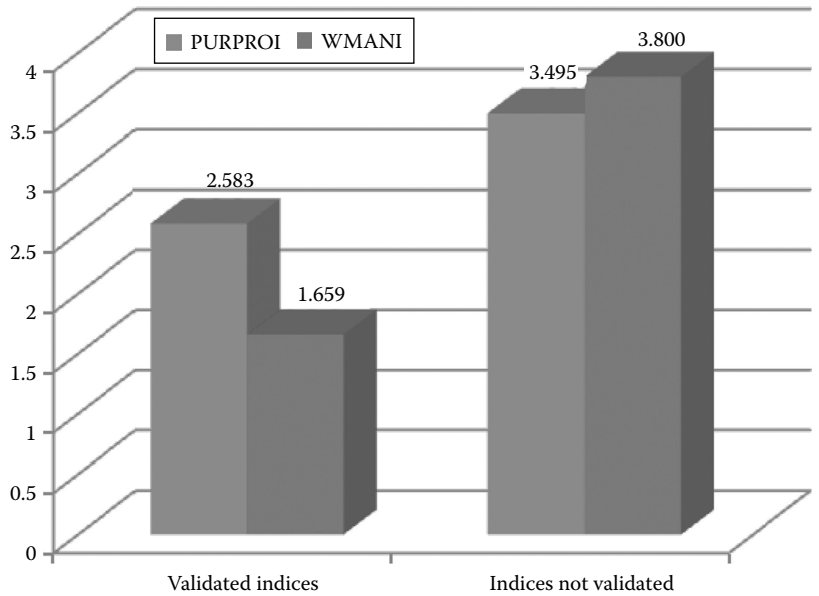


FIGURE 8.75
PURPROI and WMANI indicators before and after being validated.

8.5.1.8 Indicator EI12 WMI2

The renewal rate for the warehouse is too low, at 12.11%. This means the store is overstocked with spares. Recommended settings for rotation of stock, as stated in the previous chapter, are between 1.5 and 2.

8.5.1.9 Indicator EI11

The indicator has a historically low value of 7.2%. The common reference of 20%–30% for spare parts is indicative of an oversized stock of spare parts and is only justifiable if providers are unreliable making deliveries.

8.5.1.10 Indicator EI7

This value of 1.19% is within the threshold proposed by organizations and EFNMS SMRP that allow up to 3%.

8.5.1.11 Indicator WMI10

There are no quantified data on the maintenance cost of a purchase order.

The indicators next to those used in the data validation make up the scorecard for the stock. Comparisons with the benchmarks can be seen in Figure 8.76.

The summary of indicators relating to purchasing and stock does not give an overly optimistic view. Some indicators that are outside references are not quantified, such as the cost of a purchase order, which is unknown; therefore, its connotation is more negative than positive. This has an impact on the recommendations for improvement in the indicators for the next audit.

The indicators will be transferred to the balanced scorecard to observe the impact they have, both positive and negative in the different perspectives, distinguishing the technical recommendations for immediate improvements and noting the current contribution to the scorecard and the maintenance image within and outside of its environment.

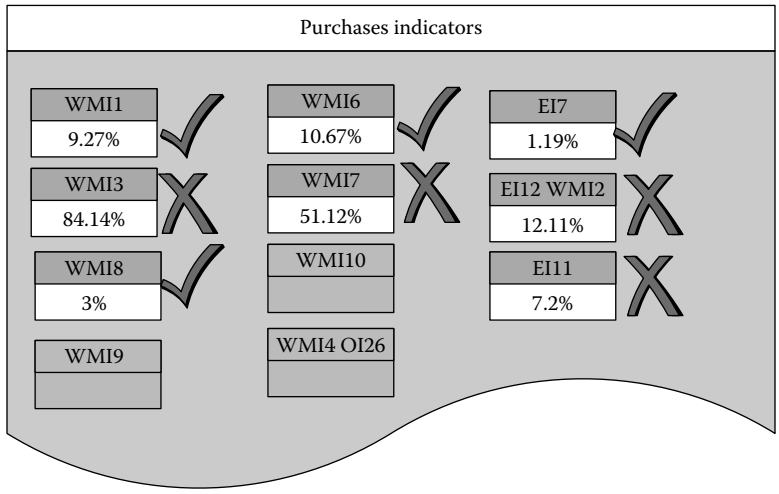


FIGURE 8.76
Summary of indicators of purchasing and stock within references and outside limits.

8.5.2 WOs System

In the proposed model, maturity level 2 also analyzes the organization's WO system, including the documentary flow generated by the WOs (Figure 8.77 and Table 8.36).

We see considerable divergence in the opinion of who can issue a WO, especially for safety equipment, spare parts, and the priorities for these. These differences will serve as the basis for recommendations for improvement.

Even with these slight discrepancies, the mean scores of the three levels in the surveys are high, close to 4; the average indicator is also satisfactory (Figure 8.78 and Table 8.37).

Figure 8.75 shows that, in fact, the different hierarchical levels, even with nuances, have a good impression of the WO system and the rigor in the compliance with it. Figure 8.79 contains the numerical indicators that examine the positive impression, ratifying it or presenting a different perception.

Validation, in this case, requires four indicators:

$$\text{WOSYSI} = \text{Survey results (WOs)} \cdot \text{WOI1} \cdot \text{WOI2} \cdot \text{WOI3} \cdot \text{WOI4}$$

These indicators represent budgetary reality and activity with the WO, that is, the reality of what they spent and what happened at the plant in availability. The indicators are described here.

8.5.2.1 Indicator WOI1

$$\text{WOI1} = \frac{\text{Maintenance labor costs over WOs}}{\text{Total costs of maintenance labor}}$$

The precision of the WO is reflected in the CMMS having an error of 6%; in other words, the indicator reaches a value of 94%.

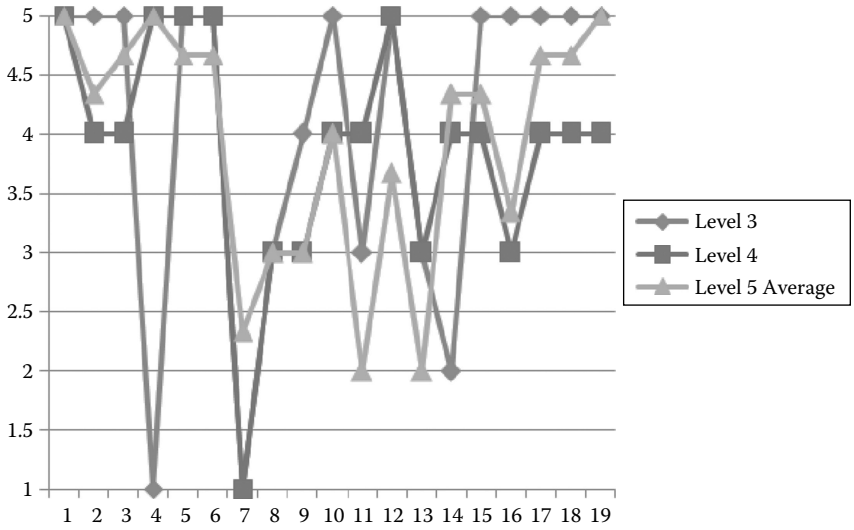


FIGURE 8.77
Surveys of maturity level 2 in the press: work orders.

TABLE 8.36

Surveys of Maturity Level 2 in the Press: Work Orders

	Work Orders System					
	Level 3	**Level 4**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**
1	5	5	5	5	5	5.000
2	5	4	5	4	4	4.333
3	5	4	4	5	5	4.667
4	1	5	5	5	5	5.000
5	5	5	5	5	4	4.667
6	5	5	5	5	4	4.667
7	1	1	1	3	3	2.333
8	3	3	4	2	3	3.000
9	4	3	4	2	3	3.000
10	5	4	4	4	4	4.000
11	3	4	1	2	3	2.000
12	5	5	1	5	5	3.667
13	3	3	1	2	3	2.000
14	2	4	5	4	4	4.333
15	5	4	5	4	4	4.333
16	5	3	5	2	3	3.333
17	5	4	5	5	4	4.667
18	5	4	5	5	4	4.667
19	5	4	5	5	5	5.000

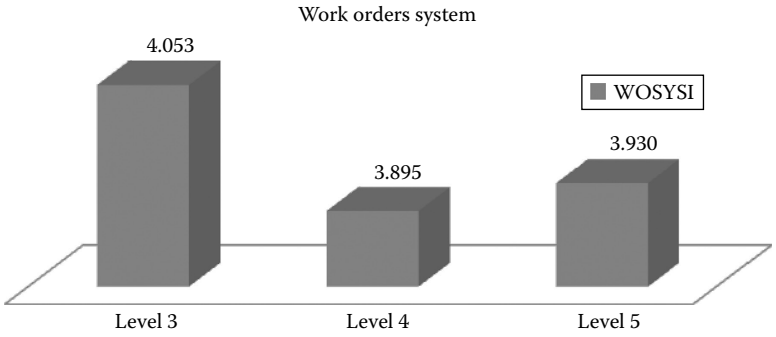


FIGURE 8.78
WOSYSI indicator before hierarchical numerical validation.

TABLE 8.37

WOSYSI Indicator before Hierarchical Numerical Validation

WOSYSI	**Work Orders System**	
	Level 3	4.053
	Level 4	3.895
	Level 5	3.930
WOSYSI Average		**3.959**

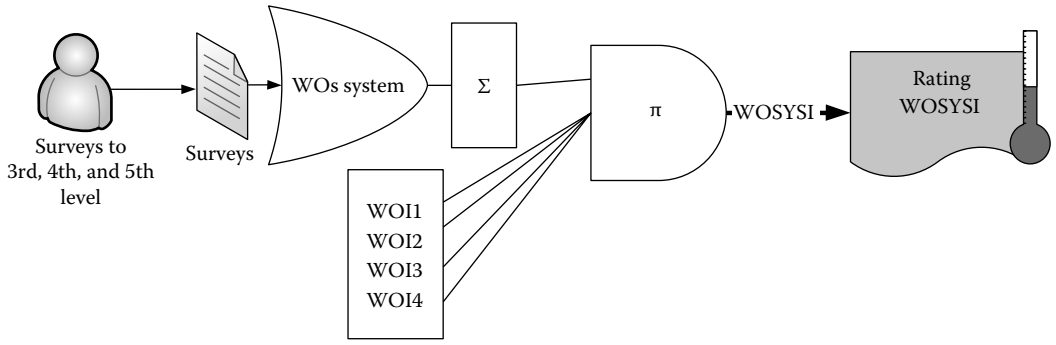


FIGURE 8.79
WOSYSI validation process.

8.5.2.2 Indicator WOI2

$$\text{WOI}2 = \frac{\text{Maintenance material costs over WOs}}{\text{Total costs of maintenance material}}$$

This indicator is 100% since the registered material costs are only for the WOs.

8.5.2.3 Indicator WOI3

$$\text{WOI}3 = \frac{\text{Subcontractors costs over WOs}}{\text{Total costs of maintenance contractors}}$$

As subcontractors constitute a significant amount of the work and maintenance budget, ignoring this indicator invalidates the WO result.

8.5.2.4 Indicator WOI4

$$\text{WOI}4 = \frac{\text{Maintenance inactivity registered in WOs}}{\text{Total maintenance inactivity}}$$

Production does not record downtime due to maintenance, so the only reliable record is in the WO. This implies a low reliability of these data.

There is no WOI3 indicator, and the WOI4 indicator value is unknown; this invalidates the indicator obtained from the surveys because the data do not represent the reality of the audited company. They do not reflect the subcontractors, an important part of the company. The work orders must be revised accordingly. In addition, a record of unavailability for production caused by maintenance, defects in quality of raw material, etc. must be established (Figure 8.80).

To sum up, the indicator must not omit important information that requires inclusion, for example, the staff in the external WOs or the parallel records in the SCADAS or production computer systems.

In addition to the indicators used in survey validation, the following indicators are calculated for the scorecard.

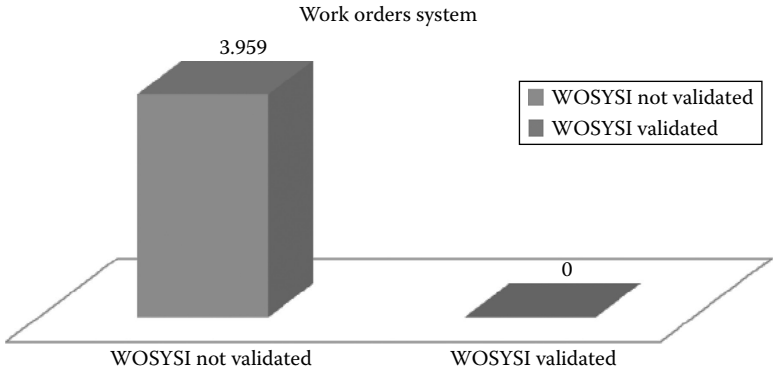


FIGURE 8.80
WOSYSI validated and not validated.

8.5.2.5 Indicators WOI5, WOI6, and OI7

There are no standing orders because this type of order is relegated to periods of assembly or modifications, inapplicable in this case. Therefore, the value of these three indicators is 0%.

8.5.2.6 Indicator OI22

$$\text{OI}22 = \frac{\text{Number of works orders performed according to planification}}{\text{Number of work orders programmed}}$$

In the WO total program, only 66% of the WOs were performed according to the planned schedule, mostly because of the increased preventive maintenance. This is a direct consequence of maturity level 1, which suffered in this aspect. The desired value is 80%, making this indicator unfavorable.

8.5.2.7 Indicator WOI15

$$\text{WOI}15 = \frac{\text{Number of work orders with more than 20\% of estimated labor}}{\text{Total number of maintenance work orders}}$$

The indicator has a value of 5.1%, making it world class. World-class value is 5%.

8.5.2.8 Indicator WOI16

$$\text{WOI}16 = \frac{\text{Number of work orders with more than 20\% of estimated materials}}{\text{Total number of maintenance work orders}}$$

WOI16 is 4.9%. It too enters world-class indices.

8.5.2.9 Indicator WOI81

The work emergency value is a very small percentage, 3.5%, lower than the recommended 5%. Therefore, it is close to the WCM.

$$\text{WOI81} = \frac{\text{Emergency orders}}{\text{Total number of work orders}}$$

8.5.2.10 Indicator WOI82

$$\text{WOI82} = \frac{\text{Preventive orders}}{\text{Total number of work orders}}$$

The WO volume for preventive maintenance, at 62.83%, is acceptable with respect to corrective and emergency WOs, except for the hours devoted to activities not classified in these three categories.

8.5.2.11 Indicator WOI83

$$\text{WOI83} = \frac{\text{Corrective orders}}{\text{Total number of work orders}}$$

The indicator is 24.83%, proportionally within recommended levels, with the exception of hours spent on tasks not related to the preservation of assets (Figure 8.81).

All these results project WCC indicators. But the surveys and some of the indices show strong deficiencies that call for reflection on certain aspects of the documentary flow of WOs and the veracity of the data. While the percentages are acceptable, being in a level 2 with a level 1 that has deficiencies in planning and work implementation, leads to major uncertainties in the data obtained.

8.5.3 Computerized Maintenance Management System

Another relevant aspect of management at this level is the proper implementation of CMMS in decision-making, as well as the accuracy and completeness of the system's information on the maintenance department (Figure 8.82).

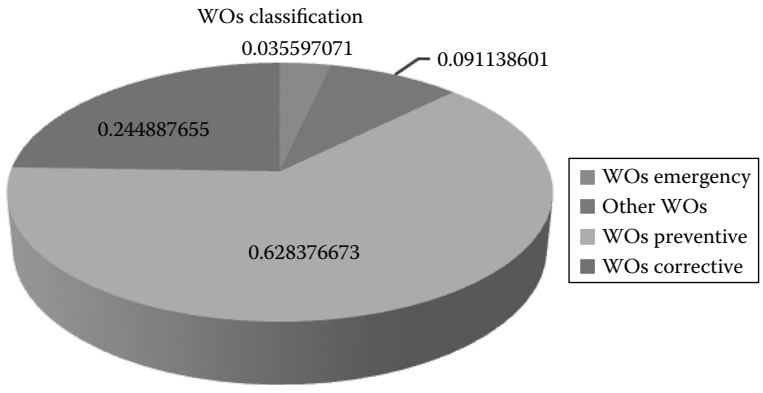


FIGURE 8.81
WO proportions by origin.

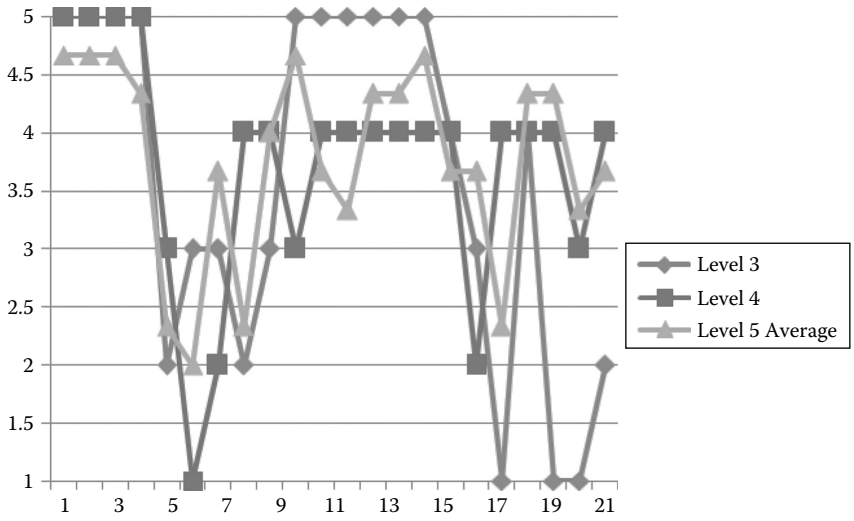


FIGURE 8.82
Surveys of maturity level 2 for the press: CMMS.

At the beginning, the surveys are fairly consistent. We observe a high correlation between the graphic patterns of responses. The discrepancies denote minor issues, such as ignorance of connectivity with other systems of the plant or the removal of indicators. All low-scoring matches converge in technical information, parts, etc. Thus, CMMS is apparently not useful as a reservoir of up-to-date information. This aspect of the data is worrying to the operators surveyed (Table 8.38).

These values translate into satisfactory overall results, around 3.5, as seen in Figure 8.83.

In the comparison chart, we see that the degree of overlap between the different sectors repeats the pattern of the responses. This value of the surveys is valid, with four indicators relating to the accuracy of data in the information system used. The indicators should reflect the system's validity as repository for information on costs, labor, material, and inventory assets (Figure 8.84).

The indicators required for validation are the following.

8.5.3.1 Indicator CMMSI1

$$\text{CMMSI1} = \frac{\text{Total labor costs in the CMMS}}{\text{Total maintenance labor costs in ERP}}$$

The CMMS indicator is 94%, close to world-class standards of accuracy and correlation of data.

8.5.3.2 Indicator CMMSI2

$$\text{CMMSI2} = \frac{\text{Total material costs in the CMMS}}{\text{Total material costs in ERP}}$$

TABLE 8.38

Surveys of Maturity Level 2 for the Press: CMMS

	Computerized Maintenance Management System					
	Level 3	**Level 4**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**
1	5	5	5	5	4	4.667
2	5	5	5	5	4	4.667
3	5	5	5	5	4	4.667
4	5	5	5	4	4	4.333
5	2	3	2	2	3	2.333
6	3	1	1	2	3	2.000
7	3	2	4	4	3	3.667
8	2	4	1	3	3	2.333
9	3	4	4	4	4	4.000
10	5	3	5	5	4	4.667
11	5	4	5	3	3	3.667
12	5	4	4	3	3	3.333
13	5	4	4	5	4	4.333
14	5	4	4	5	4	4.333
15	5	4	5	5	4	4.667
16	4	4	4	4	3	3.667
17	3	2	5	3	3	3.667
18	1	4	1	3	3	2.333
19	4	4	5	4	4	4.333
20	1	4	5	4	4	4.333
21	1	3	5	2	3	3.333
22	2	4	5	3	3	3.667

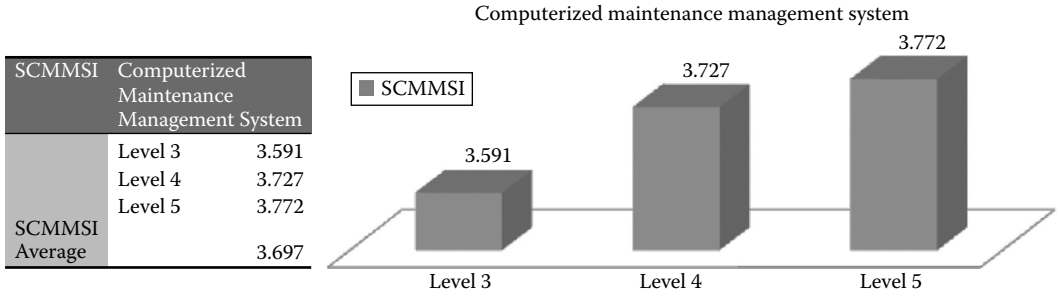


FIGURE 8.83
SCMMSI indicator before hierarchical numerical validation.

The CMMS incorporates the costs of materials. The correlation of total maintenance costs and the CMMS records is 78.18%, lower than the suggested value of 80%, but the calculation may not have considered depreciation, obsolescence, etc.

8.5.3.3 Indicator CMMSI3

$$\text{CMMSI}3 = \frac{\text{Total subcontractors' costs in the CMMS}}{\text{Total subcontractors' costs in ERP}}$$

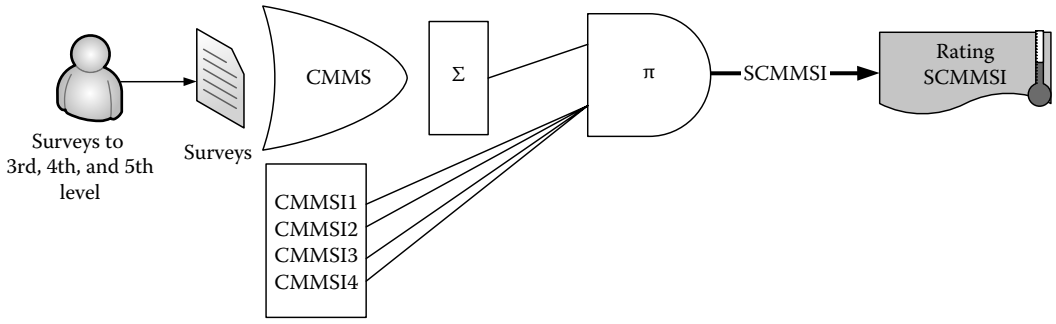


FIGURE 8.84
ISISGMAO ISISCMMS validation process.

CMMS does not incorporate subcontracting data; therefore, the value of this indicator is zero. As with WOs, this means that a percentage of costs and jobs are outside of conventional limits.

8.5.3.4 Indicator CMMSI4

$$\text{CMMSI}\,4 = \frac{\text{Total number of machines in the CMMS}}{\text{Total number of machines registered in the plant}}$$

All productive assets are found in the CMMS, so the value of this indicator is 100%.

Figure 8.82 presents the indicator obtained from the surveys; it reaches a value of 3.697. In contrast, the validated indicator is 0 because of the lack of data in CMMS on subcontracting (Table 8.39).

The center bar in Figure 8.85 shows the value of the validation of the surveys for the rest of parameters, leaving out subcontracting. This indicator shows a significant decline but maintains a value of 2.71 on 5; this is not fully satisfactory but it is better than zero. Contracts must be included in the system to reflect a substantial percentage of the work done on some of the assets (Figure 8.85).

In addition to the validated indicators, the following are incorporated into CMMS.

8.5.3.5 Indicator OI24

This indicator shows that 100% of the maintenance staff handle the equipment and enter data, making it a very positive aspect of implementation. This indicator will improve learning and growth by involving staff in a multilevel tool formerly relegated to directors. It will also positively impact an employee's skills.

TABLE 8.39
SCMMSI Validated

PLANT	Survey Results SCMMSI	CMMSI1 (%)	CMMSI2 (%)	CMMSI3 (%)	CMMSI4 (%)	SCMMSI Validated
Press	3.697	94	78.18	0	100	0

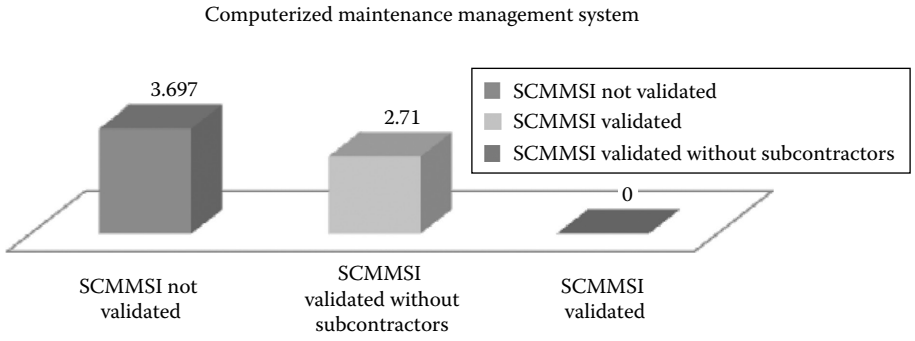


FIGURE 8.85
SCMMSI with different validations.

8.5.3.6 Indicator CMMSI5

The value of CMMSI5 is 84.14%. There is a lag between the actual number of spares and those indicated in CMMS as was the case with economic indicators and warehouse management. The value is far from world-class rates, but it is not a cause for concern.

8.5.3.7 Indicator CMMSI7

$$\text{CMMS7} = \frac{\text{Total maintenance cost of an equipment in the CMMS}}{\text{Total maintenance costs in ERP}}$$

Associated costs or costs charged to specific equipment are 85% of the total suggested amount. This is partially satisfactory considering that 15% of the maintenance budget lacks specific allocation for a given asset. This means relevant costs can be masked. The trend is positive; the index tends to increase.

8.5.4 Personnel Management and Subcontracting

The first of the analyzed aspects in the management of the staff corresponds to the definition of the job and the treatment of this definition by the relevant technical and human resources managers (Figure 8.86).

The technical responses level and the management are very consistent and match well. There are two discrepancies in versatility; the maintenance head knows the practices and priorities and stresses technical requirements while human resources search for capabilities and skills (Table 8.40).

The survey results and their average values yield very high figures. Responses are similar, with the indicator of job description high and positive. The surveys were carried out in the two departments involved, so we can conclude the jobs and the associated processes are correctly described.

The second aspect to consider is the mission of the department and the labor climate. The answers comply with all the stereotypes of the maintenance staff; human resources do not see any insulation of the department, but the staff see themselves as a separate group. This is common to all teams. They note a zero rotation in the organization; the sense of isolation is less pronounced when people are assigned to production, to maintenance, to quality, etc. The isolation is reflected in the absence of a career plan that usually exists in

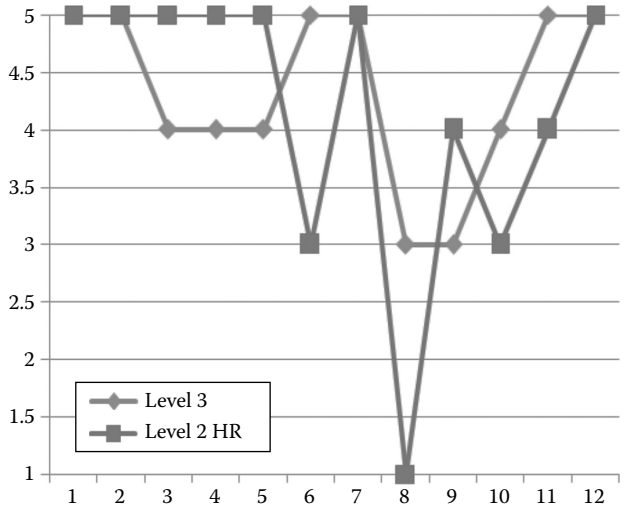


FIGURE 8.86
Surveys of maturity level 2 in the press: the workplace.

TABLE 8.40
WPLACEI Hierarchical Indicator

WPLACEI	**The Workplace**	
	Level 3	4.333
	Level 2 HR	4.167
WPLACEI Average		**4.250**

other departments. Clearly, the feeling of having peaked and not being able to rise further in the organization can have a detrimental effect (Figure 8.87 and Table 8.41).

The data obtained from these surveys should be crossed with the employment climate surveys periodically conducted by human resources. A thorough reading of the correlation between employee satisfaction with maintenance and the results from the audit will validate the views stated (Table 8.42).

The last aspect of the human factor is motivation and the growth that occurs through training and learning on the job. These have particular relevance (Figure 8.88 and Table 8.43).

The answers to the questions reveal certain nuances of interest for the audit outcome. The first is that almost all answers go beyond the 3 rating; the respondents' assessments of motivation and maintenance training are generally positive (Table 8.44).

Figure 8.89 shows the validation process for the proposed indicators obtained from the surveys relating to motivation and training. In this case, it is not possible to access times for some of the validations, so this process should be done without them.

It is important to distinguish between indicators that are zero, as in the case of subcontracting in WOs or CMMS, which invalidate the survey and process, and indicators whose value is unknown and difficult or impossible to access for the purpose of the audit. This is the case for ITI7, ITI8, ITI9, and ITI10. These indicators relate to the time lost because of a lack of knowledge or the repetition of tasks with the same cause. Collecting such data requires absolute discretion because the data are very sensitive. In the case of disasters,

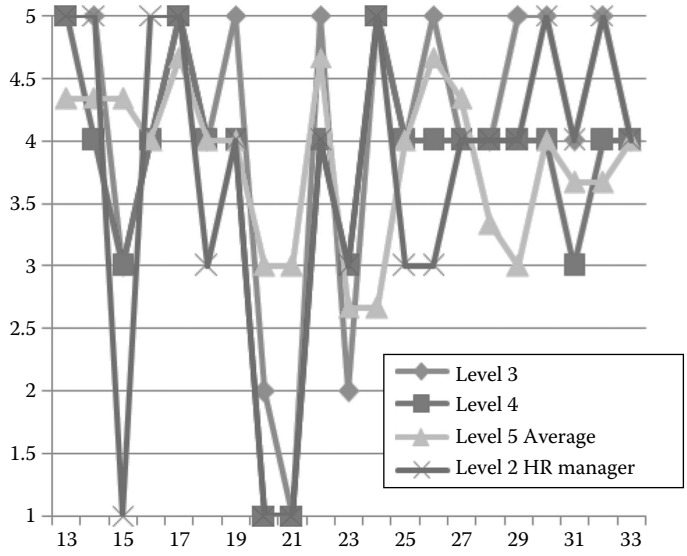


FIGURE 8.87
Surveys of maturity level 2 in the press: mission and work climate.

TABLE 8.41

Surveys of Maturity Level 2 in the Press: Mission and Work Climate

	Mission of the Work Climate Department						
	Level 3	**Level 4**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**	**Level 2 HR Manager**
13	5	5	5	4	4	4.333	5
14	5	4	4	5	4	4.333	5
15	3	3	5	4	4	4.333	1
16	4	4	3	5	4	4.000	5
17	5	5	5	4	5	4.667	5
18	4	4	4	4	4	4.000	3
19	5	4	4	4	4	4.000	4
20	2	1	3	3	3	3.000	1
21	1	1	4	2	3	3.000	1
22	5	4	5	5	4	4.667	4
23	2	3	2	3	3	2.667	3
24	5	5	2	3	3	2.667	5
25	4	4	4	4	4	4.000	3
26	5	4	4	5	5	4.667	3
27	4	4	4	5	4	4.333	4
28	4	4	2	4	4	3.333	4
29	5	4	3	3	3	3.000	4
30	5	4	4	4	4	4.000	5
31	4	3	3	4	4	3.667	4
32	5	4	3	4	4	3.667	5
33	4	4	4	4	4	4.000	4

TABLE 8.42

CLIMMISI Hierarchical Indicator

CLIMMISI	Mission of the Work Climate Department	
	Level 2 HR	3.714
	Level 3	4.095
	Level 4	3.714
	Level 5	3.825
CLIMMISI Average		**3.87**

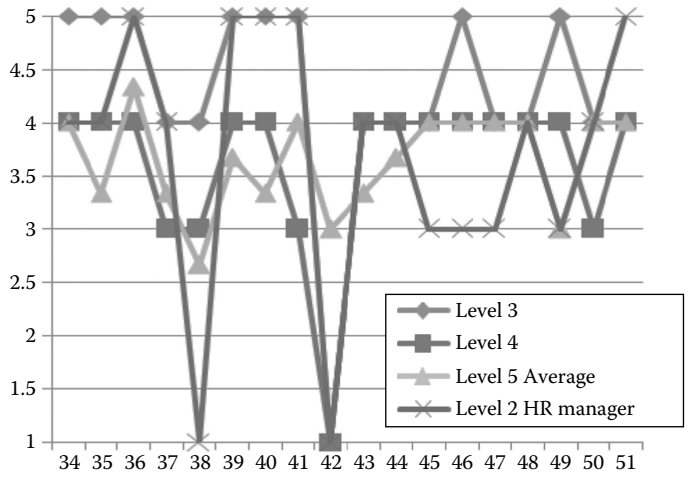


FIGURE 8.88
Surveys of maturity level 2 in the press: motivation and training.

it will be clear that a lack collective training has generated an accident. Otherwise, they are often not remembered, much less registered. Therefore, the process dispenses with them.

The same is true for T&UI1, T&UI2, and T&UI3. These are indicators of satisfaction with the equipment and technical staff; they do not reflect the employment climate survey of human resources and do not have access to them.

ITI3 and ITI4 are also human resources-related, as they show reading levels or skills and competencies. They should be recorded when special skills and capabilities are required by the maintenance operators.

Finally, the ITI5 indicator shows the correspondence between the training and the skills acquired and is not quantified. Again an indicator appears to be part of human resources, but is used here to get feedback on personal development with the training provided.

TPMI6 and HRI1 are indicators of absenteeism percentages and voluntary redundancies; here, we are dealing with zero indicators (there is no voluntary absenteeism or it is low). In the absence of other proposed indicators, we can conclude the surveys are fully validated by the present indicators.

The reduced model of Figure 8.90 with existing indicators endorses the surveys with the values of 3.81; these are satisfactory, indicating a motivated staff and training needs being met (Table 8.45).

TABLE 8.43

Surveys of Maturity Level 2 in the Press: Motivation and Training

	Motivation and Training						
	Level 3	**Level 4**	**Level 5 Operator 1**	**Level 5 Operator 2**	**Level 5 Operator 3**	**Level 5 Average**	**Level 2 HR Manager**
34	5	4	4	4	4	4.000	4
35	5	4	3	4	3	3.333	4
36	5	4	4	5	4	4.333	5
37	4	3	3	3	4	3.333	4
38	4	3	3	2	3	2.667	1
39	5	4	4	4	3	3.667	5
40	5	4	3	4	3	3.333	5
41	5	3	4	4	4	4.000	5
42	1	1	3	3	3	3.000	1
43	4	4	3	4	3	3.333	4
44	4	4	4	4	3	3.667	4
45	4	4	4	4	4	4.000	3
46	5	4	4	4	4	4.000	3
47	4	4	4	4	4	4.000	3
48	4	4	4	4	4	4.000	4
49	5	4	3	3	3	3.000	3
50	4	3	4	4	4	4.000	4
51	4	4	4	4	4	4.000	5

TABLE 8.44

MOTTRAI Hierarchical Indicator

MOTTRAI	**Motivation and Training**	
	Level 2 HR	3.722
	Level 3	4.278
	Level 4	3.611
	Level 5	3.648
MOTTRAI Average		**3.81**

This is a level where the first audit notes the absence or the lack of availability of many indicators. This has an immediate consequence in the control panel. The absence will prevent us from knowing with certainty the success of the strategy with which an indicator is associated; therefore, we cannot accurately estimate the achievement of the objectives of the strategies.

This does not this mean actions are not correct or are not aligned with the strategy. However, they are not being measured and, therefore, their impact is unknown. The observation of these shortcomings in the first audit will result in the indication of the proper placement of "sensor management" described in the previous chapter; subsequent audits will have access to these data and can follow up.

In addition to the proposed indicators such as validation, the control panel incorporates the following indicators.

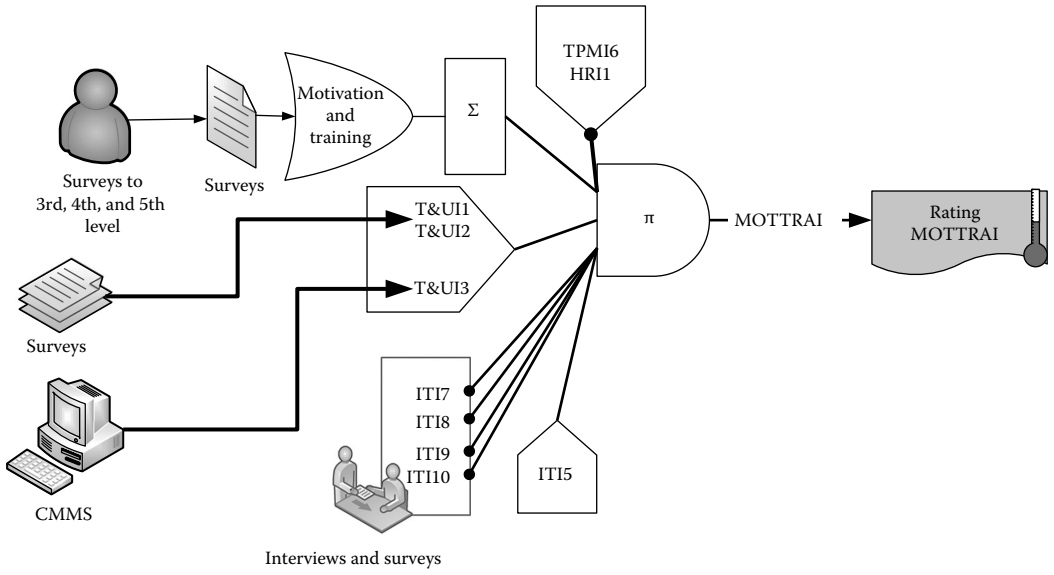


FIGURE 8.89
Validation processes for the MOTTRAI indicator.

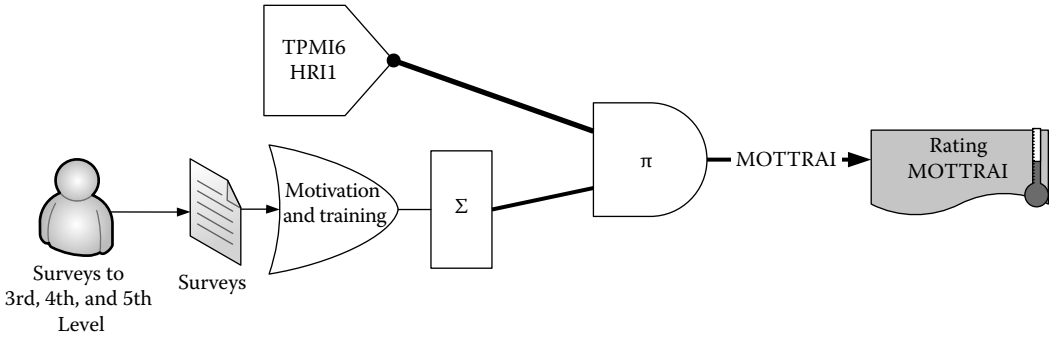


FIGURE 8.90
MOTTRAI indicator's validation process reduced.

TABLE 8.45
MOTTRAI Validated Indicator

PLANT	Survey Results MOTTRAI	TPMI6 (%)	HRI1 (%)	MOTTRAI Validated
Press	3.81	0	0	3.81

8.5.4.1 Indicator CMMSI8

The number of operators per supervisor is about eight. This is a reduced value since the maintenance team is small. Its reference value is within the proposed limits of 15–20.

8.5.4.2 Indicator CMMSI91

The ratio is identical to the previous one, that is, eight people. The value is within suggested references as it is less than 20 or 30 operators per planner.

8.5.4.3 Indicator CMMSI92

This indicator is pointless because training is outsourced or if it is done by in-house personnel, it is not posted or registered.

8.5.4.4 Indicator CMMSI10

The indicator has a null value in the absence of indirect administration staff seconded to maintenance. It does not satisfy the ratio of an administrator for every three or five workers; two administrators are necessary for that ratio.

8.5.4.5 Indicator EI8

$$\text{EI}8 = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Total maintenance costs}}$$

The indicator is 70.85%; this value is adapted to the historical trend of the 70–30 ratio. This value, however, must be calculated with caution, given the ignorance of the subcontracting staff; 30% of the maintenance budget that falls outside of this indicator may correspond to material and a subcontracted worker. If these mean a significant increase in labor, there will be a corresponding excess in the percentage.

8.5.4.6 Indicator EI13

The indicator is null because there is no indirect staff. The technical staff must assume these functions.

8.5.4.7 Indicator OI1

This indicator has a value of 10.66%, within references values, as it represents a normal percentage in industry.

8.5.4.8 Indicator OI2

There is no indirect staff. The indicator is null and valuation is necessarily negative.

8.5.4.9 Indicator OI3

There is no indirect staff. The indicator is null and valuation is necessarily negative.

8.5.4.10 Indicator HRI2

There is no immediate access to these data.

8.5.4.11 Indicator OI15

The indicator is 100%. Obviously, such versatility is a positive quality in a maintenance department. This is particularly useful in small teams to avoid duplication, especially when the team cannot be separated from a mixture of mechanics, electricity, and electronics.

8.5.4.12 Indicator OI10

All the staff work shifts, including the maintenance staff. The head of maintenance runs all shifts, even at night when production is concentrated. This democratizes all shifts, favors having internal staff, and boosts external perception.

8.5.4.13 Indicators ITI1 EI21

$$\mathrm{ITI}1 = \frac{\text{Total training budget}}{\text{Total number of employees}}$$

$$\mathrm{IE}21 = \frac{\text{Maintenance staff training cost}}{\text{Effectiveness of maintenance staff}}$$

The ITI1 and EI21 indicators have values of €115.7 and €150.5, respectively. These are the values per employee in training related to maintenance. They are too low; they show investment in maintenance training is higher but still inadequate. The value is lower than the one proposed by Padesky [257], that is, €2000 per year per employee on training. It requires reflection, given the technical sophistication of the machinery and suggests the need to update the technicians' knowledge.

8.5.4.14 Indicator ITI21

The indicator for the annual hours of training per employee and the budget for it are reduced, presenting a value of 8.6 h. This requires review.

8.5.4.15 Indicator ITI22

This indicator is not quantified. It refers to a type of training in the company that is neither formal nor measured. We must not create a negative indicator; instead, we need to use "sensor management" at the points that will allow measurement.

8.5.4.16 Indicator ITI6

In 2008, there were three trainers for a total of eight employees. This ratio is high. In addition, each trainer trained others for a small number of hours. This is an unmistakable sign of specialization, but because of the reduced number of hours taught, the indicator is not configured as relevant.

8.5.4.17 Indicator ITI11

ITI11 has a value of 0.3%. This figure is not in line with the reference value of 3% proposed by Padesky [257]. In fact, it is 10 times lower. It suggests a very small percentage of investment in training. This indicator is found in the SMRP and EFNMS works references.

8.5.4.18 Indicator OI23

OI23 is 0.6% and is below expectations. The reference value is 3%.

8.5.4.19 Indicator KAII4

This indicator is not quantified, nor are there formal presentations of suggestions. This seems to exist at the beginning, but no documents gather the information for systematization, rejection, or application. This leads to a recommendation for change in later steps.

The last aspect of the human resources staff is outsourcing, with external staff involved in the maintenance process. This aspect involves setting the recruitment policy, selecting subcontractors, and monitoring the work done.

The data relating to contracts and their process are scarce and conflicting, making them very unreliable (Figure 8.91 and Table 8.46).

We see a sharp difference in understanding. Recruiters think contracted maintenance is hired by the hour but the maintenance team denies this. Similarly, the proposed standard for the development of maintenance contracts is not used. There is also a lack of

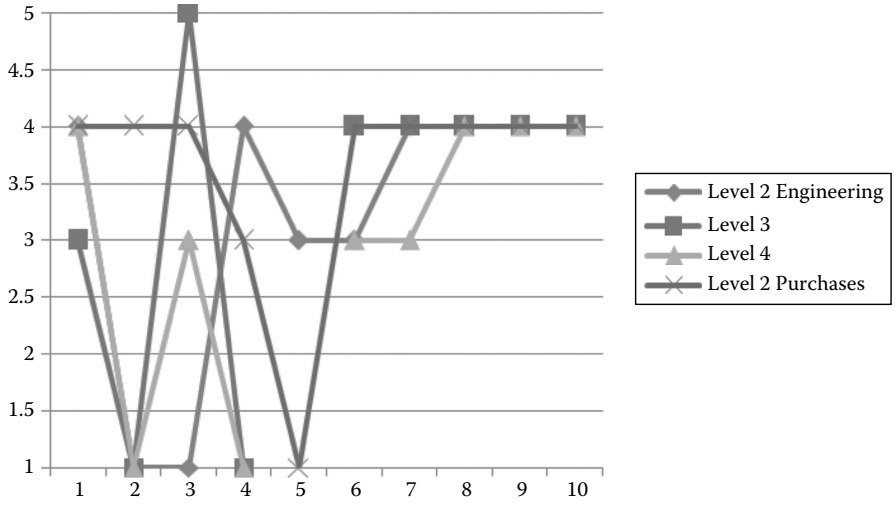


FIGURE 8.91
Surveys of maturity level 2 in the press: recruitment policy.

TABLE 8.46

Surveys of Maturity Level 2 in the Press: Recruitment Policy

	Contract Policy			
	Level 2 Engineering Manager	**Level 3**	**Level 4**	**Level 2 Purchase Management**
1	4	3	4	4
2	1	1	1	4
3	1	5	3	4
4	4	1	1	3
5	3			1
6	3	4	3	4
7	4	4	3	4
8	4	4	4	4
9	4	4	4	4
10	4	4	4	4

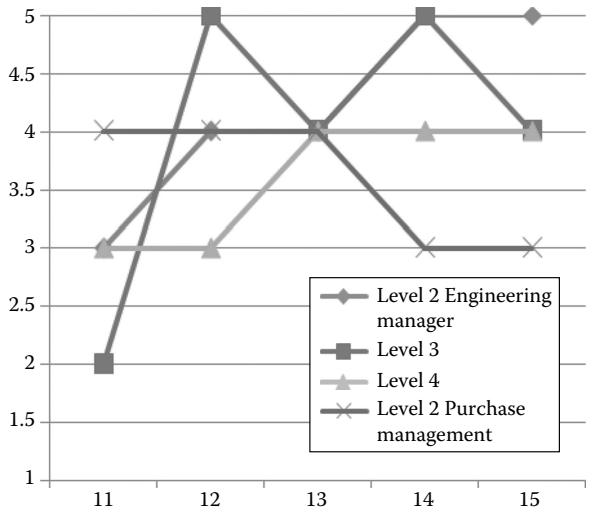


FIGURE 8.92
Surveys of maturity level 2 in the press: selection of contractors.

TABLE 8.47

Surveys of Maturity Level 2 in the Press: Selection of Contractors

	Contractors Selection			
	Level 2 Engineering Manager	**Level 3**	**Level 4**	**Level 2 Purchase Management**
11	3	2	3	4
12	4	5	3	4
13	4	4	4	4
14	5	5	4	3
15	5	4	4	3

understanding of existing maintenance procedures and standard contracts (Figure 8.92 and Table 8.47).

In understandings of the selection of contractors, there are appreciable differences in the assessment procedures, how they work, and the guarantees of each service offered (Figure 8.93 and Table 8.48).

Finally, responses on the monitoring of the various contractors show differences in the knowledge of the procedure to be followed to control the work done. We are concerned about the difference of opinions as to the existence of a procedure to monitor suppliers. There are differences in the understanding of penalties or fines for noncompliance with work. The indicators obtained from the surveys are shown later according to the hierarchical model. The values are too high when we do not consider the peculiarities of the scale that favors the trend toward positive responses (as previously discussed) (Table 8.49).

That is why values around 3.2 represent a low estimate of those involved in the process in terms of their confidence in the contractors and their knowledge of the subcontracting process (Figure 8.94).

The subcontracting indicators are not included in the system and, therefore, there is no way to analyze them. In other words, validating indicators relating to the availability of

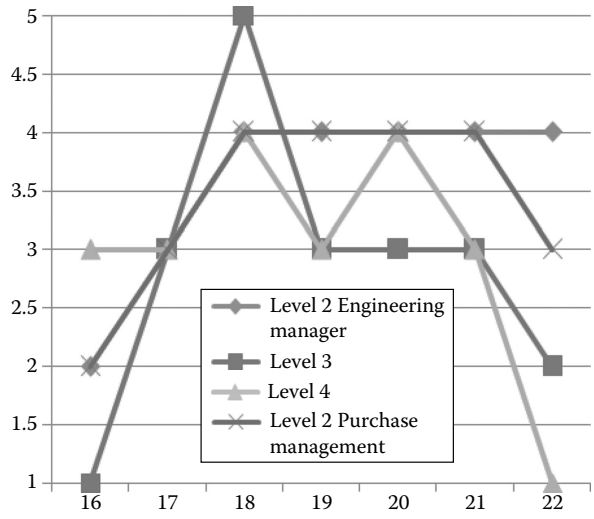


FIGURE 8.93
Surveys of maturity level 2 in the press: oversight of contractors.

TABLE 8.48

Surveys of Maturity Level 2 in the Press: Oversight of Contractors

	Contractors Supervision			
	Level 2 Engineering Manager	**Level 3**	**Level 4**	**Level 2 Purchase Management**
16	2	1	3	2
17	3	3	3	3
18	4	5	4	4
19	4	3	3	4
20	4	3	4	4
21	4	3	3	4
22	4	2	1	3

the service with respect to what has been agreed upon and the repetition of poorly done work cannot be calculated. Accordingly, we use SUBCI1 and SUBCI2.

$$\text{CONTSUPI} = \text{Survey results (CONT_SUP)} \cdot \text{CONTI1} \cdot \overline{\text{CONTI2}} =$$

$$= \text{Survey result (CONT_SUP)} \cdot \text{CONTI1} \cdot (1 - \text{CONTI2})$$

$$\text{CONTI1} = \frac{\text{Availability time of contracted services}}{\text{Required time}}$$

$$\text{CONTI2} = \frac{\text{Number of works requiring repetition}}{\text{Number of works performed by contractors}}$$

TABLE 8.49

CONTPOLI, SELCONTI, and CONTSUPI Hierarchical Indicators

CONTPOLI	**Contract Policy**	
	Level 2 Engineering	3.200
	Level 3	3.333
	Level 4	3.000
	Level 2 Purchases	3.600
CONTPOLI Average		**3.283**
CONTSELI	**Contractors Selection**	
	Level 2 Engineering	4.200
	Level 3	4.000
	Level 4	3.600
	Level 2 Purchases	3.600
CONTSELI Average		**3.850**
CONTSUPI	**Contractors Supervision**	
	Level 2 Engineering	3.571
	Level 3	2.857
	Level 4	3.000
	Level 2 Purchases	3.429
CONTSUP Average		**3.214**

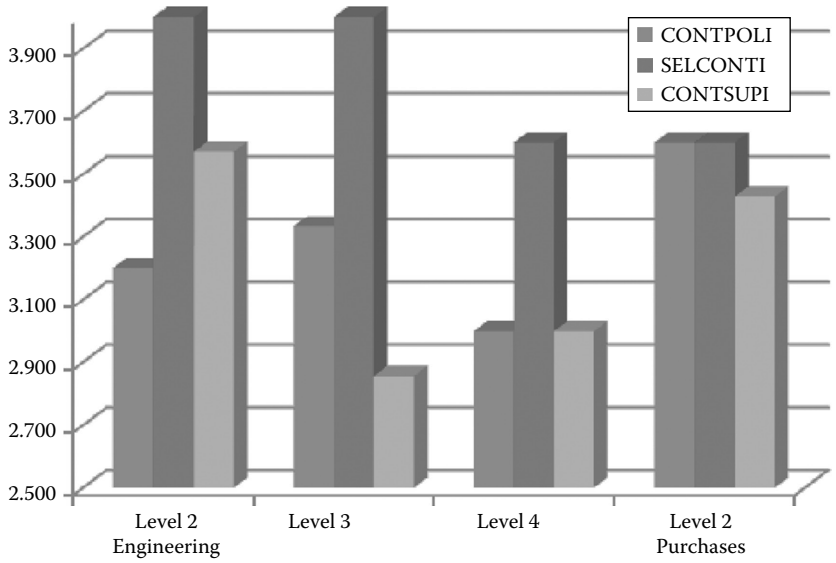


FIGURE 8.94
Hierarchical indicators relating to subcontracting.

Here, CONTI3, CONTI4, and CONTI5 relate to the technical qualification and experience of contractors; the EI22, EI23, and EI24 indicators relate to their technical specialties, whether mechanical, electrical, or instrumentation object of outsourcing.

The overall economic indicators of subcontracting EI9 and EI10 are not calculable either. In fact, human resources have no data for the EI9 indicator concerning the subcontracted cost of the staff with respect to the global maintenance budget. The only indicator we can attempt to calculate is EI10, as shown here:

$$\text{EI10} = \frac{\text{Total contracting cost}}{\text{Total maintenance costs}}$$

The absence of these items constitutes around €100,000 a year in outsourcing. This is about 20% of the total maintenance budget, in line with the proposed references, even though we know little about these hires.

8.6 Growth of the Scorecard at Higher Levels

This section describes the control panels of the two levels discussed earlier and discusses the evolution from level 1 to level 2. It explains the appearance of the control panel in its hierarchical version. The perspectives show the strengths and weaknesses in compliance and indicate whether the hierarchical level (either user or owner) is ready to work to improve the indicator that presents problems.

8.6.1 Scorecard for Level 1

In the scorecard for the paper industry, level 1 mainly provides effectiveness indicators; therefore, this perspective is more developed.

An indicator may be within the references suggested by international agencies or the company itself. In this case, the indicator is "positive" and denoted by dark gray. It will contribute to the appropriate development of the strategy and makes a positive contribution to the goal and the associated perspective.

Indicators outside the established values and whose references differ considerably from what is recommended by international agencies or the companies themselves are in middle dark gray. A number of middle dark gray indicators concentrated on a strategy or objective means the failure of the same and a negative perception of those involved.

Two more types of indicators on the control panel deserve to be taken into account. The first corresponds to the indicators that are meaningless in a particular company. This is the case of the outages for maintenance in the press; the nature of the productive function makes them unnecessary. This is reflected in a different color, gray. Finally, there is a group of indicators that cannot be calculated because there are no data logs, etc. or whose access is complex and sensitive. These data are impossible to calculate, making it impossible to know whether they are good or not. We cannot know whether the strategy is moving forward, or it is good or bad; therefore, we do not know if it contributes positively or negatively to the achievement of the associated objectives.

An example is an efficiency indicator whose parameters are "soft"; the measurement of its impact is not immediate or quantifiable; registries are rarely available to allow the auditor to estimate it.

It is important not to confuse the indicators. Because of a lack of direction by the company they may not be calculated. Or the company may not understand the data; for example, if the calculated value is zero, it may be hard to classify an indicator as positive or negative. It is important to realize when we have a zero, we cannot assume not the absence of data; rather, we should consider efficiency and inefficiency.

The level 1 of the scorecard has values very symptomatic of effectiveness. It is worth noting that the implementation of the planned work should yield visual graphic data that acknowledge the impact of failure in the level.

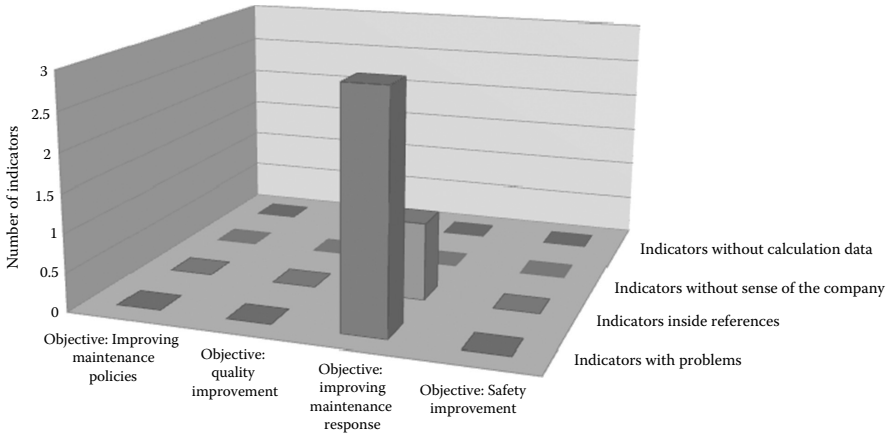
8.6.1.1 Level 1: The Customer Perspective

When too many scheduled tasks are delayed, there is too much corrective maintenance and the correlation between failures and outages for maintenance is too high, the following must be done

- Resize preventive maintenance to suit the specific department
- Plan nonurgent corrective maintenance in a better way

Both will improve the response of the department, something valued by the customer.

It is worth noting that all indicators associated with this perspective of level 1 can be calculated; all relevant data can be accessed (Figure 8.95).



	Objective: Improving maintenance policies	Objective: Quality improvement	Objective: Improving maintenance response	Objective: Safety improvement
Indicators with problems	0	0	3	0
Indicators inside references	0	0	1	0
Indicators without sense of the company	0	0	0	0
Indicators without calculation data	0	0	0	0

FIGURE 8.95
Customer perspectives: level 1 of the press.

8.6.1.2 Level 1: The Financial Perspective

This perspective is generally associated with efficiency. There is a clear attempt to improve the availability of productive assets. However, this is at the expense of an excessive increase in overtime, so financially it is penalized (Figure 8.96).

Indicators are meaningless in the financial perspective because unavailability for scheduled maintenance does not exist in this particular industry.

8.6.1.3 Level 1: The Internal Process Perspective

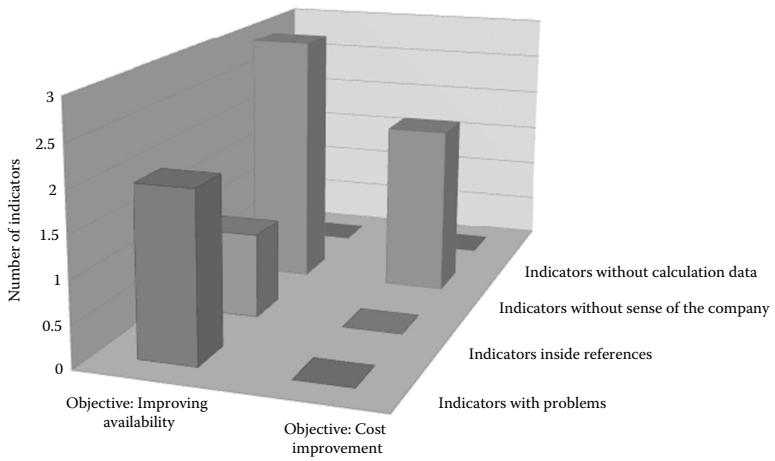
Internal processes at this level are guided by the objective of improving the organization of work. Figure 8.97 shows a large number of positive and negative indicators, which greatly complicates the goal.

When we look more closely at the control panel and the objective to improve the organization of work, we see the best strategy is operator versatility. Preventative maintenance will be reduced if staff hours are devoted to different tasks of the maintenance plan. However, the strategy of rationalizing preventive maintenance has failed as the plans for preventive maintenance are oversized for the number of staff. Therefore, the strategy is not successful.

One of the indicators seems devoid of meaning. We need to adapt the scorecard to individual companies. We must think out of the box; a false measurement could cause unnecessary alarm or suggest incorrect achievements.

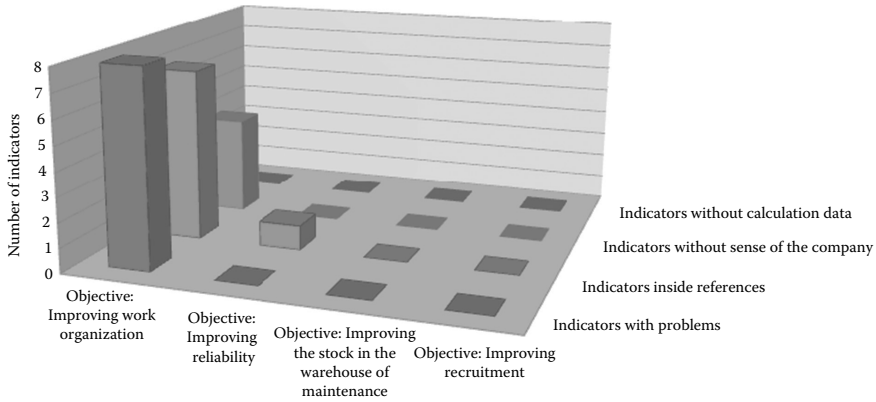
8.6.1.4 Level 1: The Learning and Growth Perspective

This perspective is not developed in level 1. There is no single indicator related to this perspective (Figure 8.98).



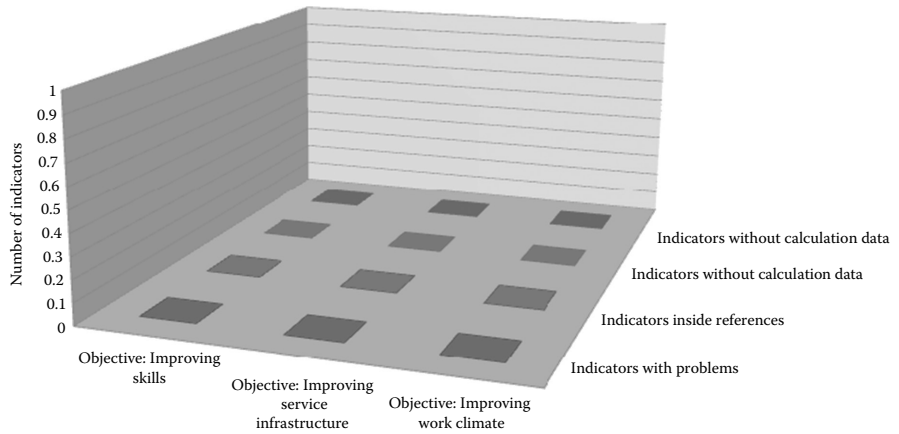
	Objective: Improving availability	Objective: Cost improvement
Indicators with problems	2	0
Indicators inside references	1	0
Indicators without sense of the company	3	2
Indicators without calculation data	0	0

FIGURE 8.96
Financial perspectives: level 1 of the press.



	Objective: Improving work organization	Objective: Improving reliability	Objective: Improving the stock in the warehouse of maintenance	Objective: Improving recruitment
Indicators with problems	8	0	0	0
Indicators inside references	7	1	0	0
Indicators without sense of the company	4	0	0	0
Indicators without calculation data	0	0	0	0

FIGURE 8.97
Internal processes perspective: level 1 for the press.



	Objective: Improving skills	Objective: Improving service infrastructure	Objective: Improving work climate
Indicators with problems	0	0	0
Indicators inside references	0	0	0
Indicators without calculation data	0	0	0
Indicators without calculation data	0	0	0

FIGURE 8.98
Learning and growth perspective: level 1 for the press.

8.6.2 Scorecard for Level 2

Level 2, as mentioned, considers efficiency. The following lists the perspectives of this level.

8.6.2.1 Level 2: The Customer Perspective

The following objectives are linked to improving the customer's perspective of efficiency:

- Improving maintenance policies
- Improving quality
- Improving the maintenance response
- Improving safety

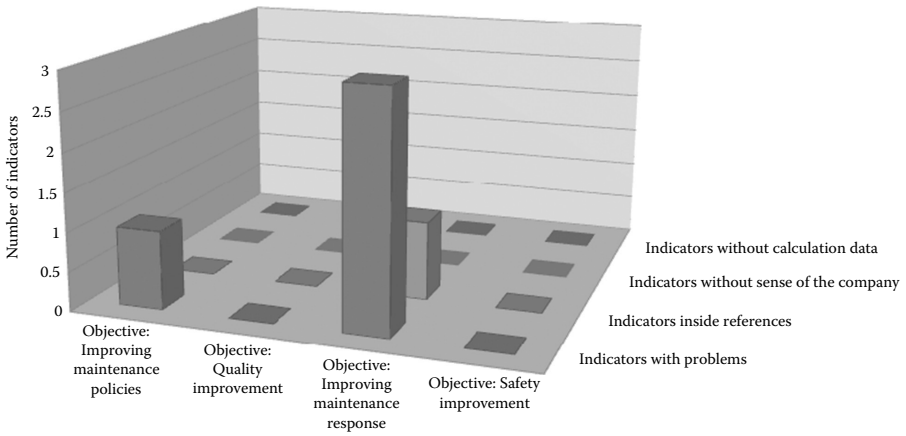
The objectives are not developed before level 2 because a WO system or the management of the maintenance warehouse implies improvement as an internal process, while training impacts the learning perspective.

In this case, level 2 assessment shows the strategy to increase the scheduled jobs has failed, and the objective of improving quality is clouded by the inability to calculate the number of jobs that must be repeated (Figure 8.99).

8.6.2.2 Level 2: The Financial Perspective

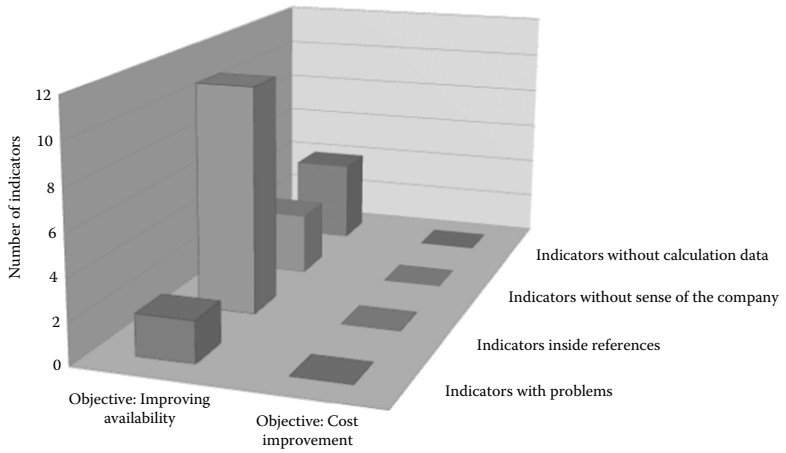
This perspective is widely developed in this level because of the premium on efficiency in the economic aspect of management and maintenance. The improvement of the economic outlook has two objectives:

1. Improve availability
2. Improve costs



	Objective: Improving maintenance policies	Objective: Quality improvement	Objective: Improving maintenance response	Objective: Safety improvement
Indicators with problems	1	0	3	0
Indicators inside references	0	0	1	0
Indicators without sense of the company	0	0	0	0
Indicators without calculation data	0	2	0	0

FIGURE 8.99
Customer perspective: level 2 of the press.



	Objective: Improving availability	Objective: Cost improvement
Indicators with problems	2	0
Indicators inside references	11	0
Indicators without sense of the company	3	0
Indicators without calculation data	4	0

FIGURE 8.100
Financial perspective: level 2 of the press.

According to the proposed model for the control panel and the chronological evolution of the audit, the costs are displayed at higher levels with their respective indicators. In level 2, the objective of improving the availability continues to develop, but the improvement of the costs does not present an indicator.

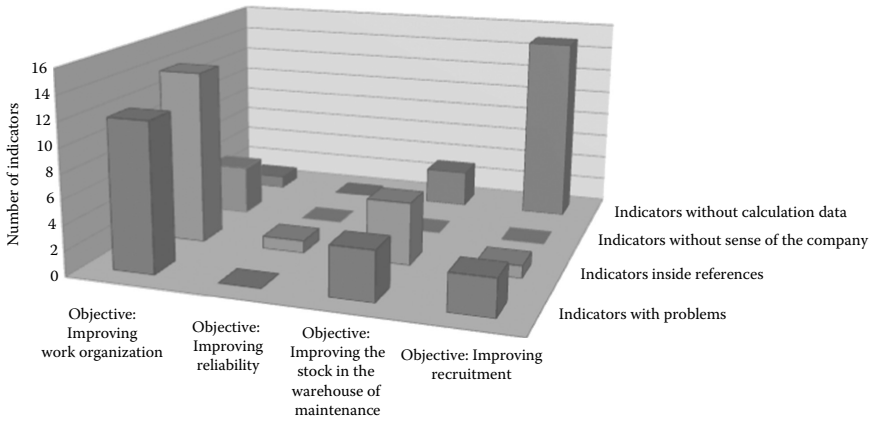
The improvement of availability is clear; WMI8 shows little work awaiting parts and WOI81 shows a reduced number of urgent WOs. These actions contribute to an improvement in the response and, therefore, greater availability of production equipment. This is evident in the low rate of urgent WOs and the associated minimum downtime.

At this level, there is an evolution in the positive indicators and an improvement in the financial perspective over the results of level 1. Results are more focused on efficiency; this appears in the objective of improving the availability of a small number of indicators. Furthermore, a series of indicators are matched with the measurement of the strategy to train personnel (Figure 8.100).

8.6.2.3 Level 2: The Internal Process Perspective

This perspective continues to develop the objective of improving the organization of work. The indicators of this objective are a mix of positive and negative with the exception of the strategy to rationalize the use of preventive which presents a completely negative aspect. As already mentioned, the number of scheduled excess jobs constitutes a fault in the size of the preventive maintenance plan (Figure 8.101).

The objective of improving reliability develops only slightly in this level. Higher levels will address this issue with policies like RCM or TPM. However, two objectives remain: the spares parts stock improvement and the subcontracting process. For the first, we can see equal numbers of negative and positive indicators, so the strategy is not met and the positive contribution to meeting the objective is dubious. More apparent, however, are the



	Objective: Improving work organization	Objective: Improving reliability	Objective: Improving the stock in the warehouse of maintenance	Objective: Improving recruitment
Indicators with problems	12	0	4	3
Indicators inside references	14	1	5	1
Indicators without sense of the company	4	0	0	0
Indicators without calculation data	1	0	3	15

FIGURE 8.101
Internal process perspective: level 2 for the press.

negative aspects derived from outsourcing. Here, we see a large number of negative indicators in addition to a huge volume of unknown indicators. We cannot quantify the goal achievement, but the measurements show no signs of being positive.

8.6.2.4 Level 2: The Learning and Growth Perspective

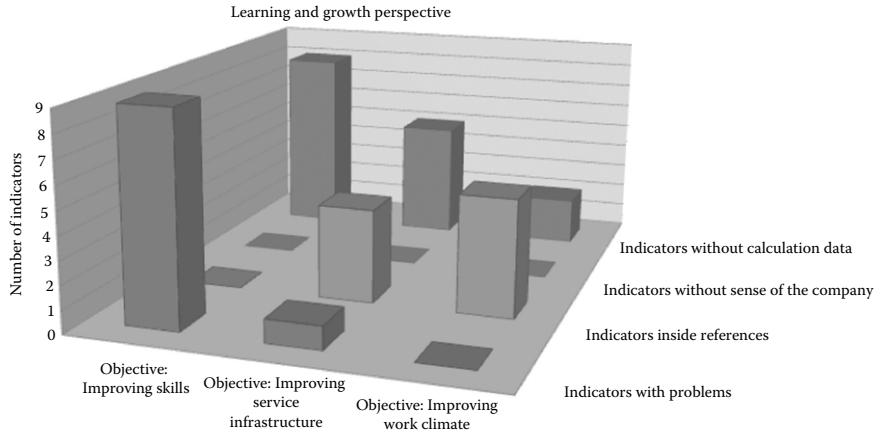
In level 2, we begin to develop the strategies to achieve the key objectives for the learning and growth perspective. Three objectives have an impact and are simultaneously affected by the maturing process of the maintenance level:

1. Improve skills
2. Improve the services infrastructure
3. Improve the labor climate

As Figure 8.102 shows, 17 indicators are measured in level 2; these correspond to almost all indicators associated with this goal. The indicators completely cover the first of the following strategies and partially cover the second.

- Improve employees' skills
- Promote employees' suggestions

That is, measuring the goal of improving skills is almost clarified. In the case of the strategy for knowledge and skills improvement, there are a large number of negative indicators associated with reduced training, along with another group of indicators for which no information is available. It is impossible to know the status of the latter, that is, if they



	Objective: Improving skills	Objective: Improving service infrastructure	Objective: Improving work climate
Indicators with problems	9	1	0
Indicators inside references	0	4	5
Indicators without sense of the company	0	0	0
Indicators without calculation data	8	5	2

FIGURE 8.102
Perspectives of learning and knowledge: level 2 for the press.

contribute positively or negatively to compliance with the strategy. In the same way, the strategy of promoting employee suggestions fails because the indicators present in this level are not measurable. As a result, the placement of sensors is appropriate for the subsequent measurement of these parameters. In conclusion, the goal is not achieved because of the negative and unknown data.

In addition to assessing the level, the control panel is able to show those involved in improvement to clearly define their responsibilities in subsequent audits.

The other two objectives as shown in Figures 8.102 represent different aspects. The infrastructure improvement has a reduced number of indicators; the labor climate reduces them even more. The improvement in service infrastructure creates a partially positive scenario; the two strategies in the indicators that can be measured are positive, with some outstanding indicators to be picked up in subsequent steps. Only an indicator relating to the material correlation in the ERP versus CMMS presents negative aspects.

Finally, the goal of improving the working environment presents all positive values with the exception of a minority that cannot be calculated. None is negative. For this reason, in what can be measured, the contribution of this level in the labor climate is entirely positive. This suggests the need for the placement of "management sensors" to enable the measurement of what is not measurable. Even so, all the indicators on work environment at this level remain positive.

8.6.3 The Hierarchy of the Control Panel and Identification with Indicators

The control panel in the different maturity levels develops strategies, completing the indicators associated with them and the objectives aimed at improving the prospects. As mentioned, indicators are classified into four types as shown in Figure 8.103.

	Indicators inside reference
	Indicators with problems
	Indicators without sense in company
	Indicators without calculation data

FIGURE 8.103
Gray color codes for indicators on scorecard.

The scorecard presents the different perspectives and the hierarchical strategies and objectives supporting the indicators, noting current problems or successes and showing the user or owner of a successful or failed indicator.

Following are some of the strategies up to maturity level 2 that have filled in most of the indicators. We can observe the effect of the hierarchy of indicators and the benefits arising from their use.

The strategy for planning urgent corrective maintenance is associated with the goal of improving the maintenance response. This strategy presents indicators in two levels, the maintenance head and the control person or supervisor. The head of maintenance has a worrying indicator because the entire time of unavailability is due to urgent corrective maintenance. If we want to eradicate the sense of simply fighting fires, we must correct that indicator. In contrast, the supervisor has to deal with too much corrective maintenance; the preventive must, therefore, be replanned. These two actors are responsible for the success of this strategy (Figure 8.104).

The improvement of staff competence has a different strategy, as it is related to the goal of learning and growth. These indicators are pessimistic at high levels, while at lower levels they are either negative or data for their calculation are unknown. Both are delimited by the relevant policy actors; in this case, the general director must increase formative actions and place sensors at lower levels (Figure 8.105).

The following strategy shows the need to match equipment with needs is practically ignored. The necessary indicators, as established by maintenance heads and supervisors, have no data for their calculation. Only the OI24 indicator relative to the number of people who use the computer is known. If we want to know the status of the strategy, we must urge those involved to seek information on a regular basis (Figure 8.106).

In the WCC strategy to increase the retention of staff, a series of indicators are showing success, as are redundancy and the index of absenteeism. This suggests the strategy to retain staff is successful and all levels are working on it in accordance with the established goals. In these data, staffing levels are calculated over the total years. This is a data type whose systematization for an audit presents few complications (Figure 8.107).

Plan the not-urgent corrective maintenance				
Level 1				
Level 2				
Level 3	OI11			
	100			
Level 4	OI16	OI17		
	38.5	0.5		
Level 5				

FIGURE 8.104
Hierarchical strategy: the plan for urgent corrective maintenance.

Improve staff technical and professionals skills							
Level 1	ITI1	EI21	ITI21	ITI11			
	115	150	8.6	0.30%			
Level 2	ITI1	EI21	ITI21	ITI11	ITI3	ITI4	ITI5
	115						
Level 3	ITI3	ITI4	ITI5	OI23	ITI6	ITI22	
				0.60%	0.375		
Level 4							
Level 5							

FIGURE 8.105
Hierarchical strategy: improve staff technical and professional skills.

Adapt technical and administrative equipment to service needs							
Level 1							
Level 2							
Level 3	T&UI3	OI24					
		100%					
Level 4	T&UI1	T&UI2					
Level 5							

FIGURE 8.106
Hierarchical strategy: match technical and administrative equipment with required service.

Increase the level of staff retention				
Level 1				
Level 2	HRI1	HRI2		
	0%			
Level 3	HRI1	HRI2	TPMI6	
	0%		0%	
Level 4	TPMI6			
	0%			
Level 5	TPMI6			
	0%			

FIGURE 8.107
Hierarchical strategy: increase the level of staff retention.

The strategy to relocate personnel properly shows equal success. This strategy with its principal actors, that is, the maintenance head and his/her supervisor, is a success in most of the indicators. For this strategy to be successful, preventive maintenance must be increased by redistributing the maintenance hours (Figure 8.108).

A clear example of a strategy with problems relates to the rationalization of the implementation of preventive maintenance. In this case, the actors are the plant head, the maintenance head, and his/her supervisor. Level 2 must perceive that too much of the budget has been allocated to corrective maintenance. However, only 40% of the planned runs and forecasting costs are bad. Finally, the maintenance head will discover that the hours devoted to planned maintenance are minimal; this means that the maintenance policy is

Relocate the staff more suitably							
Level 1							
Level 2							
Level 3	OI12	OI13	OI14	OI15	OI18	OI19	OI20
	Polyvalence	Polyvalence	Polyvalence	100%	22/59.9	0%	
Level 4	OI12	OI13	OI14	OI15	OI18	OI19	OI20
	Polyvalence	Polyvalence	Polyvalence	100%	22/59.9	0%	
Level 5							

FIGURE 8.108
Hierarchical strategy: relocate staff appropriately.

Streamline preventive implementation			
Level 1			
Level 2	PMI11	PMI12	
	61.34		
Level 3	OI5 WOI12	PMI7	RCMI3
Level 4	PMI4	PMI5	CMMS6
	41.15	75.89	
Level 5			

FIGURE 8.109
hierarchical strategy: streamline preventive implementation.

not in accordance with WCM parameters. These levels will be held accountable for the performance on these indicators (Figure 8.109).

The strategy of adapting the department size to company requirements suggests the need to clearly identify the indicator or its owner and user in addition to finding the problem, deciding how to solve it, identifying the solution architect, etc. (Figure 8.110).

The strategy to determine what is necessary in the store does not pose a problem to the high levels where the budget or the plant shows no signs of a problem. Rather, the maintenance head sees problematic indicators, such as the percentage of what has been consumed or an overly low stock rotation. The maintenance director is a major player and owner of a few indicators that he alone can improve. Certain macro commands may not concern the direction, but they may be relevant to the maintenance chief (Figure 8.111).

Adapt the department size to the company's actual needs						
Level 1	OI1	EI8	EI13			
	10%	70%	0			
Level 2	OI4	OI9	OI10			
			100%			
Level 3	CMMS8	CMMS91	CMMS92	CMMS10	OI2	OI3
	8	8		0	0%	0%
Level 4						
Level 5						

FIGURE 8.110
Hierarchical strategy: match department size with the real needs of the company.

Redefine necessary articles for the maintenance warehouse						
Level 1	EI7					
	1.19%					
Level 2	EI7					
	1.19%					
Level 3	EI11	EI12	WMI2			
	7.20%	12.11%	12.11%			
Level 4	WMI1	WMI3	CMMS5	RCMI8		
	9.27%	84.14%	84.14%			
Level 5						

FIGURE 8.111
Hierarchical strategy: redefine items needed for the maintenance warehouse.

Verify the coexistence of current hiring system					
Level 1	EI10				
	20%				
Level 2	EI9				
Level 3	EI9	EI22	EI23	EI24	WOI3
					0%
Level 4	WOI3	EI22	EI23	EI24	CMMS3
	0%				0%
Level 5					

Rate the level of the contractor's performance					
Level 1					
Level 2	CONTI3	CONTI4	CONTI5		
Level 3	CONTI1	CONTI2			
Level 4	CONTI1	CONTI2			
Level 5					

FIGURE 8.112
Hierarchical strategy: verify suitability of current recruitment system.

There are problems in the first audit when we find the type of cases presented later. First, we see an almost total absence of data in a crucial issue, in this case, outsourcing. The general director sets a percentage of contracted work within the patterns by which the goal is achieved, and lower levels are responsible for distributing this budget. However, there are no qualification records of the contractors' experience or a complete lack of understanding of the external staff working in the plant. As mentioned, this does not imply these values are zero; they are simply not known and sensors for measurements are appropriate. The case of the middle dark gray indicators on levels 3 and 4 is different; here the data are null. Information on WOs has not been entered into CMMS. In this case, the negative value in middle dark gray indicates not ignorance but a deliberate absence of data which must be corrected (Figure 8.112).

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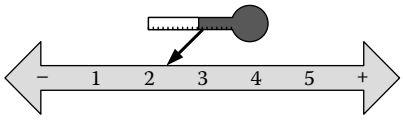
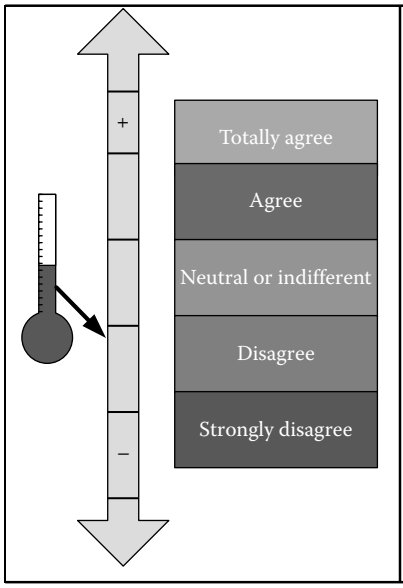
Appendix: Instructions for Completing the Survey

The surveys will be filled qualifying from 1 to 5 expressed the degree of agreement with the question or statement stated. In the event that the answer may be a yes or a no, it will answer 5 or 1, respectively, with 2°, 3°, and 4° when you do not want to answer definitively but with a certain degree of approximation to the affirmation or denial.





5. Defines an optimal situation. The maximum degree assumed that 100% of the time the activity is performed as defined in the question referred.

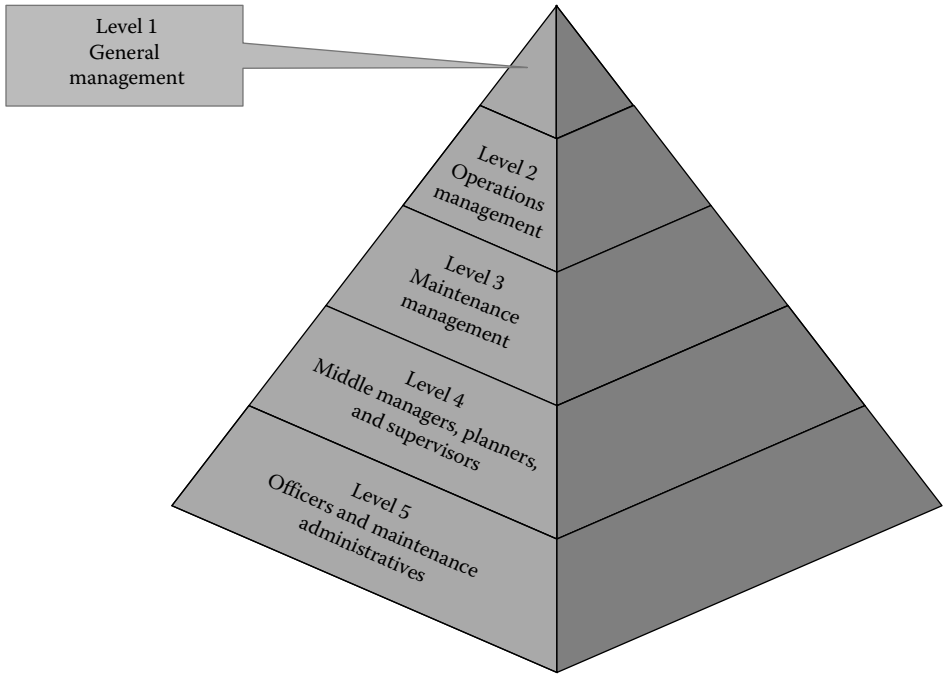
4. Defines a good situation but with caveats. Most of the time, it acts as a question, but sometimes, voluntarily or involuntarily they obviate.

3. Average location. The fulfillment of the question is random. We can find similar rates of compliance and noncompliance.

2. Poor situation. Almost never made the statement is true.

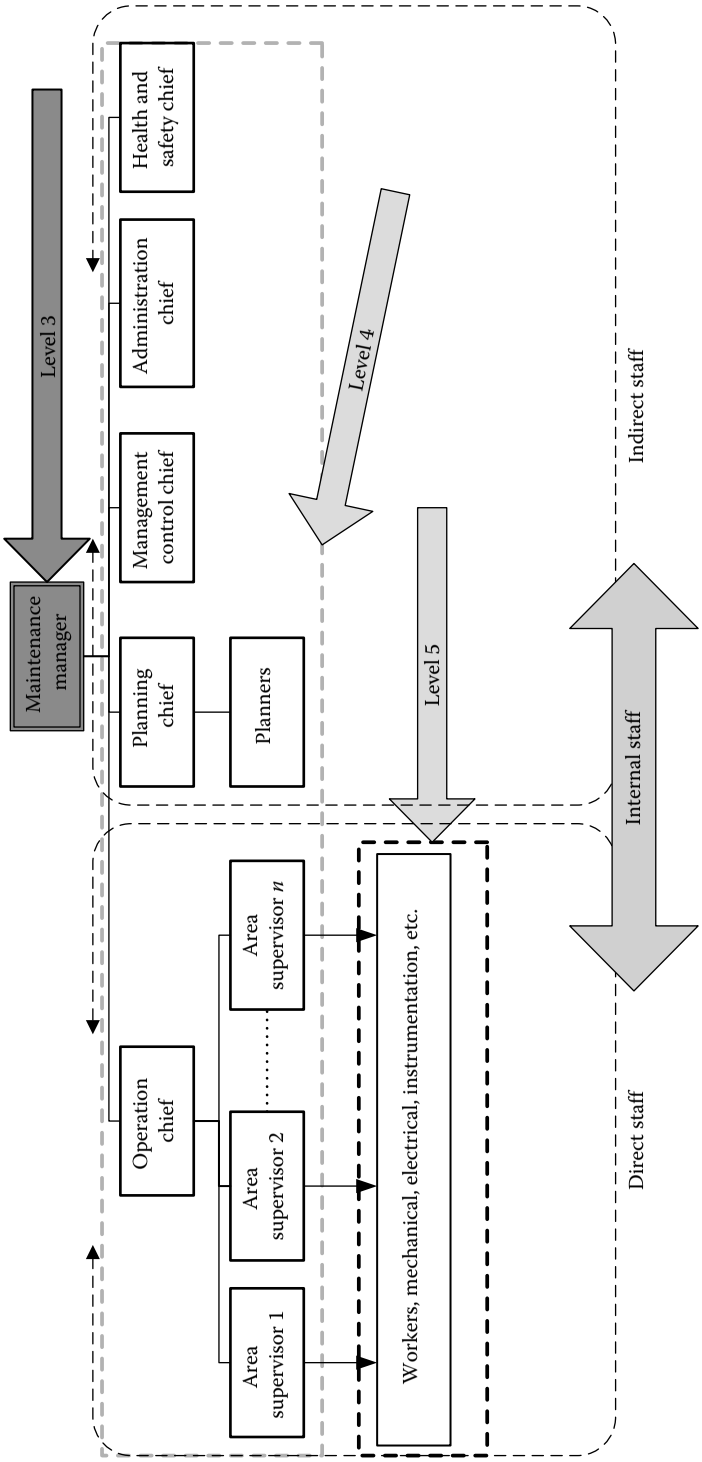
1. Never the assertion made is true. Ignorance, now being voluntarily implemented the system or on any occasion is performed as indicated.

Hierarchical levels to which the survey is conducted are structured as follows:

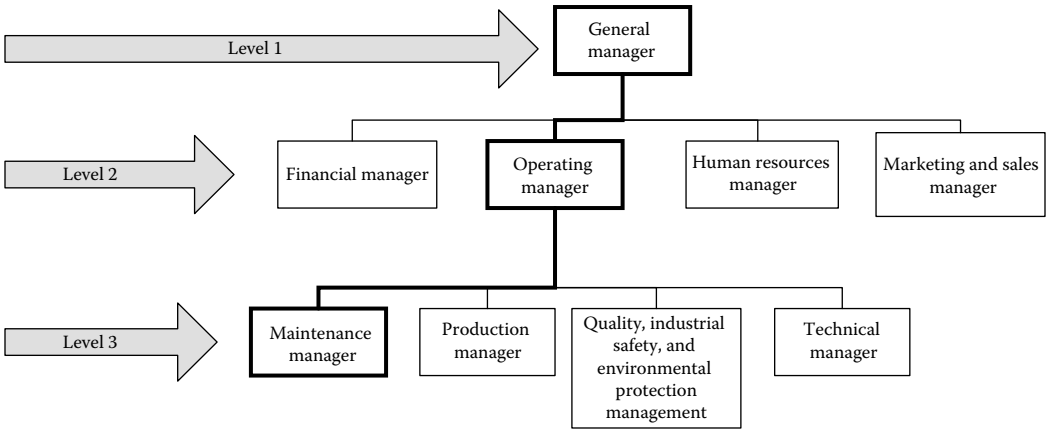


Hierarchy of maintenance levels

In some cases, it will be necessary to conduct the survey at equivalent levels of WOher related maintenance departments because in the upper pyramid only it is observed those positions directly related to the direct hierarchy of the department, starting on the basis of official and administrative personnel and reaching to the maximum level of the company representation.


Level 3
Maintenance manager
Planning chief
Planners
Management control chief
Administration chief
Health and safety chief
Level 4
Level 5
Indirect staff
Internal staff
Direct staff
Operation chief
Area supervisor 1
Area supervisor 2
Area supervisor *n*
Workers, mechanical, electrical, instrumentation, etc.

In this way, there will be times when level 3 will be surveyed at both headquarters and production maintenance or quality (level's counterparts in organizations that have operations area).



Similarly, as can be seen in the organizational chart, there will be a need to survey the areas responsible for two equivalent hierarchical levels responsible for operations such as finance directors or human resources.

A.1 Level 0 of Evolution: Management Commitment and Knowledge with Maintenance

Target audience of the survey: Levels 1, 2, and 3

1. Is it "maintenance" integrated into the business plan of the company?
2. Are there specific measurable objectives for maintenance?
3. Are there agreed indicators on the maintenance performance?
4. Is there a maintenance organizational chart with a management and middle management perfectly defined and located in the overall organizational chart?
5. Are these objectives specifically integrated into the overall business objectives?
6. Do all staff understand the stated objectives and the need for their involvement to achieve the same?
7. Are the results versus targets set regularly checked?
8. Do they take and implement improvement actions to improve maintenance efficiency?
9. Is the effectiveness of these actions measured?
10. Is there a coherence in the maintenance strategy between different plants or productive areas of the company?

1	2	3	4	5

Indicators

$$\text{EI1} = \frac{\text{Maintenance total costs}}{\text{Assets replacement value}}$$

$$\text{OEE} = \text{OEEI1} \times \text{OEEI2} \times \text{OEEI3}$$

$$\text{OEEI1} = \text{Availability} = \frac{\text{Total activity time}}{\text{Programmed time}}$$

$$\text{TI1} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Maintenance unavailability time}}$$

$$\text{TI2} = \frac{\text{Availability time achieved during the required time}}{\text{Required time}}$$

$$\text{OEEI2} = \text{Performance efficiency} = \frac{\text{Actual production for the programmed time}}{\text{Planned production for the programmed time}}$$

$$\text{OEEI3} = \text{Quality rate} = \frac{\text{Total production} - \text{Defects}}{\text{Total production}}$$

$$\text{EI3} = \frac{\text{Maintenance total costs}}{\text{Quantity produced}}$$

$$\text{TPMI5} = \text{Decrease the unit production cost}$$

A.2 Level 1 of Evolution

Objective public of the survey: Levels 3, 4, and 5

Questionnaire: Works planning

WORK-PLAN Works planning

1. Is there a work request to the maintenance department coming from other areas, such as production, quality, or labor risks?
2. Is work prioritized?
3. Is there a known workload according to projected work?
4. Is this work programmed?
5. Is this work planned?
6. Is the time required for planned and programmed work known to a certain degree of accuracy?

7. Is there any control over execution and results?
8. Has 95% of the maintenance been programmed at least one day before being realized?
9. Are spares, hardware, necessary equipment and papers prepared and adapted for the work?
10. Do the planners clearly indicate the hardware to use and components to be replaced?
11. Have instructions or procedures for the work been established?
12. Do the personnel know what they are going to do the day before a task is done?
13. Is the planner's function defined?

Questionnaire: Works execution

WORK-EXEC Work execution

1. Is there a relationship between the program and the unforeseen?
2. What is the work program of scheduled maintenance?
3. Have the procedures for preventive maintenance been defined?
4. Have the procedures for corrective maintenance been defined?
5. Are any maintenance procedures defined for periodic inspections (checklist, descriptions, steps, frequency, etc.)?
6. Are the necessary procedures adapted to the abilities or skills, materials, and tools?
7. Is there a method to analyze the differences between the theoretical plan, actual implementation, unintelligibility, deviations, and anomalies?
8. Is the ratio of outstanding work and scheduled jobs known?
9. Is the relationship between overtime and the time for unscheduled jobs and scheduled jobs known?
10. Is preventive maintenance based on the condition/status of the component?
11. How is equipment reviewed when a shift begins?
12. Is there a daily routine?
13. Are daily maintenance and interventions registered?
14. Is the amount of time required to diagnose a fault known?
15. Is the exact number of pending jobs known per period?
16. Does the team have control over the necessary hours to finish work?
17. Is the information useful?
18. Is there an emergency work and program record?
19. Are jobs recorded by type of mechanical maintenance, electrical, and so on, according to the personnel involved?
20. Is lost production time quantified by faults?
21. Are delays quantified for maintenance?
22. How is control maintained over the time spent on repairs?
23. How is real time compared with the time stipulated in work orders (WOs)?

Indicators

$$\text{OI25} = \frac{\text{Direct maintenance man-hours in scheduled activities}}{\text{Total planned man-hours for direct staff}}$$

$$\text{OI5} = \text{WOI12} = \frac{\text{Planned and scheduled maintenance man-hours}}{\text{Total number of maintenance man-hours available}}$$

$$\text{WOI13} = \text{OI21} = \text{PMI10} = \frac{\text{Maintenance overtime}}{\text{Total number of maintenance worked hours}}$$

$$\text{PMI2} = \frac{\text{Man-hours spent on emergency works}}{\text{Total worked man-hours}}$$

$$\text{PMI4} = \frac{\text{Preventive maintenance tasks performed}}{\text{Preventive maintenance tasks scheduled}}$$

$$\text{PMI9} = \frac{\text{Number of PM delayed tasks}}{\text{Number of PM pending tasks}}$$

$$\text{PMI5} = \frac{\text{Tasks' estimated costs PM}}{\text{Tasks' real costs PM}}$$

$$\text{PMI11} = \frac{\text{Preventive maintenance total costs}}{\text{Preventive maintenance total costs} + \text{Corrective maintenance total costs}}$$

$$\text{EI20} = \frac{\text{Cost of programmed maintenance stops}}{\text{Maintenance total costs}}$$

$$\text{PMI12} = \frac{\text{Preventive maintenance unavailability time}}{\text{Preventive unavailability time} + \text{Corrective unavailability time}}$$

$$\text{TI20} = \frac{\text{Planned and scheduled maintenance time causing unavailability}}{\text{Planned and scheduled maintenance time that requires unavailability}}$$

$$\text{TI7} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailability time by planned maintenance}}$$

$$\text{OI11} = \frac{\text{Spent time on emergency corrective maintenance}}{\text{Unavailability total time linked to maintenance}}$$

$$\text{TI8} = \frac{\text{Preventive maintenance time that generates unavailability}}{\text{Unavailability total time by maintenance}}$$

$$TI9 = \frac{\text{Systematic maintenance time that generates unavailability}}{\text{Unavailability total time by maintenance}}$$

$$TI10 = \frac{\text{CBM time that causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$OI12 = \frac{\text{Man-hours of mechanical maintenance internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI13 = \frac{\text{Man-hours of electrical maintenance internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI14 = \frac{\text{Man-hours of instrumentation maintenance internal staff}}{\text{Total man-hours of direct maintenance staff}}$$

$$OI16 = \frac{\text{Corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI17 = \frac{\text{Emergency corrective maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI18 = \frac{\text{Preventive maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI19 = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$OI20 = \frac{\text{Systematic maintenance man-hours}}{\text{Total maintenance man-hours}}$$

A.3 Level 2 of Evolution

Target audience of the survey: Levels 3, 4, 5

Purchases department, quality, and finances

Questionnaire: Purchases

PUR-PRO Purchases procedure

1. Is there a procedure for purchasing in the company? Is it applied?
2. Is a purchasing procedure for management of spare parts applied?

3. Does this procedure specify the authorization levels required for the amount of the order?
4. Does the purchasing procedure meet the requirements of flexibility and speed?
5. Does the purchasing procedure have emergency plans and priorities? Does it require signatures or special authorizations?
6. Are costs associated with a purchase order, such as transport, call, fax, and so on, known?
7. Are there alternative means to make an urgent purchase?
8. Are the specifications for orders sufficient?
9. Is each purchase order checked for technical specification?
10. Does the purchasing department participate in the definition of purchase specifications?

SUP-MAN Supplier management

1. Is there a broad knowledge of market availability (price/suppliers)?
2. Is there a procedure for approval/acceptance of suppliers?
3. Are there formal agreements with general suppliers?
4. Are these agreements applied in everyday purchases?
5. Do negotiations with the supplier include purchases and maintenance together?
6. Is there a supplier evaluation (service/price) periodically?

Questionnaire: Spares

MAT-REC Materials reception

1. Is there a suitable system of quality control for purchased materials?
2. Are the reception personnel reliable?
3. Can all kinds of supplies be accepted?
4. Is there a defined procedure for storing the spares?
5. Have storage conditions been defined for spares (temperature, rotation, moisture)?

WAR-MAN Management of the store

1. Is there an analysis of risks and critical conditions to define the minimal stock?
2. Is the store inventory value known?
3. Are order costs taken into account to determine the ideal delivery date?
4. Is there a control system for spares management: place, quantity, rotation, and so on?
5. Is there a defined breakpoint for the spares quantity?
6. Is there any guide or procedure that defines whether a component is repaired or is replaced with a new one?
7. Is the service quality known? That is the percentage of times that maintenance obtains correctly the spare part requested?
8. Are entire or partial inventories done?
9. Is stock rejected because of technological obsolescence, scarce use, or damage?
10. Does a stores catalog exist for each piece of critical equipment?

Indicators

$$\text{WMI1} = \frac{\text{Line articles in the inactive stock}}{\text{Total line articles in stock}}$$

$$\text{WMI3} = \frac{\text{Total controlled spare parts in warehouse}}{\text{Total available inventory (controlled + uncontrolled)}}$$

$$\text{WMI4} = \text{OI26} = \frac{\text{Total number of spare parts fulfilled by order}}{\text{Total number of spare parts requested}}$$

$$\text{WMI8} = \frac{\text{Maintenance work orders awaiting for spare parts}}{\text{Total number of work orders}}$$

$$\text{WMI6} = \frac{\text{Total number of urgent purchase orders}}{\text{Total number of purchase orders}}$$

$$\text{WMI7} = \frac{\text{Total number of one article purchase orders}}{\text{Total number of purchase orders}}$$

$$\text{WMI9} = \frac{\text{Material costs charged to credit card}}{\text{Total costs of maintenance materials}}$$

$$\text{EI12} = \frac{\text{Total cost of maintenance articles}}{\text{Average inventory value of maintenance articles}}$$

$$\text{EI11} = \frac{\text{Total cost of maintenance articles}}{\text{Maintenance total costs}}$$

$$\text{EI7} = \frac{\text{Average inventory value of maintenance articles}}{\text{Assets replacement value}}$$

$$\text{WMI10} = \text{Internal costs to process a purchase order}$$

$$\text{WMI2} = \frac{\text{Annual cost of warehouse use}}{\text{Total inventory estimation}}$$

Questionnaire: Work Orders

Target audience of the survey: Levels 3, 4, and 5

WO-SYS Work orders system

1. Is there a WO system?
2. Does this system analyze all maintenance activities (predictive, preventive, and corrective)?
3. Does it use the WOs?

4. Can other departments different of maintenance emit WOs?
5. Are the WOs managed through CMMS?
6. Is there a control of progress of WOs?
7. Is there a permanent or blank WO to upload certain items within hours?
8. Is the length of time between the failure warning and the WO issuance known?
9. Is the average time for approval of a WO known?
10. Are people and necessary times, as well as work fulfillment, seen clearly?
11. Are WO safety instructions clear?
12. How are WOs used for all types of work (planned, unplanned, mechanical, electrical, improvements, etc.)?
13. Does the WO procedure as a machine provision include work at height, cutting and welding, fire risk areas, electrical, confined spaces, ATEX zones or WO, according to work performed?
14. Are priorities defined in the WO?
15. Do workers inform the WO scheduler when they have completed a task?
16. Are control deviations from the plan in WO relative to time or materials to the reality of execution periodically performed?
17. Are WOs archived according to the equipment and component?
18. Is it possible for a person or persons performing the WO to indicate in the WO observations the result of the work done, such as problems identified?
19. Is it possible for personnel performing the WO to make additional comments either about the machinery condition or on possible improvements to make?

Indicators

$$\text{WOI5} = \frac{\text{Maintenance labor costs charged to permanent work order}}{\text{Total maintenance labor costs}}$$

$$\text{WOI6} = \frac{\text{Costs of maintenance materials charged to permanent work order}}{\text{Total costs of maintenance material}}$$

$$\text{WOI7} = \frac{\text{Costs of specific equipment charged to a permanent work order}}{\text{Total costs of a specific equipment}}$$

$$\text{WOI1} = \frac{\text{Maintenance labor costs over WOs}}{\text{Total costs of maintenance labor}}$$

$$\text{WOI2} = \frac{\text{Maintenance material costs over WOs}}{\text{Total costs of maintenance material}}$$

$$\text{WOI3} = \frac{\text{Subcontractors costs over WOs}}{\text{Total costs of maintenance contractors}}$$

$$\text{WOI4} = \frac{\text{Maintenance inactivity registered in WOs}}{\text{Total maintenance inactivity}}$$

$$\text{TI16} = \frac{\text{Total operating time}}{\text{Number of maintenance work orders}}$$

$$\text{OI22} = \frac{\text{Number of works orders performed according to planification}}{\text{Number of work orders programmed}}$$

$$\text{WOI15} = \frac{\text{Number of work orders with more than 20\% of estimated labor}}{\text{Total number of maintenance work orders}}$$

$$\text{WOI16} = \frac{\text{Number of work orders with more than 20\% of estimated materials}}{\text{Total number of maintenance work orders}}$$

$$\text{WOI81} = \frac{\text{Emergency orders}}{\text{Total number of work orders}}$$

$$\text{WOI82} = \frac{\text{Preventive orders}}{\text{Total number of work orders}}$$

$$\text{WOI83} = \frac{\text{Corrective orders}}{\text{Total number of work orders}}$$

Questionnaire: CMMS

Target audience of the survey: Levels 3, 4, and 5

CMM-SYS

1. Does the plant have maintenance management or CMMS software?
2. Does everyone have access to the software with a corresponding ID?
3. Is CMMS allocated for an hour according to the operator's instructions?
4. Does the CMMS have the component technical information of equipment?
5. Is there a CMMS for equipment and its components with a specified code?
6. Is this numerical system used in a formal way as part of the technical documentation, applications for replacement, and/or work orders?
7. Is technical information updated in each computer system?
8. Are maintenance plans/tokens reported in this system and periodically generated automatically?
9. Is CMMS used to plan work and control pending jobs?
10. Have the maintenance work software procedures been established?
11. Does each team have an associated maintenance program that can be displayed in a simple way?

12. Does CMMS have records of historical maintenance for each team?
13. Does CMMS have records of performed maintenance?
14. Does CMMS have a register of the availability of all spare parts in the store?
15. Is the documentation updated in a systematic and regular way in the system?
16. Is the information compared in a systematic and regular way with similar records on WO systems?
17. Does CMMS have a connection with WO systems, such as purchasing, finance, or HR, to refresh and interchange information?
18. Is there easy access to the information contained in the system?
19. Does CMMS have records of production operators who work on the equipment?
20. Is a training program implemented for the use of CMMS?
21. Does CMMS have accurate information to take control of efficiency indices?

Indicators

$$\text{OI24} = \frac{\text{Effective of the maintenance internal staff using computer}}{\text{Effective of the internal direct staff}}$$

$$\text{CMMSI1} = \frac{\text{Total labor costs in the CMMS}}{\text{Total maintenance labor costs in ERP}}$$

$$\text{CMMSI2} = \frac{\text{Total material costs in the CMMS}}{\text{Total material costs in ERP}}$$

$$\text{CMMSI3} = \frac{\text{Total subcontractors costs in the CMMS}}{\text{Total subcontractors costs in ERP}}$$

$$\text{CMMSI4} = \frac{\text{Total number of machines in the CMMS}}{\text{Total number of machines registered in plant}}$$

$$\text{CMMSI5} = \frac{\text{Total spare parts number in the CMMS}}{\text{Total spare parts number in plant}}$$

$$\text{CMMS7} = \frac{\text{Maintenance total cost of an equipment in the CMMS}}{\text{Total maintenance costs in ERP}}$$

Questionnaire: Personnel management and subcontractors

Target audience of the survey: Level 3 (Maintenance Manager) human resources management

WOR-PLA Work place

1. Is there a definition of the job of each maintenance operator?
2. Is there a detailed description of the knowledge required for each job?

3. Are these job descriptions reviewed periodically?
4. Are descriptions used to identify training needs as well as to define them?
5. What is the definition and content of these descriptions as they relate to a department's established goals and strategies for future operation?
6. Is there versatility among the maintenance personnel?
7. Is there balance between officers and administrative controls in the maintenance department?
8. What is the premier specialization among the staff?
9. How are descriptions of staff expertise used to define levels of staff and assign jobs?
10. Is the burden of remaining work of the staff known?
11. Is the location of the distributed daily working hours of the operators (tasks) known?
12. Is there a control system for input and output staff?

Target audience of the survey: Levels 3, 4, and 5

Human resources management

MIS-CLIM Company mission and labor climate

1. Is the maintenance work considered a mixture of physical and intellectual effort?
2. Is there a climate of pride in the company among the maintenance personnel?
3. Is there a sense of isolation in the maintenance department?
4. Does the staff have all technical means and amenities required in the workplace?
5. Are autonomy and initiative considered important in maintenance work?
6. Does the staff have autonomy and show initiative?
7. Is there camaraderie and collaboration among maintenance personnel?
8. Is there a policy on staff rotation in the company?
9. Does it apply to maintenance?
10. Is there a feeling that the maintenance personnel play an important role in the company?
11. Is there a career plan for maintenance personnel?
12. Does the maintenance personnel know the company's goals, mission, and vision?
13. Do personnel have the main mission of focusing on the availability of the installation or equipment?
14. Is the staff familiar with the company's goals?
15. Does the maintenance staff have seniority in the company?
16. Do they have regular meetings to learn about the department's goal and talk about themselves?
17. Are the vision and objectives clearly known and understood by the department?
18. Does the staff recognize the difference between preventative work that anticipates major problems and corrective work?
19. Is the relationship positive and collaborative between production and maintenance?

20. Is the attitude positive toward the higher levels of maintenance?
21. Do departments related to maintenance collaborate well?

Target audience of the survey: Levels 3, 4, and 5

Human resources management

MWO-TRA Motivation and training

1. Are staff members treated equitably?
2. Is (positive or negative) feedback provided for errors and successes?
3. Has a climate of respect been established so that staff is listened to?
4. Are there periodic meetings with the staff to communicate the results of the department with respect to evolving goals and/or plans for the future?
5. Does the system provide for both suggestions and effective management?
6. Is there a system of performance evaluation and professional development or career plans?
7. Is the system used to detect training needs?
8. Is the system used to establish objectives and ensure that workers achieve them?
9. Is the system used to "reward" employees on the basis of fulfilled "objectives"?
10. Are there sufficient tools and equipment for the work to be done?
11. Is the training level sufficient for the technology of the equipment?
12. Are training results evaluated? Is this evaluation ongoing?
13. Does the training ensure the versatility of the technical staff?
14. Does staff give training information about technologies and methodologies to their colleagues in the classroom, workshop, or field?
15. Does staff make proposals to their superiors about training needs?
16. Does staff evaluate the positive impact of the training acquired?
17. Does good information reduce training errors and downtime? Does this feeling exist?
18. How high is the turnover of maintenance staff?

Indicators

$$\text{CMMSI8} = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of supervisors}}$$

$$\text{CMMSI91} = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of planners}}$$

$$\text{CMMS92} = \frac{\text{Total number of full-time maintenance employees}}{\text{Number of trainers}}$$

$$\text{CMMS10} = \frac{\text{Total number of maintenance technicians}}{\text{Number of administrative support staff}}$$

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI13} = \frac{\text{Cost of indirect maintenance staff}}{\text{Maintenance total costs}}$$

$$\text{OI1} = \frac{\text{Effective number of internal maintenance staff}}{\text{Total effective of internal employees}}$$

$$\text{OI2} = \frac{\text{Effective number of indirect maintenance staff}}{\text{Effective of internal maintenance staff}}$$

$$\text{OI3} = \frac{\text{Effective number of indirect maintenance staff}}{\text{Effective of direct maintenance staff}}$$

$$\text{HRI2} = \frac{\text{Sum of years in staff list}}{\text{Total number of employees}}$$

$$\text{OI15} = \frac{\text{Effective number of internal maintenance staff with various activities}}{\text{Effective of internal maintenance staff}}$$

$$\text{OI10} = \frac{\text{Direct maintenance staff working in shifts}}{\text{Total effectives of direct maintenance staff}}$$

$$\text{ITI1} = \frac{\text{Total training budget}}{\text{Total number of employees}}$$

$$\text{EI21} = \frac{\text{Maintenance staff training cost}}{\text{Effective of maintenance staff}}$$

$$\text{ITI21} = \frac{\text{Total training hours}}{\text{Total number of employees}}$$

$$\text{ITI22} = \frac{\text{Total interpersonal training hours}}{\text{Total number of employees}}$$

$$\text{ITI6} = \frac{\text{Total number of trainers}}{\text{Total number of maintenance employees}}$$

$$\text{ITI11} = \frac{\text{Annual training budget}}{\text{Annual workers payroll budget}}$$

$$\text{OI23} = \frac{\text{Number of man-hours for maintenance internal staff training}}{\text{Total maintenance man-hours}}$$

ITI5 = Correspondence level between training provided and abilities acquired

$$\text{KAII4} = \frac{\text{Number of suggestions given by maintenance employees}}{\text{Total number of maintenance employees}}$$

ITI3 = Workers reading level

ITI4 = Skills level sectorals and nationals tests

$$\text{ITI7} = \frac{\text{Inactivity time operating mistakes due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI8} = \frac{\text{Inactivity time maintenance mistakes due to lack of training}}{\text{Total inactivity time}}$$

$$\text{ITI9} = \frac{\text{Time lost due to lack of knowledge}}{\text{Total worked time}}$$

$$\text{ITI10} = \frac{\text{Repeated maintenance time due to lack of knowledge}}{\text{Total worked time}}$$

$$\text{T\&UI1} = \frac{\text{Satisfied maintenance operators with personal equipment}}{\text{Total number of operators}}$$

$$\text{T\&UI2} = \frac{\text{Maintenance officers satisfied with the technical equipment available}}{\text{Total number of maintenance officers}}$$

$$\text{T\&UI3} = \frac{\text{Performed investments in maintenance equipment}}{\text{Planned investments in maintenance equipment}}$$

$$\text{TPMI6} = \frac{\text{Total absenteeism hours}}{\text{Total considered hours}}$$

$$\text{HRI1} = \frac{\text{Voluntary dismissals}}{\text{Total number of employees}}$$

Questionnaire: Subcontracts

Target audience of the survey: Levels 2, 3, and 4

Purchases management, finances management, and human resources management

REC-POL Recruitment policy

1. Can the company subcontract services because of a lack of qualified personnel and heavy workload?
2. Is staff available at all hours for routine maintenance work?
3. Are outsourcing costs considered a service to be managed by the company's own staff?
4. Is there a standard defined contract?
5. How does the company compose contracts, taking into account the recommendations of UNE-EN 13269:2003?
6. Is there a policy for or formal methodology of work recruitment?
7. Is the recruitment policy effective and efficient?
8. Are the specifications for contracts clear?
9. Is the service quality clearly defined?
10. Are the service scope and trading conditions defined?

CONT-SEL Contractors selection

1. Are there processes for evaluating suppliers based on know-how, response time, cost, experience, compliance with safety regulations, and so on?
2. Does the maintenance supervisor participate in the selection of contractors and awarding of work?
3. Does the contractor know the labor policy of the company?
4. Does the company know the economic solvency of the contractor?
5. Does the company know the contractors professionalism?

CONT-OVER Contractor oversight

1. Is there a follow-up handbook on subcontracting?
2. Is there a formal mechanism of work control of contractors?
3. Is there a fluid and friendly relationship between internal and external staff?
4. Is there a formal mechanism to ensure the quality control of contractors' work?
5. Is there a formal mechanism to monitor safety in the contractors' work?
6. Is there a formal mechanism for deadline control in the work of the contractor?
7. Are there any penalties for delays?

1	2	3	4	5

Indicators

$$\text{EI9} = \frac{\text{Total cost of external staff used in maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI10} = \frac{\text{Total contracting cost}}{\text{Maintenance total costs}}$$

$$\text{CONTI1} = \frac{\text{Availability time of contracted services}}{\text{Required time}}$$

$$\text{CONTI2} = \frac{\text{Number of works requiring repeat}}{\text{Number of works performed by contractors}}$$

$$\text{CONTI3} = \text{Years of experience in the reference field}$$

$$\text{CONTI4} = \text{Quality certifications as supplier}$$

$$\text{CONTI5} = \text{Technological level of outsourced staff}$$

$$\text{EI22} = \frac{\text{Total contracting cost of mechanical maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI23} = \frac{\text{Total contracting cost of electrical maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI24} = \frac{\text{Total contracting cost of instrumentation maintenance}}{\text{Maintenance total costs}}$$

A.4 Level 3 of Evolution

Questionnaire: CBM

Target audience of the survey: Levels 3 and 4

CBM, Condition-based maintenance

1. Is maintenance performed when doing the inspection?
2. Are there any predictive maintenance routines for critical equipment?
3. Is there a defined frequency for these routines?
4. Is there a procedure for each of these routines?
5. Is there an analysis of the results of predictive maintenance (i.e., future trends) versus production data?
6. Are preventive maintenance actions performed based on that analysis?
7. Is there a reduction in the number of breakdowns since CBM was started?
8. Have maintenance habits and the corrective and preventative percentages changed since was CBM started?

9. Do calculations justify that the use of these techniques avoid unnecessary costs?
10. Does internal staff perform the predictive analysis?
11. Is staff trained in CBM?
12. Is there a mechanism to improve or add routines of predictive maintenance?
13. Is monitoring based on established indicators such as vibration, temperature, and so on?
14. Do they conduct short daily meetings to review and control scheduled tasks, analysis, and results obtained in the routes?
15. Are corrective actions defined and assigned to the staff in daily maintenance interventions?

Indicators

$$\text{PMI6} = \frac{\text{Number of failures that should have been avoided}}{\text{Total number of failures}}$$

$$\text{TI10} = \frac{\text{CBM time which causes unavailability}}{\text{Total unavailability time due to maintenance}}$$

$$\text{PMI7} = \frac{\text{Total number of work orders generated in MP inspections}}{\text{Total number of work orders generated}}$$

$$\text{CBMI11} = \frac{\text{Total predictive maintenance hours}}{\text{Total maintenance hours}}$$

$$\text{CBMI12} = \frac{\text{Predictive maintenance costs}}{\text{Maintenance total costs}}$$

$$\text{OI19} = \frac{\text{CBM maintenance man-hours}}{\text{Total maintenance man-hours}}$$

$$\text{MTBF} = \text{CBMI4} = \frac{\text{Total hours considered}}{\text{Number of failures of equipment}}$$

$$\text{CBMI2} = \text{Avoided costs due to use of predictive maintenance}$$

$$\text{CBMI3} = \frac{\text{Current maintenance costs}}{\text{Maintenance costs before CBM program}}$$

$$\text{EI17} = \frac{\text{CBM maintenance cost}}{\text{Maintenance total costs}}$$

Questionnaire: Integration of maintenance and production

Target audience of the survey: Levels 2, 3, and 4

Production management and medium management

PROD-PLAN Production planning

1. Is there a plan for daily production?
2. Is there a weekly agreed-upon maintenance program?
3. Does this program include planned stop pages?
4. Are there established times for stops and format changes?
5. Is this daily production and maintenance program reviewed?
6. Are times stipulated for equipment maintenance?
7. Has the volume of maintenance work that can be done without harming production been calculated?
8. Is there a long-term plan of production that includes major maintenance activities?

NO-AS Knowledge of assets

1. Is there a list of the company's assets? Is the list coded?
2. Is there a technical sheet for each item?
3. Is there any connection between the management software for maintenance and production?
4. Is there a shop floor layout to describe and identify all the computers?
5. Does the production system have lines in parallel?
6. Are the lines identified based on the critical process?
7. Are production areas separated based on some criteria?
8. Has a criticality analysis been performed to concentrate resources on critical assets?
9. Can the incidence of failure be quantified for other equipment?
10. Has each asset been analyzed in terms of regulations?
11. Are these rules met?
12. Does some equipment produce bottlenecks?
13. Does the company know how much time each process on the production line takes?
14. Is there a diagram of the installation process?
15. Are there any diagrams for pipes (electrical, air, water) to be installed?
16. Are there PID diagrams for instrumentation and processes?
17. Are catalogs and technical information available for all computers?
18. Do production and maintenance share technical information?
19. Is the technical information accessible in case of stoppage or failure?

PERF-CON Performance control

1. Is there a system for recording failure times and sharing this information between production and maintenance?
2. Is there strict control of time from the point a machine stops until it returns to use, with all phases of maintenance timed?

3. How is WOS production entered into the system?
4. Are stoppage times and performance recorded for each machine/production line?
5. Are stoppage times and their causes analyzed?
6. Are maintenance and production analyzed together with the costs generated by stoppages?
7. Are the lost time and volume generated by these stoppages measured?
8. How are the different availabilities linked to the maintenance calculated?
9. Are the yield reductions of critical equipment recorded?
10. Are corrective actions implemented to eliminate the causes?

Indicators

$$\text{TI2} = \frac{\text{Availability time achieved during the required time}}{\text{Required time}}$$

$$\text{TI1} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Maintenance unavailability time}}$$

$$\text{TI6} = \frac{\text{Total operating time}}{\text{Total operating time} + \text{Unavailable time due to failures}}$$

$$\text{CMMSI4} = \frac{\text{Total number of machines in the CMMS}}{\text{Total number of machines registered in plant}}$$

$$\text{TI18} = \frac{\text{Number of systems covered by criticality analysis}}{\text{Total number of systems}}$$

$$\text{EI6} = \frac{\text{Availability linked to maintenance}}{\text{Quantity produced}}$$

Questionnaire: RAMS and RCM analysis

Target audience of the survey: Levels 2, 3, 4

RAMS-KNO RAMS knowledge and concepts

1. Is there a list of critical and important equipment for the company?
2. Do employees know about the difference between critical, priority, and secondary equipment?
3. Have the equipment´s critical parts been identified?
4. Are the main causes of failure known?
5. Are spares fixed depending on their condition?
6. Are the critical components of the key equipment regularly checked?
7. Do these revisions generate corrective actions and give answers?
8. Is there a formal inspection plan for components?

9. Is there a procedure for equipment modification?
10. Does this procedure take into account maintenance issues?
11. Does the modification procedure explain how to update the existing technical documentation?
12. Is it audited?
13. Is the experience of maintenance department used to select new equipment or to modify current equipment?
14. Are maintainability and reliability considered in the design or purchase of new equipment?
15. Is the accessibility of each component of the new machine considered, for example, to be able to adequately perform inspections or other maintenance tasks?
16. Are the reliability concepts known to the personnel?
17. Can the reliability of critical equipment be determined?
18. Is the failure of critical equipment understood?
19. Are maintenance costs in the cycle life of equipment analyzed?
20. Do the FMEA concepts include maintenance, production, procurement, and engineering?
21. Is FMEA a tool used in machinery acquisition?
22. Who participates in FMEA analysis used in the equipment selection process?
23. Are FMEA techniques used to develop preventive plans for critical equipment?
24. Are these techniques good enough to eliminate unnecessary inspections?
25. Is the value of the FMEA results quantified?
26. Is FMEA used to implement improvements and technical modifications?
27. Is FMEA used to design new equipment?
28. Is current maintenance analyzed with respect to RCM?
29. Is RCM implemented?
30. Are the RCM principles understood?
31. Are historical data used to improve the reliability of critical equipment?
32. Are data/historical equipment used to improve the reliability of all equipment parts?
33. Are MTBF and MTTR indicators calculated systematically for the equipment and its parts?
34. Are these indicators regularly reviewed to detect improvement, or vice versa?
35. Are the improvements implemented in the equipment preserved and archived?
36. Are tests performed and checked?
37. Are previous measurements used to prevent the recurrence of problems?

Indicators

$$\text{RAMSI1} = R(t) \text{ Reliability of equipment or system}$$

$$\text{RAMSI2} = M(t) \text{ Maintainability of equipment or system}$$

$$\text{RAMSI3} = \text{MTBF of equipment or system}$$

$$\text{RAMSI4} = \text{MTTR of equipment or system}$$

$$\text{RAMSI5} = \lambda(t) \text{ Risk rate of equipment or system}$$

$$\text{TI18} = \frac{\text{Number of systems covered by criticality analysis}}{\text{Total number of systems}}$$

$$\text{RCMI2} = \frac{\text{Number of equipment failures where they perform cause analysis}}{\text{Total number of equipment failures}}$$

$$\text{RCMI3} = \frac{\text{Number of reviewed preventive tasks in critical equipment}}{\text{Total number of preventive tasks in critical equipment}}$$

$$\text{RCMI4} = \frac{\text{Number of reviewed predictive tasks in critical equipment}}{\text{Total number of predictive tasks in critical equipment}}$$

$$\text{RCMI8} = \frac{\text{Number of reviewed spare parts in critical equipment}}{\text{Total number of spare parts in critical equipment}}$$

$$\text{RCMI5} = \text{Avoided costs due to use of RCM}$$

Questionnaire: Safety
Target audience of the survey: Levels 2, 3, 4, and 5
Human resources management
SAF-KNO Safety knowledge concepts

1. Does the company have or display safety posters at work?
2. Are safety aspects considered a priority by the company?
3. Do mechanisms inform management about unsafe conditions?
4. Does the company have safety and health committees at work?
5. Does the company provide safety workshops or lectures?
6. Is safety the first thing in work maintenance?
7. Are specific safety meetings held?
8. Are safety policies or regulations and hygiene generally known?
9. Does the company have a department responsible for health and safety?
10. Is the company aware of the added risk encountered by maintenance workers?
11. Does the company have some kind of system to reward and incentivize security?
12. What is the interest in the company about safety and hygiene in the workplace?

13. Does staff receive written or verbal instructions about security?
14. Are there regular inspections of safety control?
15. Are the safety committee's functions and hygiene in the workplace generally known?
16. Is the safety policy respected?
17. Are risks evaluated according to the job?
18. Have procedures been established, along with specific regulations for the safe performance of maintenance?
19. Is compliance with safety regulations a priority of the department?
20. Have the risks been identified to relevant operators?
21. Are maintenance program equipment and tools available?
22. Is there a calibration procedure for equipment and measurement tools?
23. Are the calibrations and the equipment inspections archived?

Indicators

$$\text{OI6} = \frac{\text{Number of injuries to maintenance staff}}{\text{Total effective of maintenance staff}}$$

$$\text{TI5} = \frac{\text{Number of injuries to maintenance staff}}{\text{Working time}}$$

$$\text{OI7} = \frac{\text{Man-hours lost by injuries of maintenance staff}}{\text{Total man-hours worked by maintenance staff}}$$

$$\text{TI3} = \frac{\text{Number of failures due to maintenance that generate environmental damage}}{\text{Calendar time}}$$

A.5 Level 4 of Evolution

Questionnaire: Cost model and financial optimization

Target audience of the survey: Levels 2 and 3

Financial management

BUD-MAN Management and budgetary control

1. Is there a previously approved budget for the department?
2. Is there monthly control of costs?
3. Is there a cost control with reference to some previously set indicators?
4. Do the periodic control results and indicators arrive at intermediate drive production and maintenance lines?

5. How is the deviation between the actual and budget costs measured?
6. Is there maintenance cost control for equipment?
7. Is high cost controlled by the type of maintenance applied?
8. Does each team perform statistical control of maintenance costs?
9. Is the inventory size defined for available equipment?
10. Does each team know the relevant spares' cost?
11. Is labor cost for maintenance known?
12. Is it more cost effective to outsource the work than to do it using own resources?
13. Can maintenance policies be defined on the basis of alternative costs?

COST-STR Cost structure

1. Is there a cost structure of well-defined maintenance?
2. Does that model include direct and indirect costs?
3. Is that cost model used for future decisions?
4. Are costs defined by production areas?
5. Is the acquisition date of the equipment known?
6. Are costs defined by equipment as well as each of the equipment's components?
7. Is the value of acquisition of the equipment known?
8. Is the depreciation rate the defined rate for the equipment?
9. Is the amount of lost production cost because of faults known?
10. Does the cost model include traditionally hidden faults?
11. Are equipment replacements annually assessed?
12. Is the cost relationship between maintenance and the total cost of the product known?
13. Is the total cost of a new piece of equipment known?
14. Is the cost of disuse known and broken down?
15. Are costs broken down into temporal and variables costs, that is, temporal (staff, planned maintenance, investment) and variable (staff, spare parts, energy, rent)?
16. Is there a relationship between maintenance personnel and production?

Indicators

$$\text{EI1} = \frac{\text{Maintenance total costs}}{\text{Assets replacement value}}$$

$$\text{EI2} = \frac{\text{Maintenance total costs}}{\text{Added value plus external maintenance costs}}$$

$$\text{EI3} = \frac{\text{Maintenance total costs}}{\text{Quantity produced}}$$

$$\text{EI4} = \frac{\text{Maintenance total costs}}{\text{Transformation cost to production}}$$

$$\text{EI5} = \frac{\text{Maintenance total costs} + \text{Unavailability costs linked to maintenance}}{\text{Quantity produced}}$$

$$\text{EI9} = \frac{\text{Total cost of external staff used in maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI10} = \frac{\text{Total contracting cost}}{\text{Maintenance total costs}}$$

$$\text{EI13} = \frac{\text{Cost by indirect maintenance staff}}{\text{Maintenance total costs}}$$

$$\text{EI8} = \frac{\text{Total cost of internal staff used in maintenance}}{\text{Maintenance total costs}}$$

$$\text{EI15} = \frac{\text{Corrective maintenance cost}}{\text{Maintenance total costs}}$$

$$\text{EI16} = \frac{\text{Preventive maintenance cost}}{\text{Maintenance total costs}}$$

$$\text{EI17} = \frac{\text{CBM maintenance cost}}{\text{Maintenance total costs}}$$

$$\text{EI18} = \frac{\text{Systematic maintenance cost}}{\text{Maintenance total costs}}$$

$$\text{EI19} = \frac{\text{Improvement maintenance cost}}{\text{Maintenance total costs}}$$

Questionnaire: Maintenance performed by production staff

Target audience of the survey: Levels 2, 3, and 4

Production manager and area supervisors

TPM Total productive maintenance

1. Is the basic level of maintenance performed by the staff handling the machine?
2. Are operators taught how to perform these small maintenance tasks?
3. Are there clearly defined routes (cleaning, lubrication, inspection) for the maintenance performed by the operators?

4. Is the staff aware of the importance of order and cleanliness?
5. Does the maintenance by production operators include basic tasks of cleaning, inspecting, and greasing?
6. Do production and maintenance work together, in agreement with established maintenance plans?
7. Are the operators responsible for housekeeping?
8. Has the management team created awareness of the importance of maintenance implementation and the need to involve maintenance and production?
9. Does each facility have a clearly defined and accessible maintenance plan?
10. Is there a realization (mode) and compliance (periodicity) audit of the maintenance plan?
11. Are there any visual indicators such as graphics or figures that show the success or failure of the maintenance program?
12. Is there a checklist for the realization of defined tasks?
13. Has the production staff received training in maintenance and safety regulations?
14. Is there a daily schedule that includes all maintenance activities?
15. Is a daily check performed and are results communicated to the staff/affected area?
16. Is there a follow-up in accordance with some established indicators?
17. Is there a policy on eliminating waste by analyzing a process involving all employees?
18. Are short daily meetings held to review and control scheduled tasks?
19. Are corrective actions defined and assigned to the staff to see the result of detected problems in daily maintenance interventions?
20. Is there a defined and assigned follow-up for these corrective actions?

Indicators

$$\text{OI4} = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of direct maintenance staff}}$$

$$\text{OI9} = \frac{\text{Maintenance man-hours by production operator}}{\text{Total man-hours of production operators}}$$

$$\text{OII1} = \frac{\text{Preventive maintenance hours by production operators}}{\text{Total preventive hours}}$$

$$\text{OII23} = \frac{\text{Preventive maintenance hours by operators year_}n}{\text{Preventive maintenance hours by operators year_}n-1}$$

$$\text{TPMI3} = \frac{\text{Critical equipment included in 5S activities}}{\text{Total number of critical equipment}}$$

A.6 Level 5 of Evolution

Questionnaire: Continuous improvement

Target audience of the survey: Levels 2, 3, 4, and 5

QUA-KAI Quality and continuous improvement

1. Are there established procedures for maintenance?
2. Are these procedures in the ISO 9000 quality system?
3. Does each team in the system have a maintenance work program?
4. Is a "Poka Yoke" philosophy used to avoid errors?
5. Does each team have maintenance records?
6. Is the register updated systematically and regularly?
7. Is there a procedure to maintain and update this information?
8. Are operator records and corresponding authorizations kept for work on equipment?
9. Are stoppages in production and their causes analyzed using FMEA to establish corrective actions?
10. Are the causes of a decline in production analyzed?
11. Are product rejections analyzed?
12. Are these analyses carried out by mixed production and maintenance teams?
13. Does the company get suggestions for improvement from the employees in production and maintenance?
14. Is the economic impact of these suggestions analyzed?
15. Is the maintenance plan upgraded every 1–2 years in accordance with worked hours and results?
16. Are advanced statistical techniques applied?
17. Are the department and its functioning regularly audited?
18. Is there a policy of improvement based on benchmarking?
19. Does the maintenance department have a regular process of benchmarking with other factories/departments in the group or sector?
20. Are the results of benchmarking reviewed and communicated?
21. Are these results used to implement improvement plans?
22. Are the Six Sigma philosophies used as a tool for continuous improvement?
23. Are the workplace and equipment improved through the 5S to impose order, cleanliness, standardization, organization, and integration?
24. Are there established indicators of operational and financial management?
25. Are the definitions of these indicators based on calculation methods, sources of information, frequency of occurrence, and responsibilities?
26. Are all the areas and relevant personnel related to the indicator and its particular definition known?
27. Have the objectives been established for each indicator?

28. Is the benchmarking program performed for these indicators?
29. Are these indicators used as a basis for decision-making?
30. Are communication indicators achieved periodically by the staff?
31. Is there a relationship between the management indicators and improvements?
32. Is specialized equipment used by the different departments to solve important problems?
33. Are the practices and fault analysis methods used by a multidepartmental improvement team?
34. Are there regular meetings and plans for these teams?

Indicators

$$\text{OI8} = \frac{\text{Man-hours used in continuous improvement}}{\text{Total man-hours of maintenance staff}}$$

$$\text{OII31} = \frac{\text{Hours of equipment improvement per production operators}}{\text{Total number of worked hours by operators}}$$

$$\text{OII32} = \frac{\text{Hours of equipment improvement per maintenance operators}}{\text{Total number of worked hours by operators}}$$

$$\text{KAII3} = \frac{\text{Critical equipment included in continuous improvement activities}}{\text{Total number of critical equipment}}$$

$$\text{TPMI2} = \frac{\text{Critical equipment included in design improvement studies}}{\text{Total number of critical equipment}}$$

$$\text{TPMI3} = \frac{\text{Critical equipment included in 5S activities}}{\text{Total number of critical equipment}}$$

$$\text{KAII4} = \frac{\text{Number of suggestions given by maintenance employees}}{\text{Total number of maintenance employees}}$$

$$\text{KAII1} = \text{Savings achieved by employees suggestions}$$

$$\text{EI19} = \frac{\text{Improvement maintenance cost}}{\text{Maintenance total costs}}$$

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"This is a very useful handbook for students and maintenance professionals alike that will enable them to align the maintenance with business requirements and create a hierarchy of measures which will allow opportunities for value creation to be identified. The rigorous performance management framework described in the book will then enable readers to strengthen areas of weakness in the maintenance strategy and its execution so that cost-effectiveness can be improved."
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Maintenance Audits Handbook: A Performance Measurement Framework explores the maintenance function and performance of an organization, and outlines the key aspects required for an effective and efficient maintenance performance measurement (MPM) system. Incorporating different aspects of traditional literature and considering various frameworks on the subject, it examines the auditing process as well as the use and development of maintenance metrics. It identifies different frameworks and models showcasing how MPM systems should be implemented as well as the values that are created when different frameworks are used.

The book presents performance indicators within a framework that classifies and sorts according to functional and hierarchical aspects. It introduces techniques that can help determine the right set of performance indicators. It also outlines a process that combines both numerical indicators with the classical result of massive questionnaires successfully incorporating both the quantitative and qualitative aspects of maintenance performance. In addition, the author provides examples of MPM frameworks that are used in organizations with condition-based, vibration-based, and reliability-centered maintenance.

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- Identify the weaknesses and strengths of the implemented maintenance strategy

Maintenance Audits Handbook: A Performance Measurement Framework provides readers with a sound foundation for developing and measuring a comprehensive maintenance improvement strategy using qualitative and quantitative data, and serves as an ideal resource for maintenance/mechanical engineers, maintenance/performance/business/production managers and industry professionals involved in maintenance.

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ISBN: 978-1-4665-8391-7
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