# Maintenance performance metrics: A state-of-the-art review

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# Maintenance performance metrics: a state-of-the-art review

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**Abstract**

**Purpose** – The purpose of this paper is to provide an overview of research and development in the measurement of maintenance performance. It considers the problems of various measuring parameters and comments on the lack of structure in and references for the measurement of maintenance performance. The main focus is to determine how value can be created for organizations by measuring maintenance performance, examining such maintenance strategies as condition-based maintenance, reliability-centred maintenance, e-maintenance, etc. In other words, the objectives are to find frameworks or models that can be used to evaluate different maintenance strategies and determine the value of these frameworks for an organization.

**Design/methodology/approach** – A state-of-the-art literature review has been carried out to answer the following two research questions. First, what approaches and techniques are used for maintenance performance measurement (MPM) and which MPM techniques are optimal for evaluating maintenance strategies? Second, in general, how can MPM create value for organizations and, more specifically, which system of measurement is best for which maintenance strategy?

**Findings** – The body of knowledge on maintenance performance is both quantitatively and qualitatively based. Quantitative approaches include economic and technical ratios, value-based and balanced scorecards, system audits, composite formulations, and statistical and partial maintenance productivity indices. Qualitative approaches include human factors, amongst other aspects. Qualitatively based approaches are adopted because of the inherent limitations of effectively measuring a complex function such as maintenance through quantitative models. Maintenance decision makers often come to the best conclusion using heuristics, backed up by qualitative assessment, supported by quantitative measures. Both maintenance performance perspectives are included in this overview.

**Originality/value** – A comprehensive review of maintenance performance metrics is offered, aiming to give, in a condensed form, an extensive introduction to MPM and a presentation of the state of the art in this field.

**Keywords** Maintenance, Performance measurement, Metrics, Key performance indicators, Indicators, Performance, Maintenance performance measurement, Framework, Hierarchy

**Paper type** Literature review

## I. Introduction

The maintenance function is inherent to production. Even so, understanding and quantifying maintenance activities can be problematic. A recent understanding is that maintenance is more than a group of people and/or a workshop and transcends the limits of a traditional department; this paper uses the terms maintenance or maintenance function to indicate this broader scope.

The scope of maintenance in a manufacturing environment is illustrated by its numerous definitions. The British Standards Institute defines maintenance as a

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combination of all the technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or to restore them to this condition (BSI, 1984; Pintelon and Van Puyvelde, 1997, 2006). Meanwhile, the Maintenance Engineering Society of Australia (MESA) indicates that maintenance is about achieving the required asset capabilities within an economic or business context (Maintenance Engineering Society of Australia (MESA), 1995). Maintenance also includes the engineering decisions and associated actions that are necessary for the optimization of specified equipment capability, with capability meaning the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality, safety and responsiveness (Tsang *et al.*, 1999). Similarly, Kelly (1989) states that the objective of maintenance is to achieve the agreed output level and operating pattern at a minimum resource cost within the constraints of the system condition and safety. The desired production output is achieved through high availability, which is influenced by the equipment reliability and maintainability, and the maintenance supportability (CEN, 2011). Finally, maintenance is also partly responsible for the technical systems' safety and for ensuring that the plant remains in good condition (Visser and Pretorious, 2003).

One can summarize maintenance objectives as follows (Kelly and Harris, 1998): ensuring that the plant functions (availability, reliability, product quality, etc.); ensuring that the plant reaches its design life; ensuring plant and environmental safety; and ensuring cost-effectiveness in maintenance and the efficient use of resources (energy and raw materials). With respect to the production equipment, proper maintenance will set system functioning as its prime objective. In short, maintenance must ensure the required reliability, availability, efficiency and capability of the whole production system. It will ensure the system life by keeping the equipment in good condition. In this case, cost has to be optimized to meet the desired plant condition (Dekker, 1996). Plant safety is also very important, as failures can have catastrophic consequences. Here the cost of maintenance has to be minimized while keeping the risks within strict limits and by meeting the statutory requirements.

For a long time, maintenance was carried out by the workers themselves, with no defined parameters. Equipment maintenance was more loosely organized, and there was no haste for the machinery or tools to be operational again. Given the current concerns about money and safety, this is beginning to change. The focus is now directed on keeping equipment operational or returning it to production as quickly as possible. The challenges are the following:

- First, there is a need for higher plant availability in a global economy. Global markets suffer from expansions, the purchase of industrial buildings and production equipment, and acquisitions of companies in the same sector, regardless of the country. Global competition means that companies want their productive capacities to remain at a maximum. Therefore, organizations are beginning to worry about keeping track of the parameters that may affect the availability of their plants and machinery.

- Second, the bottom line for production is a chrematistic focus, i.e. a focus on money making. When organizations begin to optimize their production costs, they start to question their maintenance costs. The maintenance function has, in recent years, grown in terms of assets, personnel, etc., and now consumes a significant percentage of the overall organization budget (Cross, 1988; Dekker, 1996). Thus, when establishing policies to streamline costs, the maintenance budget is a crucial part of the puzzle. At the same time, however, the organization's maintenance must meet the availability and quality parameters. A constant concern then is maximizing the availability at the lowest cost. Not surprisingly, methodologies and technologies for determining the best way to achieve this balance are becoming increasingly popular, as noted by Al-Najjar (2007).

## II. The need to measure maintenance performance

Today organizations are under pressure to enhance continuously their capabilities to create value for their customers and improve the cost-effectiveness of their operations (Tsang, 2002). In this regard, the maintenance of large-investment equipment, which was once thought to be a necessary evil, is now considered key to improving the cost-effectiveness of an operation, creating additional value by delivering better and more innovative services to customers.

With the current changes in the strategic thinking of organizations, the increased amount of outsourcing and the separation of original equipment manufacturers and asset owners, it is becoming crucial to measure, control and improve the assets' maintenance performance (Parida and Kumar, 2009). As technology has advanced, various maintenance strategies have evolved, including condition-based maintenance, predictive maintenance, remote maintenance, preventive maintenance (PM), e-maintenance, etc. The main challenges faced by organizations today are choosing the most efficient and effective strategies to enhance the operational capabilities continually, to reduce the maintenance costs and to achieve competitiveness in the industry in question. Therefore, in addition to formulating maintenance policies and strategies for asset maintenance, it is important to evaluate their efficiency and effectiveness.

Maintenance performance measurement (MPM) can be defined as the multi-disciplinary process of measuring and justifying the value created by maintenance investments, and meeting the organization's stockholders' requirements viewed strategically from the overall business perspective (Parida and Chattopadhyay, 2007). MPM allows companies to understand the value created by maintenance, to re-evaluate and revise their maintenance policies and techniques, to justify investment in new trends and techniques, to revise resource allocations, and to understand the effects of maintenance on other functions and on the stakeholders, as well as on health and safety, etc. (Parida and Kumar, 2006).

Unfortunately, maintenance metrics have often been misinterpreted and are often incorrectly used by businesses. The metrics should not be used to show workers that they are not doing their job. Nor should they be used to satisfy the organization's ego, i.e. to show that the company is working excellently. Performance measurements, when used properly, should highlight opportunities for improvement, detect problems and help find solutions (Wireman, 1998).

In their overview of the state of maintenance, its current problems and the need for adequate metrics for its quantification, Mata and Aller (2008) note that maintenance is seen in industry as a necessary evil, an expense or loss which the organization must incur to keep its production process operative. Because of this, the priorities of a company do not typically focus on maintaining assets, but on the production that they represent. However, the use of objective indicators to evaluate these processes can help to correct deficiencies and increase the production of an industrial plant. Many indicators relate the costs of maintenance to production or sales; others make it possible to determine whether the availability is adequate or what factors should be modified to achieve its increase.

This historical view of maintenance, mixed with the traditional issues of performance measurement, creates problems in the development and implementation of a comprehensive package of maintenance performance management (Woodhouse, 2004). For example, the human factor must be included in the selection of the measuring metric, its implementation and the use of the resulting measurement.

### *A. Too much data and too little information*

Data acquisition has become relatively simple and cheap through the introduction of modern and powerful hardware systems and software. On the other hand, nowadays data overload is a problem, and sophisticated data mining algorithms are required to obtain useful information, as Charnes *et al.* (1984) argue. In instances when data are more difficult to collect, one needs to decide if their value to the company and specifically to a certain hierarchical level is worth the effort and cost. This is accomplished by establishing what is important for different levels, i.e. making an analysis of objectives tailored to each organizational level emanating from the corporate levels. Once the user needs are fully understood, it is possible to determine the maintenance strategy, organization, resources and systems.

### *B. The number of performance indicators (PIs), ownership of the data and the aspects to be covered*

The number of indicators used for each key result area or department should be limited by identifying key features or key factors. Scorecards with large numbers of indicators that do not define the 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 in question. Often the maintenance department is so overwhelmed by its duties that data cannot be collected. Further, there may be a lack of historical data, making it impossible to create certain indicators. In a multifunctional organization, it is likely that other departments are collecting some data critical to the generation of maintenance-related parameters and can share that data. For example, it may be relatively simple for the production department to collect data on availability or reliability. Personnel involved with occupational safety and health issues are ideal for determining the rates of accidents, as studied in EN 15341 (CEN, 2007).

### *C. Objectives and measures*

At times, departments within the same company have conflicting interests concerning the maintenance of their equipment. However, the purpose of a company's objectives is to ensure that departmental efforts are aligned with the business needs of the whole organization (Gelders *et al.*, 1994) . Tangible goals should be tailored to the user and be free of ambiguity. Problems can be created when the management fails to set goals at the highest level or fails to ensure that these objectives are correctly translated into subgoals at lower levels. However, ambiguities disappear when the management ensures that its objectives are translated into objectives at lower levels. The objectives should be transmitted in a downward cascade, including all the company departments; the measure indicated by the selected sensors will indicate the appropriate steps to take to ensure that everyone is going in the same direction.

*D. Time lag between action and monitoring results*
Sometimes there is a delay between a policy change and the appearance of clear and apparent results associated with that change. A second delay may occur between the appearance of results and the measurement of those results. Each problem must be set against each objective, taking into account the fact that technical levels in the organization can expect faster changes in their indicators than corporate levels, whose key performance indicators (KPIs) are slower in showing visible results. Once a measure has been identified for a goal and level, and this has been implemented, the method of data collection and the frequency must be tailored to the factors involved: physical, human, financial, organizational factors, etc.

*E. The 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 give little value. The involvement of human factors in the collection of data leads to greater reliability, as data collected in this way are more closely related to indicators of ownership and responsibility (Galar *et al.*, 2011b). Technicians and operators will collect data only if they believe that they are worthwhile, and the results are made available for consultation and use.

If there is a risk that the indicators derived from the reported data will be used against people, it is almost certain that they will not be collected in an appropriate way. Moreover, if time passes and the data have not been used for any purpose, if they have been forgotten and feedback has not been transmitted, the whole process will inevitably be regarded as a waste of time. In other words, if the personnel understand the purpose and see the results, they will be motivated to collect data. Massive data collection can generate indicators unknown to the collectors, who may therefore distrust the data and fear their effects.

These issues reinforce the idea that the measurements should combine the internal functioning of maintenance with its interaction with external actors, particularly clients. At the same time, the measurements must honour the objectives of the management, as it is the management who will propose improvements after reading the indicators.

## III. The measurement: sensors and placements
Measurement is the act of assigning numbers to properties or characteristics. The measurement objective is to quantify a situation or to understand the effects of things that are observed (TRADE and PBM SIG, 1995). Measuring performance is essential in any business. Continuous improvement is the process of not accepting the status quo, as Wireman (1998) notes. Levitt (1997) agrees with Wireman and maintains that a prerequisite for the maintenance function is continuous improvement.

An ever-increasing number of studies have attempted to establish the relationship between maintenance performance and the reliability of a productive or operative system. For Kutucuoglu *et al.* (2001) and Atkinson *et al.* (1997), the measurement objectives are planning, selection, monitoring and diagnosis. Mitchell (2002) argues that measurement figures are needed to estimate the scope for competition, prioritize resources and determine the progress and effectiveness of improvement initiatives. Arts *et al.* (1998) see performance measurements as ways to control maintenance to reduce costs, increase productivity, ensure process safety and meet environmental standards. PM provides a base for improvement, since without measurement there can be no certainty of improvement (Parida *et al.*, 2003). PM is a powerful methodology which allows engineers and managers to plan, monitor and control their operation/ business. In brief, the purpose of measuring maintenance performance is to help determine future action and to improve performance based on past data. If an organization does not select the appropriate metrics to measure performance, the results can be misleading.

In TRADE and PBM SIG (1995), a performance measure is a number and a unit of measurement. The number gives the magnitude and the unit gives a meaning. Implementing measures may also be represented by the utilization of multiple units expressed as ratios between two or more fundamental units to yield a new unit (TRADE and PBM SIG, 1995). An indicator, therefore, is a combination of a set of performance measurements. To streamline PIs, KPIs are created and these can consist of several indicators and metrics. To determine the performance level, the strengths and weaknesses of a strategy must be considered; accordingly, the selected KPIs must reflect this need.

An important aspect of MPM is formulating maintenance performance indicators (MPIs), linking maintenance strategies with the overall organizational strategy (Tsang, 2002). The end user wants the fewest possible indicators to monitor the entire system, no matter how complex it may be. A review of the literature reveals that many attempts have been made to use maintenance performance measures as a means to develop an effective and efficient MPM system. The major issue in measuring maintenance performance is the formulation and selection of MPIs that reflect a company's organizational strategy and give the maintenance management quantitative information on the performance of the maintenance strategy (Arts *et al.*, 1998; Swanson, 2001).

Hernández and Navarrete (2001) proposes a battery of indicators derived from system reliability and functional safety. He defines an indicator or index as a numerical parameter which provides information about a critical factor identified within an organization and which concerns, for example, processes, people or expectations of cost, quality and deadlines. The indices should be few, easy to understand and measurable, and should make it possible, in a fast and easy manner, to learn how the system is functioning and the reasons for its behaviour. In addition, the indices must identify the key factors of maintenance and make it possible to establish records of data allowing periodic calculation to set standard values for these indicators, mark targets based on those standards, make appropriate decisions and take appropriate actions (Armitage and Jardine, 1968). Hernández and Navarrete (2001) places special emphasis on ranking these indicators; this is especially relevant when there is a large set of indicators.

Many authors agree that the first step is to develop MPIs, i.e. numerical parameters for critical factors associated with measurable physical characteristics must be identified. Besterfield *et al.* (2002) identify seven basic characteristics that can be used to measure performance: quantity, price, speed, accuracy, function, service and aesthetics.

## IV. Types of indicator: leading vs lagging and hard vs 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 a MPI (Wireman, 1998; Parida *et al.*, 2003). PIs are used to find ways to reduce the downtime, costs and waste, to operate more efficiently, and to increase the operation's capacity. A PI compares the actual conditions with a specific set of reference conditions (requirements), measuring the distance between the current situation and the desired situation (target), the so-called "distance-to-target" assessment (EEA, 1999).

The list of PIs is long, and each organization's selection of PIs will reflect its corporate strategy's objectives and requirements.

PIs can be broadly classified as leading or lagging indicators. A leading indicator warns the user about the non-achievement of objectives before there is a problem. It is one of a statistical series that fairly reliably turns up or down before the general economic status improves or deteriorates (*Encyclopedia Britannica*). A leading indicator thus works as a performance driver and alerts the head of the specific organizational unit to ascertain the present status in comparison to the reference one. Soft or perceptual measures like stakeholder satisfaction and employee commitment are often leading indicators in the sense that they are highly predictive of financial performance. Tracking such measures today leads to less worry about tomorrow's budgets (Case, 1998).

A lagging indicator normally changes direction after the economic status does so. Lagging indicators are useless for prediction, for example the value of construction completed, which is an outdated indicator as it indicates the condition after the performance has taken place. The maintenance cost per unit and the return on investment (ROI) are also examples of lagging indicators.

The establishment of a link between the lagging and the leading indicator makes it possible to control the process. Furthermore, indicators should be chosen to accord with the chosen maintenance strategy (Kumar and Ellingsen, 2000).

The complexity of some measures is an obstacle to their implementation which decreases the likelihood of their use. In maintenance, many processes can be measured directly. Time or costs are quantities whose measurement is relatively easy. Other factors, such as the adequacy of repair shops and the size and type of the maintenance teams, are particularly sensitive and can only be measured with more complicated and subjective methods. This difference suggests that the indicators fall into two broad groups, "hard" and "soft" indicators. "Hard" indicators include those measurable through the extraction and exploitation of data from simple databases, like the computer maintenance management system (CMMS) and enterprise resource planning databases; examples of hard indicators are absenteeism, purchase orders, energy consumption by area, etc. Arts *et al.* (1998) explain the development of an MPM system using the CMMS. The operational view of the maintenance function requires certain indices for performance measurement and does not require the tactical and strategic aspects of maintenance performance. In this case, the data collection and the calculation of the indicators are fast, and the measurement does not interfere in the daily work of the maintenance team. In this connection, a common database can be an important instrument for maintenance management decision making (Kans and Ingwald, 2008).

While many "soft" indicators are interesting, their measurement can be rendered problematic by the absence of sources and their lack of hard objectivity or reliability. Apart from staff qualities and the workshop size, this group includes all the measures relating to elements with a strong human component, such as the impact of a training activity on the quality of repairs, or the time required for diagnosis and improvement, which are usually not quantified in records.

Thus, the choice of measures and the indicators derived from them will be conditioned by the accessibility and reliability of the sources, especially in the case of the soft indicators that are affected by human factors.

The people who operate the equipment are a valuable source of information. The human element is indispensable in the measurement of maintenance due to its influence on repairs. However, to assess the overall status of a maintenance system and to correct critical points, more objective tools are needed. To this end, mathematical models and some indicators can be used to assess the probability that a team is performing inspection, maintenance or repair successfully, and to determine the average time for the equipment to fail after a maintenance intervention.

In other words, two actors are involved in the MPM: people and mathematical models. People provide information on their links to the company, morale, training, skills, confidence, etc.; models provide information on effectiveness and efficiency related to cost or time. Combining the two leads to the attainment of the three objectives of excellence noted by Katsllometes (2004): efficiency, effectiveness and staff involvement.

Different categories of maintenance performance measures/indicators are identified in the literature. The total productive maintenance (TPM) concept (Nakajima, 1988), launched in the 1980s, provides a quantitative metric called overall equipment effectiveness (OEE) for measuring the productivity of manufacturing equipment. It identifies and measures losses in important aspects of manufacturing, namely, availability, performance/speed and quality. This supports the improvement of equipment effectiveness and hence equipment productivity. The OEE concept has become increasingly popular and is widely used as a quantitative tool to measure equipment performance in industry (Huang and Dismukes, 2003; Muchiri and Pintelon, 2008). Arts *et al.* (1998) use the time horizon to classify maintenance control and PIs into three levels: the strategic, tactical and operational levels. The indicators proposed for operational control include the following: planned hours over hours worked, work orders (WO) executed over WO scheduled and PM hours over total maintenance hours.

Parida and Chattopadhyay (2007) propose a multi-criteria hierarchical framework for MPM that consists of multi-criteria indicators for each level of management, i.e. the strategic, tactical and operational level. These multi-criteria indicators are categorized as equipment-/process-related (e.g. capacity utilization, OEE, availability, etc.), cost-related (e.g. maintenance cost per unit of production cost), maintenance-task-related (e.g. the ratio between planned and total maintenance tasks), customer and employee satisfaction, and health, safety and the environment. Indicators are proposed for each level of management in each category.

Campbell (1995) classifies the commonly used measures of maintenance performance into three categories based on their focus. These are measures of equipment performance (e.g. availability, reliability, etc.), measures of cost performance (e.g. maintenance, labour and material cost) and measures of process performance (e.g. the ratio between planned and unplanned work, schedule compliance, etc.). Coetzee (1997) outlines four categories of maintenance performance measures with detailed indicators for each category. The first category is the maintenance results, measured by the availability, mean time to failure (MTTF), mean time to breakdown frequency (MTBF), mean time to repair (MTTR) and production rate. The second is the maintenance productivity, measured by the manpower utilization, the manpower efficiency and the maintenance cost component over the total production cost. The third is the operational purposefulness of maintenance, measured by the scheduling intensity (scheduled task time over clocked time), the breakdown intensity (time spent on breakdowns over clocked time), the breakdown severity, WO turnover, schedule compliance and task backlog. The fourth is the maintenance cost justification, measured by the maintenance cost intensity (maintenance cost per unit of production), the stock turnover and the maintenance cost over the replacement value.

The Ivara Corporation has developed a framework for defining KPIs based on their physical asset management requirements and the asset reliability process (Weber and Thomas, 2006). They propose 26 key MPIs and classify them into two broad categories, leading and lagging indicators. The leading indicators monitor the tasks that, when performed, will "lead" to results (e.g. they provide information as to whether planning took place or whether the scheduled work was completed on time), while the lagging indicators monitor the results or outcomes that have been achieved (e.g. the number of equipment failures and the downtime). The leading indicators are classified as work identification (e.g. the percentage of proactive work done), work planning (e.g. the percentage of planned work), work scheduling or work execution (e.g. schedule compliance). The lagging indicators are classified as equipment performance (the number of functional failures and safety and environmental incidents, and the maintenance-related downtime) or cost-related measures (e.g. maintenance cost per unit of output, maintenance cost over replacement value and maintenance cost over production cost).

Dwight (1995, 1999) classifies performance measures in a five-level hierarchy according to their implicit assumptions concerning the impact of the maintenance system on the business: overt (visible) bottom-line impact measurements (e.g. direct maintenance cost), profit-loss and visible cost impact measurements (e.g. total failure/downtime cost), instantaneous effectiveness measures (e.g. availability and OEE), system audits (e.g. the percentage of planned work and work backlogs) and time-related performance measurements (e.g. life cycle costing and value-based performance measurement). Dwight's research work examines the variations in the lag between an action and its outcome.

It is clear that each author has a unique way to classify maintenance indicators. They also differ in their choice of indicators. However, some indicators and categories of indicators are recognized by all authors as vital for management of the maintenance function. For example, much emphasis has been placed on equipment performance in terms of the 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, although they use a variety of terminologies to describe them, e.g. maintenance productivity and operational purposefulness (Coetzee, 1997), maintenance efforts (Campbell, 1995), and maintenance work management (Weber and Thomas, 2006). Interestingly, while the literature proposes common lists of KPIs, it lacks an agreed-upon methodological approach to selecting or deriving them. As a result, users are left to decide the relevant KPIs for their situation. Given the lack of consensus, one of the objectives in this paper is to investigate how maintenance KPIs are chosen.

Based on the literature, the commonly used MPIs fall 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). Using the definition of Weber and Thomas (2006), leading indicators monitor whether the tasks being performed will lead to the expected output and lagging indicators monitor the outputs that have been achieved. In the case of maintenance process indicators, according to Muchiri *et al.* (2010), there are three categories of indicators: work identification, work planning and scheduling, and work execution indicators. For maintenance results, there are three categories of indicators: equipment performance,

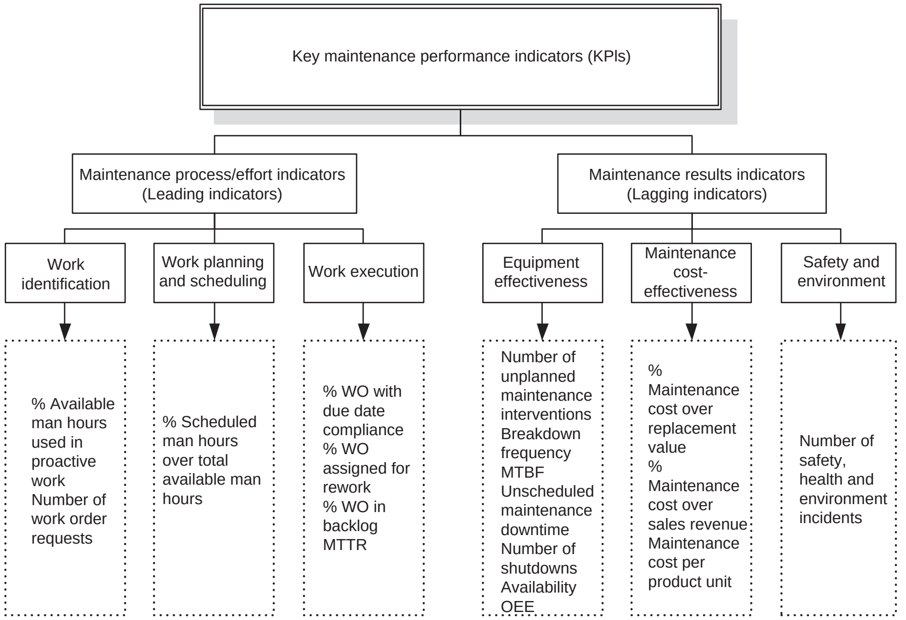



**Figure 1.**
Key maintenance performance indicators in the literature

maintenance costs and safety and environment indicators. Each category has its own PIs, as shown in Figure 1.

The objectives of the present survey include investigating the extent to which these indicators are used in industry, establishing which are the most frequently used, i.e. the popular indicators, and determining how effectively they are used in maintenance management.

## V. Grouping indicators: frameworks and scorecards

For the most part, the focus has been directed on performance measuring systems rather than on individual PIs. An overview of the most commonly used performance measurement systems, with their respective advantages and disadvantages appears below. The systems discussed differ by the choice of indicators and the manner of representation:

- Global PIs: in practice, maintenance performance is often judged on the basis of a single indicator value. More frequently, however, a complex ratio is used in which a number of relevant factors are combined, sometimes with different weights. A typical ratio is the yearly costs for materials, labour and subcontracting/the yearly budget. This is a popular concept because of its compactness. A ratio is tricky to use because of the strong aggregation, which may cause the cancellation of some effects (e.g. an increase in the labour cost and a comparable decrease in the materials cost will never be apparent in the indicator), making it difficult to know exactly what has happened (e.g. whether all the costs have increased, only one, or some, etc.).
- A set of PIs: a number of PIs are used, each highlighting an aspect of the maintenance activities. A detailed discussion is found in De Groote (1995). For example, for the maintenance stock, the following indicators are often used: the

inventory value, number of items in stock, turnover, number of new/obsolete items and number of in/out movements. This 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: various aspects of maintenance activities are evaluated at the same time; for each aspect, a different 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 (Raouf, 1994; Stephan, 1996).

The most popular set or list of indicators is a scorecard. The balanced scorecard (BSC) is frequently used to group maintenance KPIs and show different faces of the maintenance function (Tsang, 1998). The BSC is a holistic approach which groups both financial and non-financial measures to measure performance (Kaplan and Norton, 1992, 1996a, b). In any organization, the corporate objectives state the company's vision. A corporate strategy is formulated as the way to achieve these objectives. A corporate BSC is part of the corporate strategy to measure performance and compare it with the corporate objectives. BSCs are applied to different divisions and departments, right down to the employee level.

Similarly, MPIs can be translated from BSC perspectives and applied to the divisions, departments, sections and employee levels. The maintenance objectives are linked to critical success factors (CSFs), key result areas and KPIs. The CSFs support the maintenance objectives. The key result areas are the success areas where the key factors can help achieve the maintenance objectives.

Mather (2005) has adapted the maintenance scorecard (MSC) from the original BSC for asset-centric industries such as electricity generation and distribution, water treatment, oil and gas, mining, railways and heavy manufacturing. Based on RCM2, developed by Moubray (1991), and Moubray's interpretation of functional measurement and the monitoring of machine performance, as well as Kaplan and Norton's traditional BSC approach, MSC identifies a need for strategic initiatives and for ascertaining the best way to determine what form of intervention is required. Breaking down indicators from the corporate levels of management is a common practice, and it has been applied effectively on the front lines of maintenance activity.

Mather proposes using the MSC approach to develop and implement a strategy in the area of asset management. This will help identify strategic improvement initiatives and the areas which they should focus on, early in the process. The MSC is a methodology which is based on the measurement of performance, is built around the use of management indicators, and can lead the development and implementation of a strategy.

A different approach to measuring need is given by Lehtinen *et al.* (1996), who argue that measuring performance by means of scoreboards focuses on the process safety and the process environment as a necessary consequence of maintenance activities. These activities are important for plant safety. According to the authors, quality management systems, risk prevention and safety require the implementation of a metric in the maintenance department.

## VI. The hierarchy of indicators

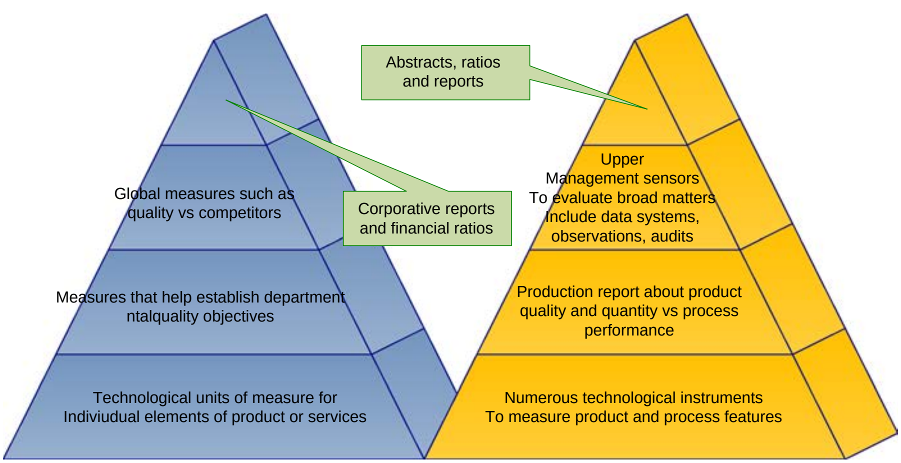
Indicators are commonly formulated at different levels and each level serves certain purposes for specific users. The users at the highest level of the management traditionally refer to aspects that affect firm performance, whereas those at the functional level deal with the physical condition of assets. The use of multiple performance measures at the level of systems and subsystems helps to solve problems. If a corporate indicator shows a problem, then the next lower level of indicators should define and clarify the cause of the weakness that has caused this problem (Wireman, 1998; Galar *et al.*, 2011a).

According to Mitchell (2002), a hierarchy of different parameters, all linked to business goals, is vital for the success of a programme for managing corporate physical assets.

Many authors agree that multifaceted maintenance requires metrics, and those metrics should serve specific levels of the organization's hierarchies. TRADE and PMB SIG (1995) shows the levels of PIs in a typical organization (Figure 2). Different organizations have different hierarchies of performance measurements.

Grenčík and Legat (2007), like TRADE and PMB SIG (1995), make an analysis of the consistency of the indicators and their management classification levels. To select the relevant indicators, the first step is to define the objectives at each level of the company. At the company level, the requirement is to determine how to manage maintenance to improve the overall performance (profits, market shares, competition, etc.). At the level of production, performance factors which have been identified through prior analysis are more important; these include improved availability, improved intervention costs, safety, environmental preservation, improvements in maintenance costs, value inventory, contracted services control, etc.

Kahn (2006) suggests using KPI to set up a hierarchical methodology to quantify project improvements in the maintenance function. He suggests that, to visualize the expected benefits, the process variations and trends should be adequately monitored. The established KPIs should be controlled and an adequate programme for continuous improvement should be set up. For Kahn, a KPI is a traceable process metric that allows decision making aimed at established business objectives; maintenance KPIs should include indicators on the corporate level, such as the OEE, or on the financial level, such as the overall maintenance budget compared to the replacement cost, etc. The financial indicators should be positive to ensure the organization's support for maintenance improvement projects. Like TRADE and PMB SIG (1995), Kahn (2006) proposes five levels of KPIs, each with its own requirements and target audience, thus




**Note:** Units of measures to the left and sensors to the right

**Figure 2.**
Pyramid used in all levels of the company

consolidating the segmentation of indicators by levels of organization. The five levels are as follows: maintenance costs, availability of equipment, OEE, production costs and performance.

Campbell (1995) classifies performance measures into three categories based on the equipment performance measure, cost measures and process performance measures. Kutucuoglu *et al.* (2001) suggest another general classification for a balanced performance measure. Their five proposed categories are as follows: 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 (1998) defines a set of indicators divided into the following groups: corporate, financial, efficiency and effectiveness, tactical and functional performance (see Figure 3). The indicators should be properly connected to the levels of the corporate vision and the company mission.

These concepts all suffer from a hierarchy that condemns the low levels to working with operational and functional indicators, while assigning the economic indicators to the top management, thereby dividing the analysis and creating indicators of first and second categories. Most authors have traditionally associated maintenance metrics with RAMS parameters, but these are only part of the performance to be measured. A few authors have included cost, and a few more have integrated a number of corporate indicators into the maintenance function.

These groups and hierarchies of PIs are ambiguous and are not user-defined. In fact, they confuse groups with organizational levels. There is no end user identification and no attempt to have responsible people involved in continuous improvement actions. In implementation, therefore, there should be multi-level indicators. According to Wireman (1998), the first layer could be at the corporate strategic level; second, the supporting level could be the financial PIs; the third level could be the efficiency and effectiveness indicators; and the fourth and fifth levels could be the tactical PIs and functional PIs, respectively. The five levels of the pyramid (see Figure 3) show the hierarchical relationship of the PIs. It should be noted that the indicators are always determined from the top down, using corporate indicators and measures; what is important to the top management is to satisfy the needs of the stakeholders/shareholders (Figure 4).

For Parida (2006), three levels of indicators must be considered from the perspective of the multi-hierarchical levels of the organization. The first hierarchical level could correspond to the corporate or strategic level, the second to the tactical or managerial

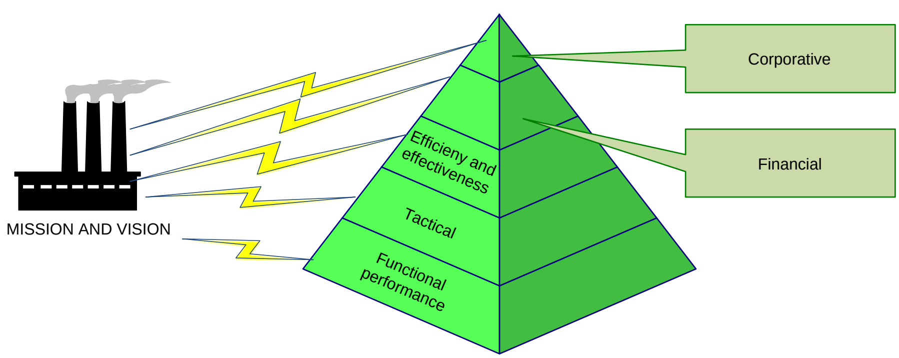



**Figure 3.**
Hierarchy of indicators in maintenance according to Wireman (1998)

level, and the third to the functional/operational level. There could be more hierarchical levels depending on the organizational structure (Parida, 2006).

These corporate PIs will vary from company to company, depending on the current market conditions, the business life cycle, the company's financial standing, etc. Thus, PIs must be tied to the long-range corporate business objectives of a specific company, meeting the needs of both the operations and the 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-, growth- and innovation-related issues. They combine the internal and external concerns of the company.

The measurement system should cover all the processes in the organization. There must be a logical interconnection between the indicators, so that the numbers can be interpreted and a good conclusion can be reached, thereby allowing good decision making. This premise implies a hierarchy of indicators addressed in a dual way (Cáceres, 2004). The maintenance indicators will be segmented according to the organization's areas of influence, depending on the interactions of the maintenance department with the departments dealing with finance, human resources, purchasing and, of course, production, to achieve the corporate objectives. Simultaneously, these indicators correspond to different levels in the organizational structure and will therefore be targeted at them.

For Cáceres, performance measurement must be comprehensive and requires an appropriate scorecard. He argues that management should be measured holistically, not only in the financial perspective, as is traditional (APQC, 1996). Maintenance performance should be based on the maintenance parameters of availability, reliability and MTTR. In addition, all the perspectives within maintenance should be integrated to cover the organizational and technological aspects, the internal processes, the customer and company perspectives and the financial perspectives.

Bivona and Montemaggiore (2005) agree with Cáceres (2004) and argue that there is a lack of linkage between the objectives of general maintenance and the business strategy adopted because of performance measurement systems. The most common PIs oversee the operational management from the unique perspective of the maintenance activity, ignoring the effects of the maintenance policies on the company performance and their impact on other departments. Some authors argue that a performance measurement system based on relations between different departments of


**Source:** Parida (2006)

**Figure 4.**
Developing performance measurement indicators from the vision, objectives and strategy

a company facilitates the communication process between the corporate strategy and the various hierarchies of the maintenance organization.

This leads to an alignment between business objectives and maintenance. To this end, most authors suggest adopting the BSC approach to the formulation of maintenance strategies, not only as a grouping of indicators, but also as a hierarchy. The systemic perspective of the BSC, in fact, supports the management in analysing the various relationships between the subsystem of maintenance and other business areas, 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 (1992) and was later adapted by Tsang *et al.* (1999) for measuring maintenance performance in an effective way. This method designs the maintenance performance measure using the following four perspectives:

- the financial perspective (the investor's view);
- the customers' perspective (the performance attributes as valued by customers);
- the perspective of internal processes (the long-term and short-term means to achieve financial and customer objectives); and
- the perspective of learning and growth;

This technique can link the maintenance strategy with the overall business strategy and develop performance measures for maintenance that are linked to the organization's success (Tsang *et al.*, 1999; Tsang, 2002).

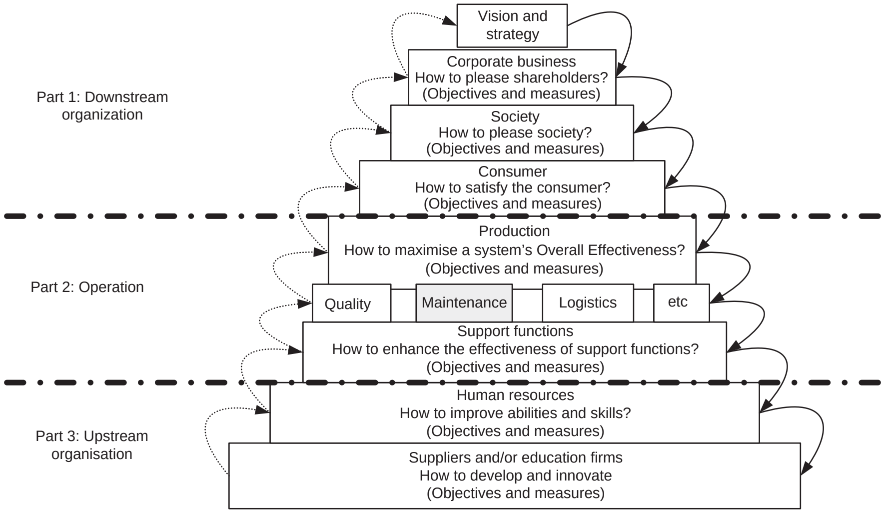
Alsyouf (2006) criticizes the BSC technique suggested by Tsang *et al.* (1999), arguing that the performance measures based on the four non-hierarchized perspectives are top-down performance measurements which do not take into account the extended value chain; i.e. the technique ignores suppliers, employees and other stakeholders. The extended BSC presented by Alsyouf (2006) incorporates performance measures based on seven perspectives: the perspectives of corporate business (financial), society, the consumer, production, the support functions, human resources and the supplier, as shown in Figure 5.

In any planning and development activity, several alternatives are offered, and one must choose the best fit. Normally, the objectives of the decision maker are reflected in various criteria. If there are a number of criteria, multi-criteria choice problems arise; this is solved by acquiring information on the relative importance of the criteria (Noghin, 2005). The selection of factors or variables constituting various performance criteria, such as productivity, effectiveness, efficiency, etc., is an important step in developing a performance measurement system in an organization. This is conceived essentially as multi-criteria decision making (Ray and Sahu, 1990).

In an MPM system, a number of criteria or goal functions must be considered from different stakeholders' points of view. These criteria can be broken down into maintenance indicators, such as the mean time between failures, downtime, maintenance cost, planned and unplanned maintenance tasks, etc.

The operational and strategic levels of these maintenance indicators need to be integrated as well. The development and identification of MPIs for an organization consider the company's vision, objectives and strategy, as well as the requirements of external and internal stakeholders, as given in Figure 4.

In our development of an MPM framework, we consider the basic four perspectives of Kaplan and Norton's (1992) BSC, along with the maintenance criteria. In addition, we




**Source:** Adopted from Alsyouf (2006)

**Figure 5.**
The need of hierarchy in the scorecard perspectives

consider health, safety, security and the environment (HSSE) and employee satisfaction to make this MPM system balanced and holistic from the organizational point of view.

*A. Multi-hierarchical levels*

MPIs must be considered from the perspectives of the multi-hierarchical levels of the organization. The first hierarchical level could correspond to the corporate or strategic level, the second to the tactical or managerial level and the third to the functional/operational level (Galar *et al.*, 2011a). Depending on the organizational structure, there could be more than three hierarchical levels. The maintenance indicators on the functional level are integrated and linked to the tactical or middle level to help the management in its decision making at the strategic or tactical level. It can be challenging to integrate MPIs from top-down and bottom-up flows of information.

Involving all the employees in this MPI development process is another challenge. So that everyone will speak the same language, the strategic goals need to be broken down into objective targets for the operation and maintenance managers, which may act as a performance driver for the whole maintenance group. Thus, the objective output from the operating level in terms of KPIs is linked to the strategic goals; moreover, the subjectivity increases as the objective outputs are integrated with KPIs at higher or strategic levels.

The three hierarchical levels are illustrated in Figure 6.

*B. MPM frameworks*

The MPM framework is a vital and integrated part of the PM system of organizations. The need to develop and implement an MPM framework is well established. The MPM framework must link performance measurements with the organizational strategy and consider criteria consisting of financial and non-financial indicators. However, there is a small amount of literature covering the development of a systematic approach to PM in maintenance, and an even smaller amount embracing every level of maintenance. One of the few works that do treat this subject is a paper by Kutucuoglu *et al.* (2001).

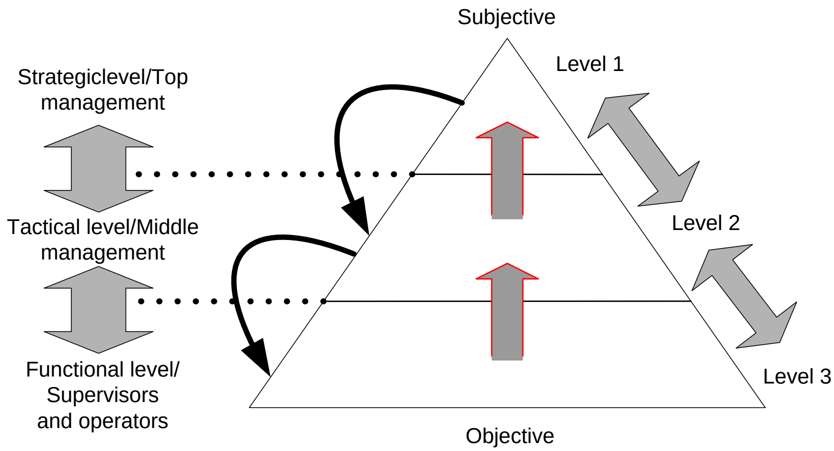



**Figure 6.**
Hierarchy levels of the MPM model

The development of an MPM system is intimately linked with the overall PM system and the overall corporate strategy. Therefore, it is imperative to investigate the shortcomings of PM systems, especially those systems based on financial measures only (Johnson and Kaplan, 1987; Dixon *et al.*, 1990) .

Tsang *et al.* (1999) mention that a US survey of 200 companies in 1995 concluded that, despite a reasonably high level of use, non-financial measures and targets are frequently treated in isolation from strategic objectives. They are not reviewed regularly and are not linked to short-term or action plans; rather, they are largely ignored or are only included as an object of interest.

In another study, Tsang *et al.* (1999) examined a maintenance organization using a structured process to identify performance measures. They found that the management was not aware that a PM system could achieve vertical alignment and horizontal integration of activities across organizational units. Thus, performance measures were primarily used for operational control only.

Coetzee (1998) 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 MPIs are set within a hierarchy, but Coetzee fails to identify the specific hierarchical levels in the organization which use them. Nor are these MPIs clearly connected to the corporate strategy. Riis *et al.* (1997) design a framework showing cross-levels and the functional integration of maintenance management which attempts to relate maintenance to manufacturing strategy. However, this framework does not take care of other customers and suppliers, such as personnel involved in design, finance and top management, and issues including HSSE, employees and corporate strategy.

Kutucuoglu *et al.* (2001) and Sharp *et al.* (1997) adapt TPM and TQM to improve maintenance performance and identify CSFs linked to maintenance. Dwight (1995) explains two other approaches, namely the "system audit approach" and the "incident evaluation approach", which define performance in terms of changes in value systems. Value is defined here as the probable future earnings of a system.

Tsang (1998) and Ahlmann (2002) adapt the BSC of Kaplan and Norton (1992) to create a strategic approach to MPM. However, Kaplan and Norton (1992) are limited in that they do not consider employee, societal or environmental aspects.

Kutucuoglu *et al.* (2001) develop a performance measurement system for maintenance using the matrix structure of the quality function deployment (QFD) method. Murthy *et al.* (2002) present the strategic maintenance management (SMM) approach, which has two key elements:

(1) maintenance management is a vital core business activity, crucial for business survival and success and, as such, it must be managed strategically; and

(2) therefore effective maintenance management needs to be based on quantitative business models that integrate maintenance with other decisions, such as production decisions, etc.

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

In a project for the Norwegian oil and gas industry, Ellingsen *et al.* (2002) suggest a PM framework based on a BSC model and a list of key indicators. The framework considers cost, operation, health, safety and environment, and organization perspectives. Maintenance and employee satisfaction are not included.

## VII. Categorization of indicators

### *A. Financial indicators*

Financial measures are often considered the top layer in the hierarchy of the measurement system and are used regularly by senior management. This level seeks to achieve a good return on its assets and to create value and its metrics are used for strategic planning. Therefore, the metrics at this level are the backbone of the organization. This level can also be used to compare the performance of departments and divisions within the parent organization.

Financial figures are lag indicators and are better at measuring the consequences of yesterday's decisions than predicting 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 (Eccles, 1995). Examples of financial measures are the ROI, the return on assets (ROA), the maintenance cost per unit of product, the total maintenance costs in relation to the manufacturing costs, etc.

Vergara (2007) proposes the net present value (NPV) for use in maintenance as one of the financial indicators. If one obtains the NPV, one knows how much could be gained from an investment if all the income could be gained and all the expenses could be paid for instantly. Therefore, the NPV is used to determine whether an investment is appropriate. It is used in many sectors and areas of the company, but rarely in maintenance. Tsang *et al.* (1999) have developed the performance measurement technique first proposed by Dwight (1994), creating a better technique which takes into account the impact of maintenance activities on the future values of the organization, instead of concentrating on short-term values. However, this technique also concentrates only on the financial dimension of performance measurement and is quite laborious to implement.

Hansson (2003) proposes using a battery of financial indicators to study the results found for maintenance departments. He suggests creating a proper benchmarking of the maintenance function, arguing that one should consider such measures as the percentage change in sales, ROA, the return on sales, the percentage change in the total assets and the percentage change in the number of employees. These are generally accepted as indicators of financial results and facilitate the comparison of results with those of other studies (e.g. Hendricks and Singhal, 1997). The correlation of such indicators with tactical maintenance indicators links maintenance with corporate strategy.

Coelo and Brito (2007) propose incorporating financial indicators into maintenance management. Their hypothesis confirms the importance of a system for measuring enterprise performance based on indicators, with special emphasis on maintenance. These authors discuss the need for integration to achieve a harmonious balance of financial PIs and the strategic vision of maintenance efficiency.

Cáceres (2004) argues that all planning systems should have the history of the company's strategy and the corporate positioning indicated in 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 focuses on the ROI, the added value to the organization and the reduced unit costs. In maintenance, the costs of each activity, the incidence rate of maintenance costs per unit of production and the maintenance costs in relation to the value of the assets are monitored to indicate the company's global position.

*B. Indicators related to human resources*

The adoption of a separate category of measures relating to human resources reveals the uniqueness of maintenance services. Maintenance organizations depend entirely on the performance of employees to achieve their objectives. However, the quality of employees' work in the maintenance services cannot be measured directly. Knowing the personnel's experience, education, training and skills is essential to measure adequately the result of the work performed. Few organizations measure the excellence of their human factor; nor do they include this factor in their assessment of the performance of the maintenance function. In addition, measures of organizational performance are often selected on the basis of convenience. Typically, these measures are either too narrowly or too broadly defined (Cameron, 1986), and they include indirect/direct labour, labour in reserve, training measures and the percentage of overtime.

According to Cáceres (2004), the application of KPIs to human resources involved in maintenance should cover what he calls the organizational dynamics perspective, where excellence focuses on the people and the culture of the organization, identifying the key skills that support internal targets. Ultimately, this is a true reflection of the labour climate in the microclimate of maintenance (Rensen, 1995).

A measure related to human resources is the company's intellectual capital (IC). Fernández and Salvador (2005) discuss the importance of IC in maintenance teams, noting that it has become a critical issue for many organizations. They 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 labour hazards. For this reason, a number of authors propose an indicator of equipment safety. Many operators in maintenance areas are affected by workplace accidents, far more so than production workers (Manuele, 2005). The maintenance staffs are more exposed to such high-risk factors as electric shocks, the dropping of heavy components, contact with chemicals, etc. For production staff in general, an accident is due to the failure of accident prevention measures or the breaking of established procedures. In any case, whatever the origin, an accident has negative effects on employee morale, stops production and affects the reliability of equipment. Guaranteeing safe equipment and a safe environment, as well as cooperating with regulatory agencies, is a maintenance function. Maintenance must be rigorous in developing and enforcing security procedures, and in maintaining barriers to prevent accidents.

*C. Indicators relating to the internal processes of the department*

Some authors refer to indicators of internal procedures as functional measures. Traditionally, this category includes processes related to efficiency that are measured within a maintenance organization. Examples of the output of such processes are: WOs, inventories and purchases, and management information.

For Cáceres (2004) the internal KPI perspective, or the process perspective, is related to the work process and to improvements in the pursuit of excellence. The purpose is to understand the processes that add value to the business and identify the drivers of domestic objectives. In the specific case of maintenance management, the indicators set are usually the repair times, overtime, certified processes, the security aspects of the activities and the implementation of plans and programmes. This perspective includes the measurement of the internal mechanics used for the proper development of other perspectives.

*D. Technical indicators*

Some authors refer to this category as the technical level of PIs. The first objective of this set of indicators is to measure the performance of equipment (assets), at least the equipment considered part of the maintenance function. Mitchell (2002) states: "At the technical level, the figures are used to monitor the performance of certain processes, systems, equipment and components". This level is concerned with the effectiveness of maintenance work.

*Functional safety as a key indicator for the client*. Cea (2002) proposes the overall indicator of functional safety as a KPI for the customer and states that functional safety is what he or she expects from the assets. Cea maintains that, for functional safety to be achieved, the user must receive the service that he or she expects from the system, with established quality and safety standards being met.

According to Blanchard *et al.* (1995), 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 during the mission; it is strongly influenced by the system reliability, maintainability and the quality of the project (Kostic and Arandjelovic, 1995; Bifulco *et al.*, 2004). Reliability is associated with the compliance function over time and the system performance. Maintainability is associated with the ability of the equipment to recover its function when it stops (Kumar, 1997; Knezevic *et al.*, 1997; Castro and Cavalca, 2003).

Therefore, according to Blanchard, direct and indirect indices of functional safety are the availability, reliability, maintainability and safety of a production system. The system must have an information subsystem based on indicators of efficiency and feedback; it must be a valid tool operationally, in such a way that the user can fully appreciate the benefits of having a "safe operating system". Indices are reflected in the operational performance of assets and the quality of the products produced. For Cea (2002), RAMS parameters are the basic components of the key indicator of functional safety. Söderholm (2005) and Cea (2002) refer to functional safety as the basis of the whole system of indicators for maintenance and to RAMS parameters as the primary indicators on which the entire scorecard should be built.

*The changing role of RAMS parameters*. For a long time, RAMS parameters were the only indicators adopted for measuring the performance of maintenance according to the purely technical or operational aspect assigned to this function. Currently, they have a more privileged role, albeit limited to the quality of the service that the maintenance function gives to its customers.

Gillett (2001) emphasizes the practice of utilizing MPIs focused exclusively on operational aspects. Without underestimating these indicators, Gillet notes the need to develop corporate indicators. In fact, many authors have recently expressed concern over the limiting of maintenance indicators and scorecards to operational aspects, which may be important for the consideration of client-related issues, but lack the broader vision of the maintenance function within a company (Geraerds, 1990).

Martorell *et al.* (1999) agree with Blanchard that there are two main categories of indicators. The first category includes the direct or basic indicators that are 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 includes indirect indicators, derived from direct indicators, such as reliability and availability. According to Martorell *et al.* (1999), the direct indicators can be linked to functional requirements, while the indirect indicators can be related to non-functional ones.

The recently published standard EN 15341 (CEN, 2007) classifies maintenance indicators into three categories, thereby echoing most of the authors cited above. The categories are technical, economic and organizational indicators. The document proposes 71 indicators, divided into three types and set on three different levels. These levels do not correspond to organizational hierarchies, but represent a progressive decomposition of higher-level indicators into more specific indicators. The classification into technical, financial and organizational indicators are both related to efficiency (resource usage; do things right) and effectiveness (meeting the desired results; do the right things).

The authors reviewed herein see the RAMS parameters as raw materials for creating more complex indicators of effectiveness, thus providing the MSC with more indicators of efficiency.

## VIII. Presentation of performance measures

One of the most important factors for a successful performance measurement system is a good introduction of the indicators to the personnel. If they are not presented and explained to the users, they may be inappropriately used. Mitchell (2002) says that "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 (1991) 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 workers in other departments has a positive impact. There are a variety of ways to present a PI, depending on the type of information needed and the type of user. Charts, graphs, figures or just numbers can deliver a PI (Besterfield *et al.*, 2002).

Lehtinen *et al.* (1996) emphasize the visual aspect and simplicity of the indicators, because these features will be a key in developing a subsequent metric. The indicator should stand out in reporting and should promote the publication of reports with proper quantification and calibration of problems. It is believed that these benefits play an important role in continuous learning, which leads to the achievement of excellence. Lehtinen *et al.* (1996) show the nature of different 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 PIs is the frequency of their presentation. Some indicators require continuous data collection, while others may have a monthly frequency. There is no advantage in measuring more frequently than needed, as this only increases costs (Kaydos, 1991).

Today technology allows the use of an online graphical user interface (GUI) for presenting and monitoring indicators tailored to each person's individual needs, thereby making it possible to use the same system for presentations throughout the hierarchy. Notices can be sent automatically to mobile devices or mailboxes to increase the information efficiency further.

## IX. Efficiency of performance measures

Metrics must be understandable, addressed to the needs of users and controllable by managers through work activities (Mitchell, 2002).

According to Kutucuoglu *et al.* (2001), to develop an efficient and effective system of performance measurement, there should be clarity concerning what indicators are to be measured, how they are to be measured, the timing of the measurement, and who should implement the measurement. In fact, for Manoochehri (1999), three obstacles to the effective development of metrics are the misidentification of indicators, less-than-rigorous data collection and the bad use of indices by the company managers.

According to Besterfield *et al.* (2002), if measurements are to be useful, they should be simple, understandable and few in numbers, so that users can concentrate on those which are most important to them.

### *A. The number of indicators to be included and their origin in the adopted metrics*

Gillett (2001) reflects on the number of indicators to include and the property of each based on studies by Woodhouse (2000), and in line with the characteristics previously proposed by Besterfield *et al.* (2002). Woodhouse argues that the human brain can only handle four to eight measurements intended to quantify the goodness of one aspect. This suggests that it would be reasonable to target a maximum of six measurements for each supervisor/manager. To achieve this objective, he proposes the measurement of key characteristics, limiting the amount of information used and the sources from which this information is extracted. In a multifunctional organization, it is likely that other departments may collect and share some of the data. For example, the collection of data on availability and reliability can be relatively simple for the production department. The department of labour risk prevention is ideal for monitoring injury rates, and the human resources staffs are better equipped to provide data on absenteeism. This supports Besterfield's thesis on the ownership of data.

Shreve (2003), in line with Woodhouse (2000) and with respect to specific indicators of condition-based monitoring (CBM), proposes the selection of six to eight indicators of high-level performance to analyse the effects of a CBM programme in a factory. These PIs can be used both in production and in maintenance to display the programme progress. The parameters for monitoring the results of the CBM should be established before its implementation.

The author further emphasizes that measurements should be directed towards the areas with the greatest impact on improving, ignoring those with a small ROI. Without constant reminders of their performance, programmes can start strong, but then rest on their initial achievements without ever reaching maturity. Proactive measurements should be the goal of the monitoring programme. The level of maturity of the programme is based on the desire to find any problems affecting production rates and product quality before they appear. Shreve (2003) and Woodhouse (2000) agree that the goal is to find the indicators with the highest ratio of implementation impact at each level instead of short-term self-satisfaction results.

*B. Data accuracy*

The performance model is expected to give the correct output result since the right data are expected to be fed into the model. The model must be accurate and consistent when processing the input data. This implies that the processing capability of the model must be strong enough to accept the required data input and release the correct information to achieve a particular task.

It is clear that the old aphorism "garbage in, garbage out" holds for any sequentially factored data system model. For the result of the model evaluation to be correct, the input data must be correct. To avoid error right from the start, the model user must ensure the correctness of the data input and, therefore, of the data computed. The values must be checked for homogeneity in units, readings, computations, etc. The input of incorrect or corrupt data in the performance measurement system is harmful, leading to wrong decisions and losses. Thus, indicators for data accuracy monitoring are necessary. However, a good performance measurement system does not require high precision (Kaydos, 1991). In most cases, one needs to know how to identify problems. Very accurate performance measurement is not required; it is more important to know if the trend is going up or down and to know how current measurement values compare to historical measures. If the way in which an indicator is calculated is changed, it is crucial to overlap so that the trend is not lost. Kaydos also stresses the importance of trust and credibility; if users do not trust the organization to generate the proper measures, the whole system is useless.

Barringer and Weber (1995) state that frequently the data available to exploit are sparse, poorly collected or of doubtful veracity. Barringer and Weber suggest that understanding how to manage the reliability of data is the first step towards solving problems. For Tavares (2002) indicators like MTBF or MTTR are particularly accurate. Their high level of accuracy is linked to the number of items observed and the observation period. The greater the number of available records is, the greater is the accuracy of the expectation values. In the absence of a high number of items, or if one wishes to obtain the average time between failures of each one separately, according to Tavares, a fairly extensive study (lasting five years or more) is advisable.

*C. The users' understanding of metrics*

The users must be able to assess or evaluate the performance of the MPM system in terms of its operation and results. More importantly, the user must know how to assess, analyse and interpret the end result of computations to discover the knowledge embedded in the operation of the MPM system. That is why user training is so important. The user must have the knowledge necessary to use a performance measurement system. It is assumed that the user has taken courses in areas such as mathematics, physics, programming, statistics, etc. to understand the model's procedure and application. As part of the training, the user must be assessed to determine the level of competence attained.

According to Manoochehri (1999), the effective use of performance measures requires user education because a misunderstanding leads to wrong decisions. Major problems that could lead 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.

Failure to use performance measurements in an organization may be the result of failure to overcome the challenges associated with the implementation of a new set of PIs. Therefore, it is very important for the implementation team to concentrate on the project, especially at the beginning. If this is not done, the result could be a loss of confidence in the new system and a lack of voluntary participation in its development.

The performance measures of the system must be designed to serve the purpose of the organization. According to Wireman (1998), multiple indicators should be associated with every level. One layer of indicators could be at the corporate level, and another at the departmental level. The levels may vary depending on the company size.

Furthermore, to implement a performance measurement system successfully, the measurements should not be numerous. Dispersion into too many areas simultaneously can lead to information overload, making it more difficult to direct limited resources to higher-value activities (Mitchell, 2002).

A challenge faced by most performance measurement systems is change. However, this is an inherent feature of the manufacturing business. A measurement system should not be affected by changes in the production characteristics, but it must be adapted to them. Moreover, indicators may become out of date (Kaydos, 1991).

## X. Benchmarks

Two categories of measures use reference numbers or benchmarks: "checklists" and "surveys". Each is quantitative in nature. Checklists are referred to as "quick and dirty" PIs; for example, one item on a checklist may be that the percentage of maintenance, repair and operation/overhaul items (MRO items) that have not improved during the last two years should not be higher than 3 per cent. Checklists are widely used by consultants. Each indicator on a checklist has an "ideal" value, or a range. The checklist approach provides quick but rough insight. Determining "ideal" values is especially difficult. "Surveys" are commonly published for specific industrial sectors such as steel, aluminium, glass, plastics, ceramics, furniture, etc., and academic research groups frequently use such techniques. Pintelon and Van Puyvelde (1997) point out that a survey typically includes the maintenance cost as a percentage of the total cost. Research allows for low-key benchmarking in specific sectors of the economy. However, a large deviation from the sector average may not necessarily mean that the performance is bad. In order to judge, a more detailed evaluation is needed (Pintelon and Van Puyvelde, 1997).

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

Applying the concept of indicators and the appropriate selection of actions to perform, based on continuous improvement, will help to achieve excellence in maintenance (Katsllometes, 2004). Therefore, according to Katsllometes, a metric that has its point of departure in world-class manufacturing (WCM) is necessary.

New trends derived from world-class manufacturing (WCM) or lean manufacturing do not give the full answer either. It sounds challenging to aim for the world-class maintenance (WCM) or world-class reliability level, but these levels have not yet been defined properly by any source. In the majority of cases, qualitative statements are used, like that a WCM organization delivers consistent uptime from week to week, minimizes the impact on production, delivers its work as planned, has "spot-on" budgeting, etc. Although this will stimulate a much more professional attitude towards the maintenance process, a company still does not know how far it is from the WCM level and when this level will be reached. Common questions concern the business (economic) impact of low equipment uptime or how much cheaper maintenance would be if a company accepted a 90 per cent weekly schedule compliance instead of aiming for 100 per cent.

Lean maintenance is another popular maintenance management framework, developed from the successful implementation of lean manufacturing. The goal is to eliminate waste, and therefore to distinguish between value adding and non-value adding maintenance activities. However, unlike lean manufacturing, lean maintenance fails to define which activities to eliminate and which to keep. Some attempts have been made to streamline maintenance processes, eliminate waste and produce breakthrough performance in areas valued by customers by applying business process reengineering, pioneered by Hammer and Champy (1993).

Of the above-mentioned methods, only world-class maintenance has been widely developed. Maskell (1991) provides a set of guidelines for designing MPMs for world-class manufacturing systems that lead to excellent performance in today's turbulent and competitive business environment. World-class maintenance ensures almost 100 per cent capacity, 100 per cent of the time of the operation. The metrics of world-class maintenance are elementary statistics. The method points out some key indicators, as well as some basic benchmarks for improvement. It comes from world-class manufacturing, and its main contribution is the proposal of six indicators globally accepted by organizations: 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 and medium companies , according to De Jong (1997).

WCM also proposes reference values for ambiguous indicators. When a company wants to be considered world class, it must achieve high goals. To this end, it can apply benchmarking to compare its performance with that of organizations with good practices and results.

Superiority in maintenance is also characterized by high levels of PM and planned maintenance as percentages of the total work. "In the best plants", at least 80 per cent of all the maintenance tasks are preplanned a day or more in advance; thus, they are pre-staged with the correct materials, skills, tools, and parts and the most appropriate timing.

Kahn *et al.* (2011) see the need to compare indicators, both within companies and with similar factories or sectors. When a company wants to compare the performance and reliability of internal or external maintenance, it needs a common platform of predefined indicators to compare identical variables and production units.

This task has been tackled 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 a harmonized project, comparing the similarities and differences between the existing indicators for maintenance and availability supported by both agencies. Comparisons have been made between the SMRP metrics and the European standardized indicators in EN 15341 (CEN, 2007). The aim is to bring about the 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 and Olver (2008) is one of the leading experts involved in the harmonization project. He has proposed some references to indicators based on practical cases in various industries and sectors, using extensive surveys, normally conducted at firms within the same sector, but highlighting the food and pharmaceutical industries.

It is important that the performance measures in the benchmarks should be meaningful. In fact, the metrics are useless without them. The benchmarks can, as mentioned, be a goal that the processes must focus on and target continuously, or a limit which these processes must not exceed or fall below, i.e. a maximum or minimum limit. In some cases, the target of an indicator will be 0 or 1, if it belongs to the efficiency or inefficiency group. Certain indicators, such as the MTBF, will be more complex, and one must resort to similar experiences concerning the machinery in question or the manufacturer's data, drawing on the expertise of the maintenance technicians.

The benchmarks will always depend both on conventions or business types and on the ranking of indicators in each sector. In this connection, it is particularly interesting to observe how Silter (2003) presents the risk-informed asset management (RIAM) model, which he uses to quantify the PIs to support decision making at power plants, not only to implement investment options in the best possible way, but also to prioritize the use of certain plant resources better and to maximize the safety of the process. With the RIAM approach, PIs incorporate cost-averse thinking. Because indicators of availability, maintainability and technical levels like vibrations or temperature will be different across companies, the hierarchy will change: for example, instead of leading economic indicators, the RIAM methodology may place safety PIs at the top of the pyramid.

It is essential to set thresholds and targets for each indicator; otherwise the MPM team measuring performance may confront a battery of numbers with upward or downward swings, but have no knowledge of what they mean. Today these benchmark points are included in the demands made on providers in the industry. Industrial sectors such as the automotive, aeronautics and energy industries are used to requesting quality parameters from suppliers, but now overall indicators of efficiency close to world-class maintenance levels are required as well.

The PIs presented in EN 15341 (CEN, 2007), *Maintenance – Maintenance Key Performance Indicators*, released in March 2007, were designed by CEN Technical Committee 319 Working Group 6 (WG6). The working group was set up by European experts in maintenance management to create an architecture of indicators to measure maintenance performance worldwide. WG6 studied all the maintenance indicators available in the literature. They also considered the guidelines, procedures and experiences of many multinational industrial companies. From these, they selected three groups of KPIs: economic, technical and organizational.

As a result, EN 15341 (CEN, 2007) is a reliable reference, a worldwide standard that can measure and develop maintenance performance, considering and managing both external and internal influencing factors.

When an organization wants to compare maintenance and availability performance internally or externally, it needs a common platform of predefined indicators or metrics. Comparison of metrics when the bases of calculations are not the same is a frustrating non-value-added activity. This challenge has been met by SMRP and

EFNMS (Svantesson, 2002; Svantesson and Olver, 2008). These two maintenance organizations have made a joint effort to compare and document standard indicators for maintenance and reliability performance.

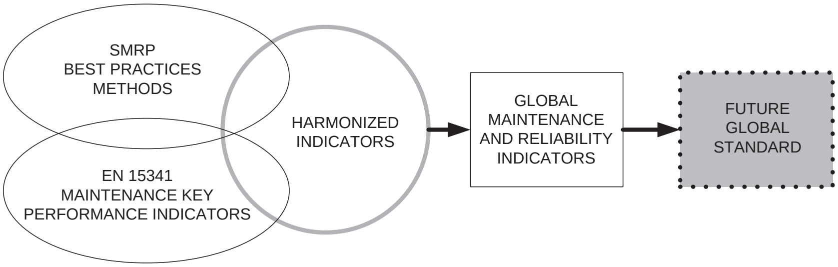
An organization should use standardized indicators or metrics such as the indicators from the EN 15341 standard or the SMRP metrics for the following reasons (CEN, 2007):

- 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 wants to construct a set of company indicators or a scorecard, the development process is simplified by access to predefined indicators;
- the predefined indicators can be incorporated into various CMMS software and reports;
- the predefined metrics can be adopted and/or modified to fit a company's or a branch's specific requirements; and
- the need for discussion and debate on indicator definitions is ended and uncertainties are eliminated.

Since 2000, SMRP has defined 67 best practice metrics to measure maintenance and reliability performance (SMRP, 2011). In 2000, EFNMS defined a set of indicators to measure maintenance performance. These indicators are now incorporated in the European standard EN 15341 (CEN, 2007). The joint EFNMS-SMRP harmonization effort, which began in 2006 (Kahn and Gulati, 2006), had the objective of documenting the similarities and differences between the SMRP metrics and the EN 15341 standard (Figure 7).

With companies producing goods and supplying services on an international scale, the need for a common understanding of the indicators used to measure maintenance and availability performance is paramount. There is no doubt that this activity will eventually be covered by a global standard guideline for maintenance indicators.

The harmonization document is designed to offer the maintenance community a set of predefined indicators to measure maintenance and reliability performance on a global basis. The indicators can be used by all organizations with a need to measure, track, report and compare maintenance and reliability performance.




**Source:** Kahn *et al.* (2011)

**Figure 7.** The process of the harmonized indicators project

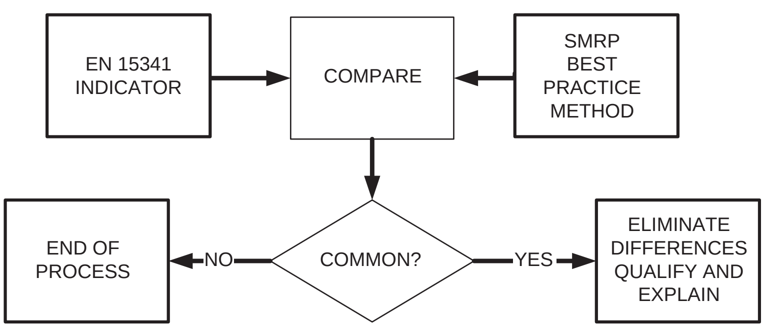
The document is also intended to give a scale for measuring maintenance or reliability performance. The indicators or metrics are supported by a set of guidelines and examples of calculations. (It is outside the scope of this document to give any recommended values or thresholds for the indicators.) This provides maintenance professionals with an easy-to-use guide to indicators and their components.

The target group for the harmonized indicators document comprises the following: maintenance managers, asset managers, plant managers, operations managers, reliability engineers, technical managers, general managers or any other personnel involved with benchmarking or maintenance and reliability performance measurement.

A joint EFNMS-SMRP working group was established with the intention of resolving differences between the EN 15341 (CEN, 2007) indicators and those being developed by the SMRP Best Practices Committee. Side-by-side comparisons were made of the indicator formulas and definitions of terms. The basis for the European terms is the EN 13306:2001 standard (CEN, 2011), Maintenance Terminology, and the IEC 60050-191:1990 standard (IEC, 1990), Dependability and Quality of Service. The SMRP definitions are contained within each indicator (metric) description, and have been compiled in an SMRP glossary of terms by the SMRP (2006) Best Practices Committee. The work of the joint EFNMS-SMRP working group resulted in two extensive lists, as there were terms or formulas that were not common to both sets.

An indicator is determined as being common if, according to the EFNMS and SMRP definitions, it has the same basic formula or can be universally applied. With regard to common indicators, it is first determined whether any differences can be eliminated without sacrificing the objective of the indicator. If the differences cannot be eliminated, they are qualified or explained. This is the essence of the harmonization process, which is graphically depicted in Figure 8. It should be noted that the grouping of the EFNMS and the SMRP indicators is different. In EN 15341, 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 (SMRP, 2006).

The joint working group has made good progress, having announced the first harmonization results in January 2007, and having published the original edition of Global Maintenance and Reliability Indicators in April 2008 (Svantesson and Olver, 2008). 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.




**Source:** Svantesson and Olver (2008)

**Figure 8.**
The harmonization process

Furthermore, the SMRP metric is recommended by EFNMS for use as a guideline to calculate the EN 15341 (CEN, 2007) indicators.

The harmonization work will continue until the complete list of SMRP indicators currently under development has been exhausted. Similar harmonization efforts are projected with other international maintenance organizations, such as COPIMAN (the Technical Committee on Maintenance of the Pan American Federation of Engineering Societies) and MESA. There are tentative plans to promulgate the use of these harmonized indicators as international standards. Discussions are being held 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 the search for proper benchmark values as thresholds or targets. The calculation of indicators is exhaustive, but the search for benchmark references is not. Thus, those maintenance managers who read EN 15341 (CEN, 2007) or SMRP Good Practices (SMRP, 2011) extract valuable information, but do not know the desired value of all the parameters, either partially or fully applied to their respective fields. In world-class maintenance, many figures have been proposed for many industries as a result of companies' experiences. Therefore, the success of WCM lies not only in the proposal of common methods for parameter calculation, but in the establishment of real numbers as targets.

## XI. Maintenance audit

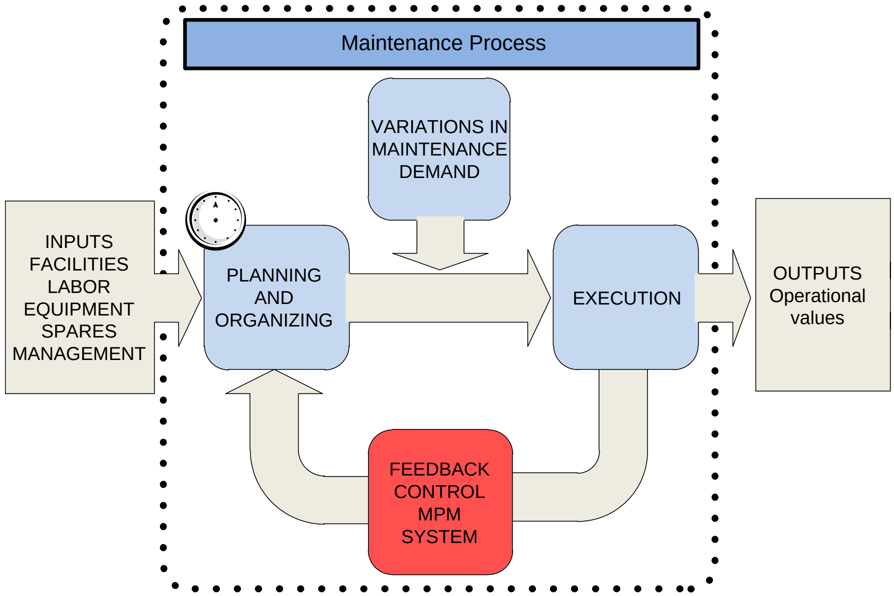
Converting forecasts into real concrete numerical values requires an extraordinary effort. If this proves too onerous, a company may choose to focus on the system and its attributes rather than on specific outcomes, using what can be termed the "system audit approach". A maintenance audit is an examination of the maintenance system to verify that the maintenance management is carrying out its mission, meeting its goals and objectives, following proper procedures and managing resources efficiently and effectively.

The maintenance audit concentrates on the maintenance system itself, as opposed to quantifying its inputs and outputs (Figure 9). The results obtained from this approach should have a level of accuracy that is compatible with the information normally available about real performance. Subjectivity in performance measurement will not be overcome, but such subjectivity will be made more visible.

Auditing, as a general technique, can be divided into two categories. The first category is general auditing based on a common assumed standard designating what constitutes a good system. This is a popular tool for consultants since it allows them to apply a consistent standard concerning what a good maintenance system should be. This is normally isolated from a deep understanding of the subject organization's business. It permits consultants to insert important attributes of which they have a good knowledge, but whose importance varies in reality from one organization to another. The general audit is a thorough review of the various dimensions in the maintenance system, including organization, personnel training, planning and scheduling, data collection and analysis, control mechanisms, measurements and reward systems, etc. To obtain 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 specific key areas in the system to be audited. Responses to these questionnaires may take one of the following forms:

- answering either yes or no;
- choosing one or more of the available options; or




**Source:** Stenström (2012)

**Figure 9.**
Input-process-output model (IPO model) of the maintenance process

- on a Likert-type scale of, for example 1-5, indicating different degrees of agreement or a lack of agreement.

Different weights may be assigned to questions to reflect their relative contributions to the system performance. Even though they may use sophisticated assessment schemes, the underlying theory of system audits is unclear. Dwight (1994) suggests a procedure that relates the state of a system element, based on information such as feedback from operations, to its contribution to the system's overall performance.

The overall performance of a maintenance system can be determined by aggregating the contributions to business success of the system elements that influence the relevant failures of assets. In this procedure, an exhaustive compilation of attributes identified as contributing to business success has to be made. The same requirements apply to the system elements that influence a failure attribute.

The more typical system audit tends to focus on the issue of conformance to a standard model, with regard to both system design and execution. It is assumed that the standard can be universally applied to achieve superior performance. The maintenance system audit questionnaires created by Westerkamp (1993) and Wireman (1990) rely on 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 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. Socio-technical systems (STS) analysis provides a methodology for designing a system that will achieve this fit (Taylor and Felten, 1993). Thus, the basic assumption of a standard reference model implicit in the design of the typical audit questionnaire is problematic.

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

A maintenance system audit is necessary for developing an improvement action plan. According to Kaiser (1991), De Groote (1995), The Institute of Internal Auditors (Stice *et al.*, 1992), Mann (1983) and Duffuaa and Raouf (1996), the maintenance system audit helps the management to achieve the following:

(1) ensure that the maintenance is carrying out its mission and meeting its objectives;

(2) establish a good organization structure;

(3) manage and control resources effectively;

(4) identify areas of problems and resolve them;

(5) improve the maintenance performance;

(6) increase the quality of the work;

(7) automate and recommend information systems to increase effectiveness and productivity; and

(8) develop the culture of continuous improvement.

The audit process is usually conducted on site. It reviews key elements in the following way (Zancolich, 2002): interviewing key people in the organization; conducting site inspections; reviewing process flows and mapping maintenance functions and control; reviewing relevant documentations; 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 analysed to formulate action plans for improvement.

Westerkamp (1987) has developed an audit scheme that covers 14 factors contributing to maintenance productivity. He advocates automating the auditing process and focusing on the following factors: organization staffing and policy; management training; planner training; craft training; motivation; negotiation; management control; budget and cost; WO planning and scheduling; facilities, store, material and tool control; PM and equipment history; engineering; work measurement; and data processing. He suggests obtaining information about these factors by using a set of questions about each.

Kaiser (1991) has developed a maintenance management audit that includes key factors in the process of maintenance management: organization; workload identification; work planning; and work accomplishment and appraisal. Each component has six to eight factors. Using structured statements and weights, Kaiser obtains an overall score for the maintenance system. In brief, necessary improvements can be identified from the audit process.

Duffuaa and Raouf (1996) have conducted a study on continuous maintenance productivity improvement using a structured audit and have proposed a structured audit approach to improve maintenance systems. They include the following factors in their audit: organization and staffing; labour productivity; management training; planner training; craft training; motivation; management and budget control; WO planning and scheduling; facilities; supplies/stores, material and tool control; PM and equipment history; engineering and condition monitoring; and work measurement, incentives and information systems. They propose using the analytic hierarchy process to determine the factors' weights and to compute a maintenance audit index. They also suggest root cause analysis to develop an improvement action programme.

Duffuaa and Ben-daya (1995) propose the use of statistical process control tools to improve the maintenance quality, and Raouf and Ben-daya (1995) suggest employing a total maintenance management (TMM) framework. An important component of TMM is a structured audit.

De Groote (1995) argues in favour of a maintenance performance evaluation approach based on a quality audit and MPIs. The quality audit should be conducted in the following four stages: a survey of the influencing parameters; analysis of the collected data, conclusions and recommendations; derivation of an improvement action plan; and justification of the proposed improvement plan based on cost-benefit analysis. The evaluation should include the following five major factors: production equipment; organization and management of maintenance; material resources; human resources; and work environment.

PricewaterhouseCoopers (PwC, 1999) has developed a questionnaire to evaluate maintenance programmes. The questionnaire includes ten factors: 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 features several statements about each factor; each statement is given a score ranging from 0 to 4.

Al-Zahrani (2001) has reviewed audit programmes and surveyed managers and engineers in government and private organizations in the Eastern Province of Saudi Arabia to assess the factors affecting maintenance management auditing, with the aim of developing a suitable auditing form for facilities maintenance. He proposes an audit form consisting of 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 that are relevant to the performance of the maintenance system.

In the literature, five structured audit programmes for maintenance systems have been developed by Westerkamp (1987), Kaiser (1991), Duffuaa and Raouf (1996), PwC (1999) and Al-Zahrani (2001). The audit programmes consist 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.* (1999) present a systems audit technique, based on STS analysis, for predicting the future maintenance performance, as well as a data envelopment analysis technique, a non-parametric quantitative approach to benchmarking organizational maintenance performance in comparison with competitors. Using a four-stage quality audit approach, De Groote (1995) defines PIs in terms of ratios rather than absolute terms to develop a system for maintenance performance.

Many authors argue that it is necessary to obtain both qualitative and quantitative results (Galar *et al.*, 2011b). Clarke (2002) suggests that an audit must contain a maintenance radar (a Bell-Manson spider graph) which imagines all the economic aspects, human factor aspects, etc. of maintenance. In his view, a product of the audit must be good operative and technical maintenance practices. Like many others, Tavares (2002) makes use of a maintenance radar in audits to represent the different areas of maintenance influence and dependency. Many authors agree that these radars should be generated from massive surveys. Despite the reliability of the surveys, the numerical data of systems are not included in the radars, and they become subject to a strong human factor (Papazoglou and Aneziris, 1999).

More recently Kumar *et al.* (2011) developed an audit in this category. Their model proposes a mixture of qualitative aspects, received through questionnaires, and different weights of maintenance KPIs that should strongly correlate with the questionnaire answers. This model shows the relation between trends in questionnaires and indicators in a way that validates the correlation or highlights the divergence, merging qualitative and quantitative measures.

## XII. Benefits of a performance measurement system

Kutucuoglu *et al.* (2001) take advantage of the QFD technique, using its ease of implementation, its alignment of PIs with corporate strategy, and its ability to hold both subjective and objective measures, to develop an effective performance measurement system for the maintenance function. Their MPM system incorporates the key features necessary for effective MPM, i.e. a balanced view of the maintenance system, cross-functional structure, vertical alignment of PIs, etc. The introduction of PIs can:

- clarify the strategic objective;
- link maintenance department objectives to core business processes;
- focus actions on CSFs;
- keep track of trends in development; and
- identify possible solutions to problems.

Various industrial sectors have benefited from the introduction of indicators in their maintenance departments. Espinoza (2005), on the basis of his research on the aluminium industry in England, states that, in an effort to gain a competitive advantage over its main rivals, this industry is using a series of MPIs through which its effectiveness can be monitored continuously (reliability, availability and use of equipment). Effective maintenance, according to the author, will improve the ratio between unplanned and planned activities. Espinoza says that the increased number of scheduled jobs in this industry indicates that the maintenance strategy is effective. Other authors, like Racoceanu *et al.* (2002), have developed scorecards with sets of indicators in the machine tool sector to increase competitiveness.

Once indicators have been embedded in the organizational hierarchy, the benefits obtained by the organization, according to Wireman (1998), include the proper development, evolution and progression of the maintenance model. Wireman proposes a sequential implementation of steps to ensure that all the functions necessary for the proper management of maintenance are in place: PM, inventory and procurement, the WO system, the CMMS system, technical training and staff relationships, staff involvement in operations, predictive maintenance, RCM, TPM, statistical optimization, and finally continuous improvement. Wireman (1998) considers that each of these activities is a section in the maintenance management process, as expressed in the pyramid shown in Figure 10. Wireman (1998) suggests that a PM programme should be implemented before moving to the next level of the pyramid and working one's way all up the pyramid. Before considering the application of RCM, for example, predictive maintenance programmes, the involvement of staff in maintenance functions, appropriate WO systems and management of maintenance resources are required. The involvement of operators and employees constitutes the next stage; TPM programmes will help for that purpose. Finally, optimization techniques will complete the organizational structure necessary for continuous improvement.

It is a mistake to reorganize a department using one technique, and it is advisable to avoid consultants and companies that advocate a single technology as a solution to a problem. When the department is in a state of "stagnation" with respect to ratios or indicators, there is a need for a drastic change in the maintenance philosophy. Reengineering may be a possible solution, but it is worth knowing that, while moving up in the maturity pyramid of maintenance evolution, the next level will be more complex. Zaldívar (2006) shows that, when employees and managers perform functions in a process-oriented environment, organizations can measure their performance and pay them based on the value which they create. In organizations that have undergone major reengineering, contribution and performance become the main bases for compensation and, therefore, in most cases, they are a success. Concerns with quality guarantees and product reliability are causing organizations to focus their decisions on the efficiency and quality of maintenance management. When the process of reengineering is applied in maintenance, it affects other processes in the organization, and fewer people are needed to achieve standards of quality and efficiency. Zaldívar (2006) states that, with fewer managers, fewer administrative

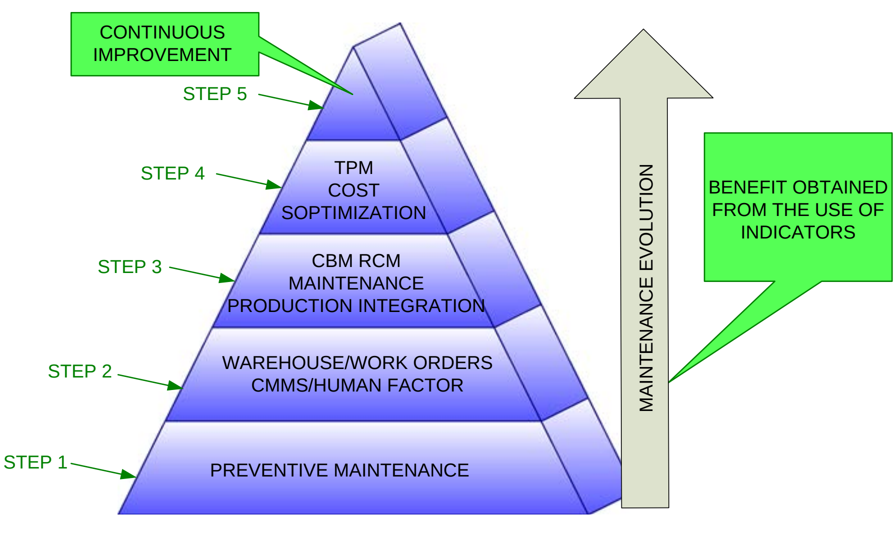



**Figure 10.**
Construction of the maintenance management process by Wireman (1998)

levels, and, consequently, a predominance of flat structures, stable performance and a qualitative jump in each technical-economic indicator are assured, bringing the organization closer to the top of the pyramid of Figure 10.

This sequential development requires appropriate indicators associated with each level, from the operations related to each team to the strategies of the organization at the top of the pyramid. Proper measurement of the state of maturity at each level will help to develop the next step. Unsystematic CBM implementations or isolated and uncoordinated strategies do not usually give good results, as noted by González (2005). Proper progression through the pyramid is essential (as in the sequential development pyramid of the comprehensive maintenance programme and the proposed hierarchy of KPIs).

In his investigation of the ability of a maintenance process to reach maturity by climbing the pyramid shown above, Schneidewind (1999) notes the need for stability to ensure product quality. The use of metrics in the maintenance process predicts reliability and risk, thereby ensuring stability. Schneidewind (1999) stresses the need for strengthening each layer of the organization, as greater maturity will facilitate the jump to the next level. The evolution of the maintenance process should not be precipitated or accelerated.

## XIII. E-maintenance

Today's competitive manufacturing depends on the manufacturer's ability to provide customers with lean services and life-cycle costs for sustainable values at all times. E-maintenance is transforming the maintenance function into a service business to support customers anywhere and anytime with the use of the internet, web-enabled wireless communication and technology. E-maintenance enables companies, using predictive intelligent embedded sensors to monitor their assets through web-based wireless communication to prevent unexpected breakdowns. E-maintenance systems can compare the performance of a company's product with that of other companies' products, using a global network system to focus on degradation monitoring and prognostics. Such information will greatly facilitate business decisions (Koç and Lee, 2001).

The main problem with performance measurement for decision making is the non-availability of relevant data and information. However, recent applications of information and communication technology and other emerging technologies facilitate the easy and effective collection of data and information (Parida and Kumar, 2004). The two most important achievements of performance measurements are the identification of opportunities to improve existing equipment and plants, and improved supplier performance. To cite one example, MPM has become part of the decision-making process in the mining industry, where the use of condition monitoring is extremely important.

E-maintenance is a maintenance management concept whereby plants and machinery are monitored and managed by computer software, involving the use of intelligent sensors, databases, wireless communication, the internet, online GUIs, etc. Levrat *et al.* (2008), Muller *et al.* (2008), Thun (2008), Campos (2009), Cao *et al.* (2009), Emmanouilidis *et al.* (2009), Jantunen *et al.* (2009), Jeong *et al.* (2009) and Jun *et al.* (2009) have carried out studies investigating the monitoring of manufacturing performance using wireless communication technologies and investigating the impact of such monitoring on maintenance performance. Today, with the availability of unique e-maintenance solutions, the manufacturing and the 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 centre by linking users, technicians/experts and manufacturers. It is useful for the process industry, as it can help to reduce the overall costs, ensure savings in resources through OEE and yield a better return on the maintenance investment.

Some existing e-maintenance solutions provide server-based software and equipment-embedded internet interface devices (health management cards). These e-maintenance solutions provide 24/7 (24 hours a day, seven days a week) real-time monitoring, controls and alerts. The system converts data into information, available to all concerned for decision making and predicting the performance condition of the plant and machinery on a real-time basis. This enables the system to meet supply chain requirements.

## XIV. Conclusions

Many attempts have been made to accomplish the development and implementation of an effective MPM system that can create value for organizations. The issues considered include the following: how to align the organizational strategy to the strategies of the maintenance function; how to link maintenance performance measures to the organization's hierarchies and establish effective communication between them; and how to translate MPIs at the operational level into information for the corporate level to create value for the organization and its customers (Parida and Kumar, 2009). Most (but not all) researchers have developed frameworks based on financial (tangible) measures.

Section XII discussed features of an effective and efficient MPM system, as proposed by Kutucuoglu *et al.* (2001). Alsyouf (2006) has outlined the following characteristics of a holistic performance measurement system:

- it can assess the contribution of the maintenance function to the strategic business objectives;
- it can identify the strengths and weaknesses of the implemented maintenance strategy;
- it can establish a sound foundation for a comprehensive maintenance improvement strategy using qualitative and quantitative data; and
- it can re-evaluate the criteria used for benchmarking.

In brief, an effective MPM system should focus on measuring the total maintenance effectiveness, i.e. the internal and external effectiveness (Parida and Kumar, 2006). Frameworks that measure maintenance performance by considering only financial impacts might help to improve the internal processes of the maintenance function, but they fail to account for the impact of maintenance strategies on functions external to the maintenance function, such as functions dealing with production, logistics, customers, employees and organizational goals.

Other frameworks, like the value-based BSC proposed by Liyanage and Kumar (2003) and the framework using QFD, may account for the financial and non-financial impacts of maintenance strategies, but do not guarantee the improvement of the maintenance performance on the tactical and the strategic levels. Nor do they consider the impact of maintenance strategies on the extended value chain, i.e. the suppliers, etc.

A framework using the extended BSC is more complete for the following reasons: it provides information on both the qualitative and the quantitative impacts of maintenance strategies; it can control the different hierarchies of the organization; and it strives for both internal and external effectiveness. Similarly, the multi-criteria and multi-hierarchical framework for MPM is effective and efficient, as it incorporates the total maintenance effectiveness concept, as well as the characteristics presented by

Alsyouf (2006) and Kutucuoglu *et al.* (2001). In addition, it gives a causal relationship between PIs at different organizational levels and PIs that are based on both financial and non-financial aspects.

With respect to the maintenance strategies under investigation in this paper and based on the evaluation of the frameworks in the literature, it seems clear that the extended BSC and the multi-criteria and multi-hierarchical frameworks are effective tools for evaluating and measuring the performance of condition-based maintenance and predictive maintenance; the BETUS tool is useful for e-maintenance and remote maintenance performance evaluation.

Evaluating the performance of maintenance strategies using effective financial and non-financial measures has been a major concern in maintenance operations literature. To this end, a number of techniques and frameworks have been developed. However, the application of these frameworks in a practical environment has met with limited success.

With respect to the first objective of this research overview based on a review of the literature, we have identified a number of different techniques for formulating PIs to measure maintenance performance. However, as discussed previously, these MPM techniques can only help to determine the right set of PIs and are independent of the maintenance strategy. Therefore, we could not arrive at the optimal technique for evaluating condition-based maintenance, remote maintenance, RCM, e-maintenance, etc.

As for the second objective, the literature discusses a number of frameworks and models, showing how MPM systems should be implemented or used and how they can create value, financial as well as non-financial, for organizations. The review has also shown what value is created when different frameworks are used. Through case studies, the literature has demonstrated what value is created and how it is created by using these MPM frameworks for organizations with condition-based, vibration-based and reliability-centred maintenance. However, the literature has failed to identify what value is created and how value is created when these frameworks are employed by an organization using e-maintenance or remote maintenance.

Moreover, the literature shows no attempts to create a framework or model linking two different maintenance strategies and comparing their effectiveness and efficiency. Nor has any attempt been made to link MPM frameworks with particular maintenance strategies, such as condition-based maintenance, remote maintenance, predictive maintenance, etc.

Given these gaps in the literature, the following potential future research directions are clear:

- Attempting to find an optimal MPM framework for a particular maintenance strategy, e.g. condition-based maintenance, remote maintenance and e-maintenance.
- Comparing the effectiveness of different maintenance strategies (e.g. CBM, remote maintenance and e-maintenance), using a particular framework, such as an extended BSC (Alsyouf, 2006) or a multi-criteria and multi-hierarchical framework (Parida, 2007).
- Combining a multi-hierarchical and multi-criteria framework with an extended BSC framework, in order to consolidate their features in a single framework.
- Using the multi-criteria and multi-hierarchical framework to evaluate the effectiveness of e-maintenance.

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