Maintenance Performance Metrics: A State of the Art Review

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Abstract— **This paper provides an overview of research and developments 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, looking at such maintenance strategies as condition based maintenance, reliability centered 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.

The paper asks the following research questions:

- **What approaches and techniques are used for Maintenance Performance Measurement (MPM) and which MPM techniques are optimal for evaluating maintenance strategies?**
- **In general, how can MPM create value for organizations, and more specifically, which system of measurement is best for which maintenance strategy?**

The body of knowledge on maintenance performance is both quantitative and qualitative 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 others. Qualitative-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.

Keywords— **KPI, indicator, performance, Maintenance Performance Measurement (MPM), framework, hierarchy**

I. Introduction

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

The scope of maintenance in a manufacturing environment is illustrated in its numerous definitions. The British Standards Institute defines maintenance as a combination of all technical and associated administrative activities required to keep equipment, installations and other physical assets in the desired operating condition or to restore them to this condition (BSI 1984; Pintelon 1997; Pintelon and VanPuyelde 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 (MESA 1995). Maintenance also includes engineering decisions and associated actions that are necessary for the optimization of specified equipment capability, where capability is the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality, safety and responsiveness (Tsang et al. 1999). Similarly, Kelly 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 system condition and safety (Kelly 1989). The desired production output is achieved through high availability, which is influenced by equipment reliability, maintainability and maintenance supportability (EN 13306:2001). Finally, maintenance is also partly responsible for technical systems' safety and for ensuring that the plant remains in good condition (Visser and Pretorious 2003).

One can summarize maintenance objectives as the following (Kelly and Harris 1998); ensuring the plant functions (availability, reliability, product quality etc.); ensuring the plant reaches its design life; ensuring plant and environmental safety; ensuring cost effectiveness in maintenance and the efficient use of resources (energy and raw materials). With respect to 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 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 current concerns about money and safety, this is beginning to change. The focus is now to keep 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, purchase of industrial buildings, production equipment, 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 is chrematistic, i.e. related to money-making. When organizations begin to optimize their production costs, they start to question their maintenance costs. This function, in recent years, has grown in 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 availability and quality parameters. A constant concern, then, is maximizing availability at the lowest cost. Not surprisingly, methodologies and technologies to determine the best way to achieve this balance are increasingly popular, as noted by Al-Najjar (2007).

II. The Need to Measure Maintenance Performance

Today, organizations are under pressure to continuously enhance 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 change in the strategic thinking of organizations, the increased amount of outsourcing and the separation of OEMs 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, e-maintenance etc. The main challenges faced by organizations today are choosing the most efficient and effective strategies to enhance and continually improve operational capabilities, to reduce maintenance costs and to achieve competitiveness in the industry. 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) is defined as the multidisciplinary process of measuring and justifying the value created by maintenance investment, and taking care of the organization's stockholders' requirements viewed strategically from the overall business perspective (Parida and Chattopadhyay, 2007). MPM allows companies to understand the value created by maintenance, to re-evaluate and revise their maintenance policies and techniques, justify investment in new trends and techniques, revise resource allocations, and to understand the effects of maintenance on other functions and stakeholders as well as on health and safety etc. (Parida and Kumar 2006).

Unfortunately, these maintenance metrics have been often misinterpreted and they 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).

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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 maintaining to production or sales; others make it possible to determine whether availability is adequate or what factors should be modified to achieve its increase.

This historical view of maintenance, mixed with 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. That being said, data overload is now a problem, and sophisticated data mining algorithms are required to get useful information as Charnes et al. (1985) 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. analyzing objectives tailored to each organizational level which emanate from the corporate levels. Once user needs are fully understood, it is possible to determine the maintenance strategy, organization, resources and systems.

B. The number of performance indicators, ownership of the data and the aspects to be covered

The number of indicators used for each figure or department should be limited by identifying key features or key factors. Scorecards with large numbers of indicators 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 an organization. Often, the maintenance department is overwhelmed in its duties, so 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 these parameters and can share them. For example, it may be relatively simple for the production department to collect data on availability or reliability. Occupational Safety and Health people are ideal for determining the rates of accidents, as studied in EN 15341 (2008).

C. Objectives and measures

At times, departments within the same company have conflicting interests in the maintenance of their equipment. But the purpose of the objectives is to ensure that departmental efforts are aligned with business needs (Gelders et al., 1994). Tangible goals should be tailored to the user and be free of ambiguity. Problems can be created when 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 management ensures that its objectives are translated into objectives at lower levels, Objectives should be transmitted in a downward cascade, including all 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 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 time that the measurement is taken. Each problem must be set against each objective, taking into account that technical levels can expect faster changes in their indicators than corporate levels, whose KPIs are slower to show visible results. Once a measure has been identified for a goal and level, and this is 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 collecting

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

If there is a risk that the indicators derived from the reported data are used against people, it is almost certain that they will not be collected in an appropriate way. Also if time passes and the data have not been used for anything, if they have been forgotten and feedback has not been transmitted, people will inevitably see the whole thing as a waste of time. In other words, if people understand the purpose and see the results, they will be motivated to collect data. Massive data collection can generate unknown indicators for the collectors; thus, they may 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, they must honor the objectives of management, as it is 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 [1]. Measuring performance is essential in any business. Continuous improvement is the process of not accepting the status quo, as Wireman [2] notes. Levitt (1997) agrees with Wireman and maintains that a prerequisite for the maintenance function is continuous improvement.

An increasing number of studies attempt 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), measurement objectives are planning, selection, monitoring and diagnosis. Mitchell [5] 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. [6] see performance measurements (PM) 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, results could be misleading.

In TRADE [1], 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 multiple units expressed as ratios of two or more fundamental units to yield a new unit, TRADE [1]. Some applications develop an indicator of performance measurement. An indicator, therefore, is a combination of a set of performance measurements. To streamline performance indicators, Key Performance Indicators (KPIs) are created; these could consist of several indicators and metrics. To determine 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, linking maintenance strategies with 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 Maintenance Performance Indicators (MPIs) that reflect a company's organizational strategy and give maintenance management quantitative information on the performance of the maintenance strategy (Arts, Knapp and Mann 1998; Swanson 2001).

Hernandez [9] proposes a battery of indicators from system reliability and functional safety. He defines an indicator or index as a numerical parameter that provides information about a critical factor identified within an organization, for example, processes, people, or expectations of cost, quality and deadlines. Indices should be few, easy to understand and measurable; it should be fast and easy to learn how things are going and why. In addition, they must identify the key factors of maintenance; establish records of data allowing periodic calculation to set standard values for these indicators, mark targets based on those

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standards, make appropriate decisions and take appropriate actions (Armitage and Jardine 1968). Hernandez 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 maintenance performance indicators, i.e. numerical parameters on 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. Type Of Indicators: Leading Versus Lagging and Hard Versus Soft

PIs are used to measure the performance of any system or process. A PI is a product of several measures (metrics). When used to measure maintenance performance in an area or activity, it is called a maintenance performance indicator (MPI) (Wireman, 1998; Parida et al, 2003). PIs are used to find ways to reduce down time, costs and waste, operate more efficiently, and increase the operation's capacity. A PI compares 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 performance indicators 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 economy does (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 commitments are often leading indicators in the sense that they are highly predictive of financial performance. When such measures are tracked today, it leads to less worry about tomorrow's budgets (Case, 1998).

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

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. Others, 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'. 'Hard' indicators include those measurable through the extraction and exploitation of simple databases, like CMMS (computer maintenance management system), ERP (Enterprise Resource Planning) databases, presence, purchase orders, energy consumption by area etc. Arts, Knapp and Mann (1998) explain the development of a MPM system using the CMMS. The operational view of the maintenance function requires certain indices for performance measurement; it does not require the tactical and strategic aspects of maintenance performance. In this case, the data collection and calculation of the indicators are fast, and measurement does not interfere in the daily work of the maintenance team. Here, 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, their hard objectivity or their lack of reliability. Apart from staff and workshop size, this group includes all 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, 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, with special emphasis on 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, and determine the average time for 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, and confidence and so on; 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 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 its productivity. The OEE concept has become increasingly popular and is widely used as a quantitative tool to measure equipment performance in industries (Huang and Dismukes 2003; Muchiri and Pintelon 2008). Arts and Mann use the time horizon to classify maintenance control and performance indicators into three levels: strategic, tactical and operational (Arts and Mann 1998). Indicators proposed for operational control include: planned hours over hours worked, work orders (WO) executed over WO scheduled, and preventive maintenance (PM) hours over total maintenance hours.

Parida proposes a multi-criteria hierarchical framework for MPM (Parida 2007) that consists of multi-criteria indicators for each level of management, i.e. strategic, tactical and operational. 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 production cost), maintenance task related (e.g. ratio of planned and total maintenance tasks), customer and employee satisfaction, and health, safety and environment (HSE). Indicators are proposed for each level of management in each category.

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

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

Dwight classifies performance measures in a five-level hierarchy according to their implicit assumptions on the impact of the maintenance system on the business (Dwight 1995; Dwight 1999): overt (visible) bottom-line impact measurements (e.g. direct maintenance cost), profit-loss and visible cost impact measurements (e.g. total failure/down time cost), instantaneous effectiveness measures (e.g. availability, OEE), system audits (e.g. % planned work and work backlogs) and time related performance measurements (e.g. life cycle costing and value based performance measurement). Dwight's work looks at the variations in 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

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function. For example, much emphasis has been placed on equipment performance in terms of number/frequency of breakdowns, MTTF, availability and OEE. Similarly, maintenance cost-related measures are deemed important. Measures of maintenance efforts are considered important by many authors, though they use a variety of terminologies to describe them (e.g. maintenance productivity and operational purpose fullness (Coetzee 1997), maintenance efforts (Campbell 1995), maintenance work management (Weber and Thomas 2006)). Interestingly, while the literature proposes common lists of KPIs, it lacks an agreed-upon methodological approach to select or derive 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 is chosen.

Based on the literature, the commonly used maintenance performance indicators 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 Fig. 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. Under maintenance process indicators and 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, maintenance costs and safety and environment indicators. Each category has its own performance indicators, as shown below.

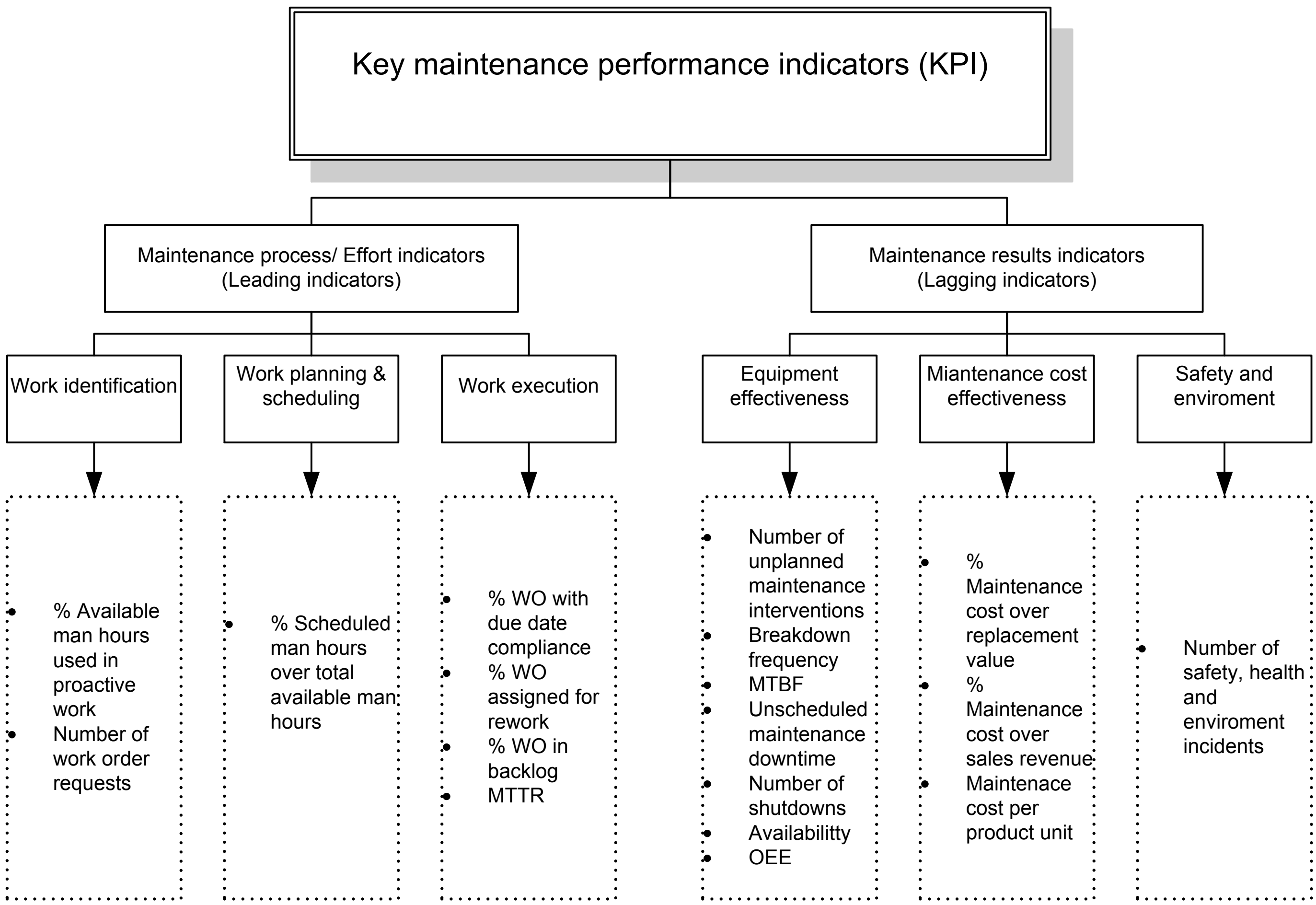

Fig. 1 Key maintenance performance indicators in the literature.

The survey objectives include investigating the extent to which these indicators are used in industries, establishing which are most frequently used, i.e. 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 put on performance measuring systems rather than on individual performance indicators. 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 the indicators and the manner of representation.

- Global PIs: In practice, maintenance performance is often judged on 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: yearly costs for materials, labor and subcontracting/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 cancellation of some effects (e.g. an increase in labor cost and a comparable decrease in materials cost will never be apparent in the indicator), making it difficult to know what exactly happened (did all costs increase, or only one, or some, etc.?).

- 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 maintenance stock, the following indicators are often used: inventory value, number of items in stock, turnover, number of new/obsolete items and number of in/out movements. This gives a more complete view of 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 balanced scorecard is a holistic approach which groups both financial and non-financial measures to measure performance (Kaplan and Norton, 1992, 1996a, 1996b). 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 balanced scorecard is part of the corporate strategy to measure performance and compare it with the corporate objectives. These balanced scorecards are applied to different divisions and departments, right down to the employee level.

Similarly, maintenance performance indicators can be translated from balanced scorecard perspectives and applied to the divisions, departments, sections and employee levels. The maintenance objectives are linked to critical success factors, key result areas, and key performance indicators. The critical success factors support the maintenance objectives. The key result areas are the success areas where the key factors can help achieve the maintenance objectives.

Daryl Mather (2005) has adapted the Maintenance Scorecard, MSC from the original balanced scorecard for asset-centric industries such as electricity generation and distribution, water treatment, oil and gas, mining, rail, and heavy manufacturing. Based on RCM2 by John Moubray and his interpretation of functional measurement and monitoring machine performance, as well as Kaplan and Norton’s traditional BSC approach, MSC identifies a need for strategic initiatives and determining how to best 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 strategy in the area of asset management. This will help identify strategic improvement initiatives and the areas they focus on, early in the process. The MSC is a methodology based in the measurement of performance, built around the use of management indicators, which can lead the development and implementation of a strategy.

A different approach to measuring need is given by Lehtinen and Wahlström [7]; they argue that measuring performance by means of scoreboards focuses on the process safety and 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.

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VI. The Hierarchy of Indicators

Indicators are commonly formulated at different levels as well. Each level serves certain purposes for specific users. 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 [2]).

According to Mitchell [5], a hierarchy of different parameters, all linked to business goals, is vital for the success of a program to manage corporate physical assets.

Many authors agree that multifaceted maintenance requires metrics, and those metrics should serve specific levels of the organization's hierarchies. TRADE [1] shows the levels of performance indicators in a typical organization, Fig. 2. Different organizations have different hierarchies of performance measurements.

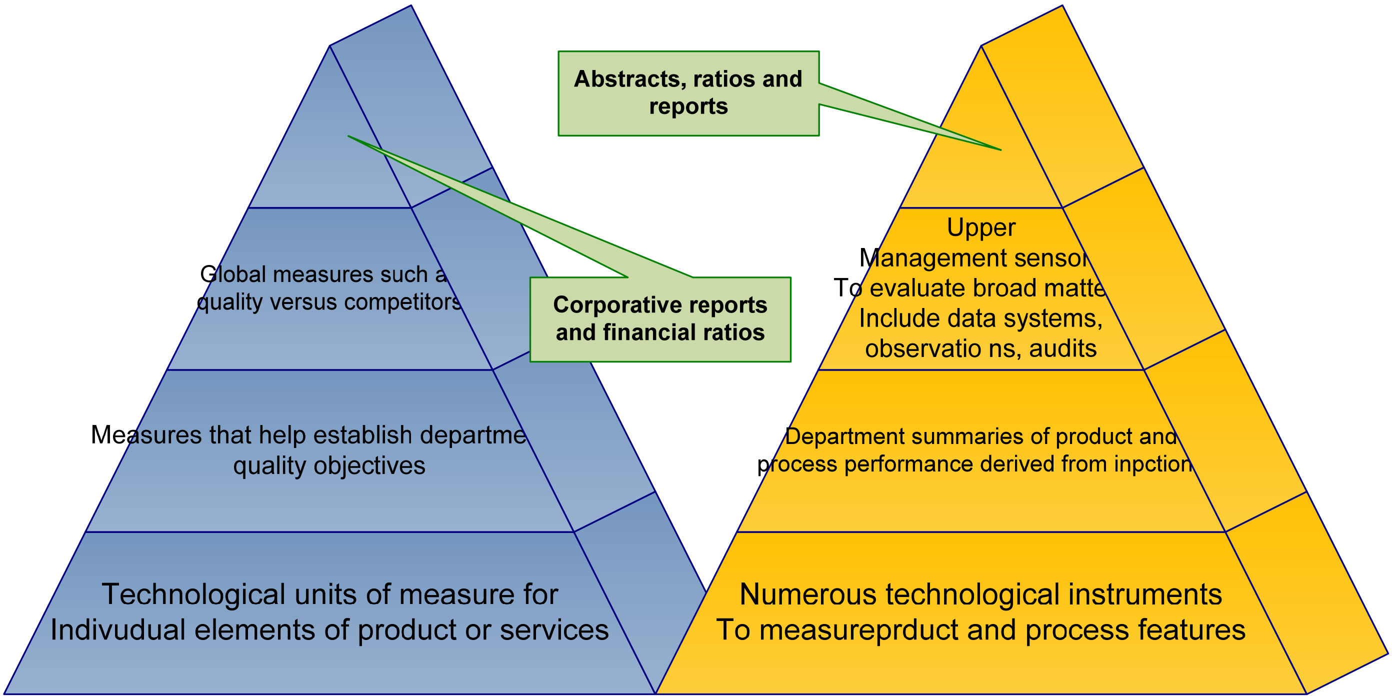

Fig. 2 Pyramid used in all levels of the company, TRADE [1]. Units of measures to the left and sensors to the right.

Grenčík and Legat [17], like TRADE [1], make analyze 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 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 [18] suggests using Key Performance Indicators (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 program for continuous improvement should be set up. For Kahn, a KPI is a traceable process metrics that allows decision making aimed at established business objectives; maintenance KPIs should include indicators of corporate level, such as the OEE, or financial, such as the overall maintenance budget compared to replacement cost, and so on. These financial indicators should be positive to ensure the organization's support for maintenance improvement projects. Like TRADE [1], Kahn proposes five levels of KPIs, each with its own requirements and target audience, thus consolidating the segmentation of indicators by levels of organization. The five levels include: Maintenance costs; Availability of equipment; OEE; Production costs; Performance.

Campbell (1995) classifies performance measures into three categories based on 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 include: equipment related performance measures; task related performance measures; cost related performance measures; immediate customer impact related performance; learning and growth related measures

Wireman [2] defines a set of indicators divided into groups: (a) corporate, (b) financial, (c) efficiency and effectiveness, (d) tactical (e) functional performance, see Fig. 3. The indicators should be properly connected to the levels of corporate vision and company mission.

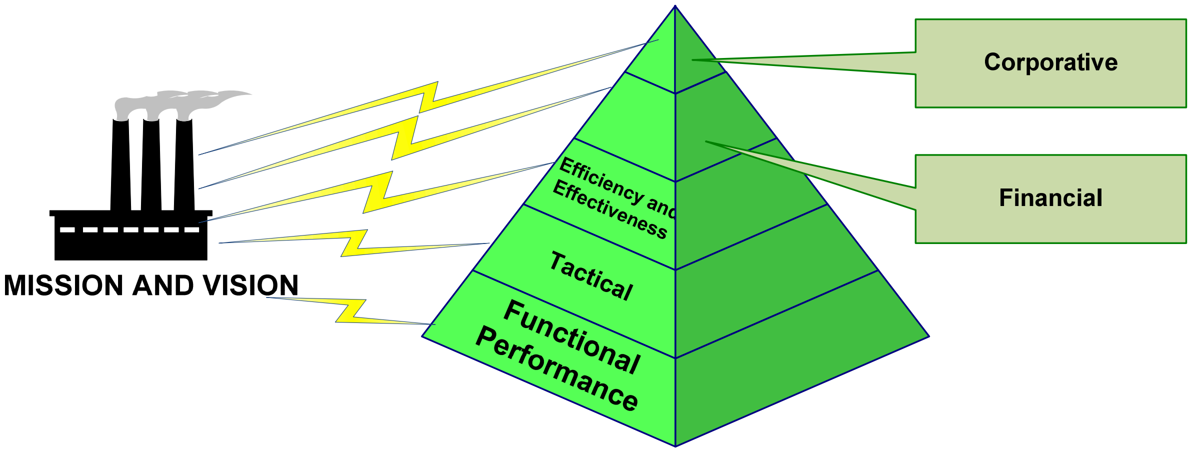

Fig. 3 Hierarchy of indicators in maintenance according to Wireman [2].

These concepts all suffer from a hierarchy that condemns low levels to work with operational and functional indicators, while assigning economic indicators to 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 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 non 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, the first layer could be at the corporate strategic level; the supporting level could be the financial PI; the third would be efficiency and effectiveness indicators, with fourth and fifth levels of tactical PIs and functional PIs respectively. The five levels of the pyramid (see Fig. 3) show the hierarchical relationship of the PIs. It should be noted that the indicators are always determined from top down, using corporate indicators measures; what is important to top management is to satisfy the needs of the stakeholders/shareholders.

Fig. 4 Developing Performance Measurement Indicators from Vision, Objectives and Strategy. Source (Parida, 2006).

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For Parida (2006), indicators in three levels 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 level, and the third to the functional/operational level. There could be more hierarchical levels depending on the organizational structure, [Parida A., 2006].

These corporate PIs will vary from company to company, depending on 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 processes in the organization. There must be a logical interconnection between 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, Caceres (12). Maintenance indicators will be segmented according to the organization's areas of influence, due to the interactions of the maintenance department with finance, human resources, purchasing and, of course, production to achieve corporate objectives. Simultaneously, these indicators correspond to different levels in the organizational structure, so they will be targeted to 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 maintenance parameters of availability, reliability, mean time to repair. In addition all perspectives within maintenance should be integrated to cover organizational and technological aspects, internal processes, customer and company perspectives and financial perspectives.

Bivona and Montemaggiore [13] agree with Cáceres [12] and argue 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 performance indicators oversee operational management from the unique perspective of the maintenance activity, ignoring the effects of maintenance policies on company performance and their impact on other departments. Some authors argue that the performance measurement system based on relations between different departments of 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 balanced scorecard approach to the formulation of maintenance strategies, not only as grouping of indicators but also as a hierarchy. The systemic perspective of the balanced scorecard, in fact, supports management in analyzing the various relationships between the subsystem 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 balanced scorecard method first developed by Kaplan and Norton (1992) later adapted by Tsang et al. (1999) for measuring maintenance performance is an effective way to measure maintenance performance. It designs the maintenance performance measure using the following four perspectives:

- Financial (the investor's view)
- Customers (the performance attributes valued by customers)
- Internal processes (the long-term and short-term means to achieve financial and customer objectives)
- 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 2002) and (Tsang et al. 1999).

Alsyouf (2006) criticizes the balanced scorecard 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. it ignores suppliers, employees and other stakeholders. The extended balanced scorecard presented by Alsyouf (2006) incorporates performance measures based on 7 perspectives: corporate business (financial), society, consumer, production, support functions, human resources and supplier perspectives, as shown in Fig. 5.

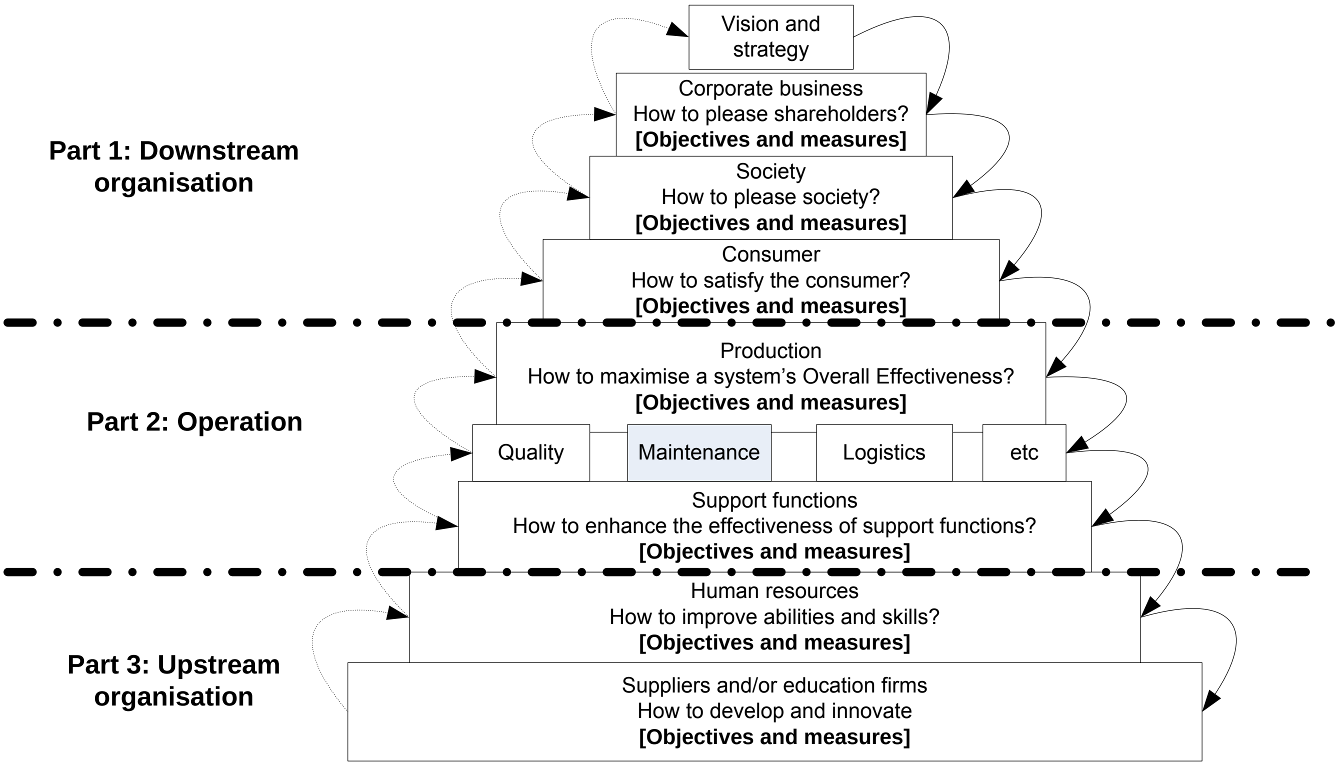

Fig. 5 Adopted from Alsyouf (2006).

In any planning and development activity, offers several alternatives, 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 having 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 mean time between failure, downtime, and 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 Fig. 4.

In our development of a MPM framework, we consider the basic four perspectives of Kaplan and Norton's balanced scorecard, along with the maintenance criteria. In addition, we consider health, safety, security and environment 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. 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 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.

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Involving all employees in this MPI development process is another challenge. So that everyone speaks the same language, the strategic goals need to be broken down into objective targets for operating maintenance managers, and this 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 strategic goals; moreover, the subjectivity increases as the objective outputs are integrated with KPIs at higher or strategic levels.

The three hierarchical levels appear in Fig. 6.

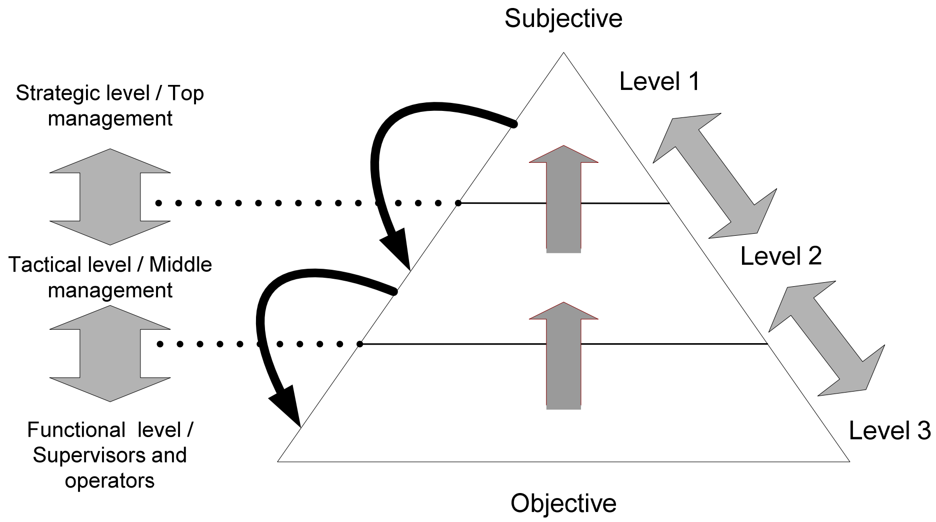

Fig. 6 Hierarchy levels of MPM model.

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, little literature covers the development of a systematic approach to PM in maintenance; even less embraces every level of maintenance. A possible exception is work by Kutucuoglu et al. (2001).

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

Tsang et al. (1999) says that a US survey of 200 companies in 1995 concluded that despite reasonably high level use, non-financial measures and targets are frequently treated in isolation from strategic objectives. They are not reviewed regularly, nor are they linked to short-term or action plans; rather, they are largely ignored or for interest only.

In another study, Tsang et al. (1999) looked at 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 hierarchy in the organization who uses 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, it does not take care of other customers and suppliers, such as design, finance, top management and issues including health, safety, security and environment (HSSE), employee, and corporate strategy.

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

Tsang (1998) and Ahlmann (2002) adapt the balanced scorecard 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; so

(2) Effective maintenance management needs to be based on quantitative business models that integrate maintenance with other decisions, such as production 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 maintenance and operation impact on equipment degradation and managing maintenance from a strategic perspective. This approach is not balanced and integrated, as it does not consider all stakeholders.

In a project for the Norwegian oil and gas industry, Ellingsen et al. (2002) suggest a PM framework based on a balanced scorecard 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 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.

The 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 such measures are the return on investment (ROI), return on assets (ROA), the maintenance cost per unit of product, the total maintenance costs in relation to manufacturing costs, etc.

Vergara [19] proposes the net present value (NPV) for use in maintenance as one of the financial indicators. NPV consists of knowing how much could be gained from an investment if all income and expenses could be made instantly. Therefore, 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) presents a better performance measurement technique first proposed by Dwight (1994) 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 [20] 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, return on assets, return on sales, the percentage change in total assets and the percentage change in

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the number of employees. These are generally accepted as indicators of financial results and facilitate comparison of results with other studies, e.g. Hendricks and Singhal [21]. The correlation of such indicators with tactical maintenance indicators links maintenance with corporate strategy.

Coelo and Brito [22] propose incorporating financial indicators into maintenance management. This hypothesis confirms the importance of a system for measuring enterprise performance based on indicators, with special emphasis on maintenance. Coelo and Brito [22] discuss the need for integration to achieve a harmonious balance of financial performance indicators and the strategic vision of maintenance efficiency.

Cáceres [12] argues that all planning systems should show the history of strategy and corporate positioning indicated in its financial goals, linking them to the sequence of actions to be undertaken with customers, internal processes and finally with the employees themselves. This perspective is focused on return on investment, added value to the organization and reduced unit costs. In maintenance, the costs of each activity the incidence rate of maintenance costs per unit of production and maintenance costs on the value of 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. But the quality of employees' work in the maintenance services cannot be measured directly. Knowing their experience, education, training and skills is essential to adequately measure the result of work done. 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). Measures include indirect/ direct labor, labor in reserve, training measures, and percentage of overtime.

To Cáceres [12], the introduction of KPIs to maintenance human resources 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 labor climate in the microclimate of maintenance, Rensen, (1995).

A measure related to human resources is the company's intellectual capital (IC). Fernandez and Salvador [23] discuss the importance of intellectual capital 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 balanced scorecard.

In the area of human resources in maintenance, special attention must be paid to the prevention of labor 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 [24]. The maintenance staff is 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 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 these processes are: work orders, inventory and purchasing, and management information.

For Cáceres [12] 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, indicators are usually set as repair times, overtime, certified processes, security aspects in the activities and the implementation of plans and programs. 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 performance indicators. The first objective of this set of indicators is to measure equipment (assets) performance, at least that equipment considered part of the maintenance function. Mitchell [5] says: '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 [25] proposes the overall indicator of functional safety as KPI for the customer; it is what he or she expects from the assets. For Cea, 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. [26], functional safety is 'the probability of the system to complete its mission, since the system was available at the beginning of the mission'. Functional safety is a measure of the system condition at one or more points during the mission; it is strongly influenced by the system reliability and maintainability and the quality of the project Bifulco et al. [27], Kostic and Arandjelovic [28]. Reliability is associated with the compliance function over time and system performance. Maintainability is associated with the ability of the equipment to recover function when it stops, Kumar [29], Castro and Lucchesi [30] Knezevic et al. [31].

Therefore, according to Blanchard, direct and indirect indices of functional safety are the availability, reliability, maintainability and safety of a production system. This system must have an information subsystem based on indicators of efficiency and feedback; it must be a valid tool operationally, whereby 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 [25], RAMS parameters are the basic components of the key indicator, i.e. functional safety. Söderholm [32] as well as Cea [25], refers to functional safety as the basis of the whole system of indicators for maintenance and to RAMS parameters as the primary indicators on which to build the entire scorecard.

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.

Killet [34] emphasizes the practice of maintenance performance indicators focused exclusively on operational aspects. Without underestimating these indicators, Killet 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 that 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. [35] 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 cost. The second category includes indirect indicators, derived from direct indicators, such as reliability and availability. For Martorell et al. [35] 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 [36] classifies maintenance indicators into three categories, thereby echoing most of the authors cited above. The categories are technical, economic and organizational indicators. The paper proposes more than seventy 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 refers to aspects of effectiveness (time-consuming task) and efficiency (cost and manpower involved). Effectiveness falls within the realm of technical indicators, while efficiency is financial and organizational. Organizational indices, due to the high importance of human factors in the maintenance function, play an independent role. However, some authors consider them attached to costs and part of efficiency.

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All authors see the RAMS parameters as raw materials for creating more complex indicators of effectiveness, thus providing the maintenance scorecard 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. If they are not presented and explained to users, they may be inappropriately used. Mitchell [5] 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 [37] 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 performance indicator, depending on the type of information needed and the type of user. Charts, graphs, figures or just numbers can deliver a performance indicator, Besterfield et al. [10].

Lehtinen and Wahlström [7] emphasize the visual aspect and simplicity of the indicators, because this will be a key in developing a subsequent metric. The indicator should stand out in reporting and promoting an atmosphere of reports with proper quantification and calibration of the problem. It is believed that this environment is an important part of continuous learning from which excellence is achieved. Lehtinen and Wahlström [7] 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 performance indicators is the frequency of their presentation. Some indicators require continuous data collection; others may have a monthly frequency. There is no advantage to measuring more frequently than needed, as it only increases costs, Kaydos [37].

Today, technology allows the use of an online graphical user interface (GUI) for presenting and monitoring indicators tailored to each person's personal 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 further increase information efficiency.

IX. Efficiency of Performance Measures

Metrics must be understandable, addressed to the needs of users and controllable by managers through work activities, Mitchell [5].

According to Kutucuoglu et al. (2001), to develop an efficient and effective system of performance measurement, it should be clear what indicators are to be measured, how to do it, the timing, and who should implement the measurement. In fact, for Manoochehri [38], 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. [10] to be useful, measurements should be simple, understandable, and few in numbers so that users can concentrate on those that are most important to them.

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

Killet [39] 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 [10]. 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 to extract this information. 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 labor risk prevention is ideal for monitoring injury rates, and the human resources staff is better situated to provide data on absenteeism. This supports Besterfield's thesis on ownership of data.

Shreve [41,] 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 analyze the effects of a CBM program in a factory.

The performance indicators can be used both in production and in maintenance to display the program 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 areas with the greatest impact on improving, ignoring those with a small ROI. Without constant reminders of performance, programs can start strong, but then rest on the initial achievements without ever reaching maturity. Proactive measurements should be the goal of the monitoring program. This level of maturity is based on the desire to find any problems affecting production rates and product quality before they appear. Shreve [41] and Woodhouse (2000) agree that the goal is to find 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 is 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 strong enough to accept the required data input and release the correct information to achieve a particular task.

It is clear that 'garbage in, garbage out' holds for any sequential-factored data system model. For the result of 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 data computed. The values must be checked for homogeneity in units, readings, computations, etc. The introduction 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 [37]. 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 up or down and to know how its current value compares to historical measures. If the way 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 [42] say 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 the problems. For Tavares, [43] 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 more records that are available, the greater the accuracy of the expectation values are. 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 (five years or more) is advisable.

C. Metrics understanding by users

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, analyze and interpret the end result of computations to discover 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.

In Manoochehri [38], 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.

The failure to use performance measurements in an organization may be the result of not overcoming the challenges associated with the implementation of a new set of performance indicators. It is, therefore, very important for the implementation team to concentrate on the project, especially at the beginning. If this is not done, it could result in 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 [2], 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 company size.

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Furthermore, to successfully implement a performance measurement system, 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 [5].

A challenge faced by most performance measurement systems is change. But this is part of the manufacturing business. A measurement system should not be affected by changes in production characteristics but it must be adapted to them. Moreover, indicators may become out of date, Kaydos [37].

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’ performance indicators; for example, the percentage of MRO-items (maintenance, repair and operation/overhaul items) that has not moved during the last two years should not be higher than three 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, aluminum, glass, plastics, ceramics, furniture, etc, and academic research groups frequently use such techniques. Pintelon and Van Puyvelde [44] point out that a survey typically includes maintenance cost as a percentage of 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 [44]).

Benchmarks must be developed to provide the measurement system with the highest possible meaning, and positive or negative variations of the indicators most have a clear sense for the operator. Benchmarks are 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 to compare units of the same plant for an improvement, or external, 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 [11]. Therefore, according Katsllometes, a metric that begins with World Class Manufacturing (WCM) is necessary.

New trends derived from World Class Manufacturing (WCM) or Lean Manufacturing ([3]) do not give the full answer either. It sounds challenging to aim for the World Class Maintenance (WCM, or World Class Reliability, WCR) level, but this level has not yet been defined properly by any source. In the majority of cases, qualitative statements are used like: a WCM organization delivers consistent uptime week–to-week, minimizes 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 this level and when it 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 % weekly schedule compliance instead of aiming for 100 %. Even a highly rewarded quantitative method like Six Sigma has not yielded breakthrough results in the maintenance arena, mainly because maintenance data cannot apply these kinds of statistical techniques.

Lean Maintenance is another popular maintenance management framework, developed 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. But 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 the business process reengineering (BPR) 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 maintenance performance measurements for World Class Manufacturing systems that lead to excellent performance in today's turbulent and competitive business environment. World Class Maintenance ensures almost 100% capacity, 100% of the time of the operation. The metric of World Class is elementary statistics. It 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 Medium Companies (SME) 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. It therefore looks to benchmarking among organizations with good practices and results.

Benchmarks to identify world-class maintenance management have been accepted ever since a landmark study conducted in the 1980s by A. T. Kearney Co. produced ‘a mountain of maintenance and operational data’. Many researchers have adapted benchmark data in programs designed to assess maintenance activities and assist organizations in their drive for excellence. According to Kearney, there is a high correlation between maintenance operational ‘style’ and overall plant performance. Facilities that ranked worst in overall efficiency tend to have a ‘reactive’ character, a ‘fix-and repair’ approach. At the other end of the spectrum, the world’s best manufacturers, those enjoying the highest productivity and output quality, invariably display maintenance that is well-planned, fully integrated, and proactive.

Superiority in maintenance is also characterized by a high level of preventive maintenance (PM) and planned maintenance as percentages of the total work. ‘In the best plants’, at least 80 percent of all 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.

According to Lemos [44], the indices should use standard equipment to perform the same operation

Kahn and Olver [45] see the need to compare indicators, both within companies and in similar factories or sectors. When a company wants to compare the performance and reliability of internal or external maintenance, it needs a common platform of predefined indicators to compare identical variables and means of 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). Recently, these two organizations have been working on a harmonized project, comparing the similarities and differences between existing indicators for maintenance and availability supported by both agencies. Comparisons have been made between the SMRP metrics and the European standardized indicators EN 15341 [46]. 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 (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 food and pharmaceutical industries.

It is important that the performance measures are meaningful in the benchmarks. 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. These can be in the form of maximum or minimum limits. In some cases, the target of an indicator will be zero or one, 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 in machinery 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. For example, it is particularly interesting to observe how Silter (2003) presents the Risk Asset Management Model (RIAM) which quantifies the performance indicators to support decision making at the plant, not only to implement investment options in the best possible way, but also to better prioritize the use of certain plant resources and maximize the safety of the process. With the RIAM approach, these performance indicators incorporate cost-averse thinking. 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 performance indicators 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 what they mean. Today, these benchmark points are included in the demands made on providers in the industry. Industrial sectors such as automotive, aeronautics and energy are used to requesting quality parameters from suppliers but now overall indicators of efficiency close to World Class Maintenance levels are required as well.

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The EN 15341 Maintenance Key Performance Indicators released in March 2007 were designed by the 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. The WG6 group looked at all 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, EN15341 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 calculation are not the same is a frustrating non-value-added activity. This challenge has been met by SMRP and EFNMS, Svantesson (2002) and Svantesson (2008). These two maintenance organizations conducted 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 standard EN 15341 or the SMRP metrics for the following reasons (EN 15341):

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

Since 2000, SMRP has defined 70 Best Practice Metrics to measure maintenance and reliability performance. In 2000, EFNMS defined a set of indicators to measure maintenance performance. These indicators are now incorporated in the European standard EN 15341 Maintenance Key Performance Indicators released in May 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 standards (Fig. 7).

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

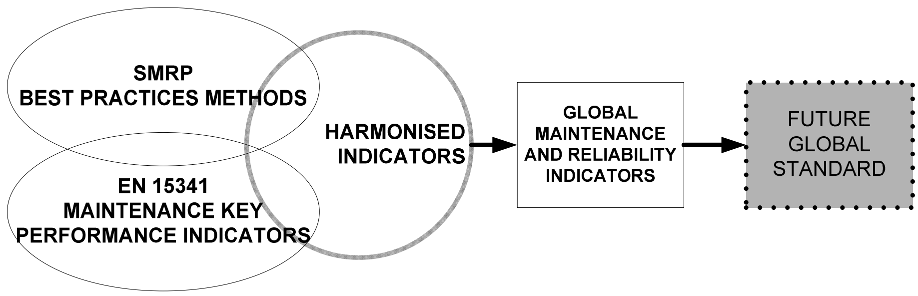

Fig. 7 The process of the harmonized Indicators Project.

D. Objective of the harmonized indicator document

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.

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

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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 is comprised of: 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 intended to resolve differences between the EN 15341 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 standard EN 13306:2001 Maintenance Terminology and the standard IEC 60050-191:1990 Dependability and Quality of Service. The SMRP definitions are contained within each indicator (metric) description, and have been compiled in a SMRP Glossary of Terms, SMRP Best Practices Committee (2007. This resulted in two extensive lists, as there were terms or formulas common to both sets.

An indicator is determined to be common if it has the same basic formula or could be universally applied. For these common indicators, it was first determined whether any differences could be eliminated without sacrificing the objective of the indicator. If differences cannot be eliminated, the differences are qualified or explained. This is the essence of the harmonization process, which is graphically depicted in Fig. 8. It should be noted that the grouping of 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 Best Practices Committee (2006).

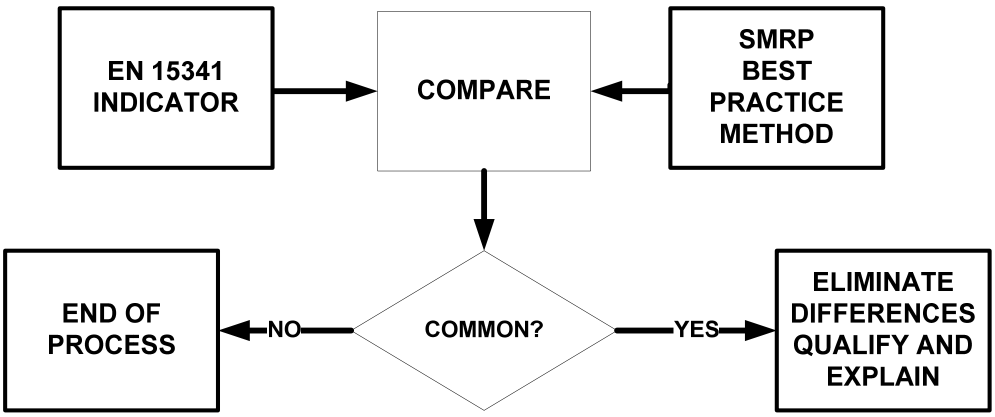

Fig. 8 The harmonization process. Source: Svantesson (2008)

The joint working group made good progress, announcing the first harmonization results in January 2007, and publishing the original edition of Global Maintenance and Reliability Indicators in April 2008, SMRP Best Practices Committee (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. Furthermore, the SMRP metric is recommended by EFNMS for use as a guideline to calculate the EN 15341 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 (Technical Committee on Maintenance of the Pan American Federation of Engineering Societies) or MESA (Maintenance Engineering Society of Australia). There are tentative plans to promulgate the use of these indicators as international standards. Discussions are ongoing with CEN/TC 319 to consider proposing the harmonized metrics as global standards or guidelines.

However, the goals of this harmonization process are far from the search for proper benchmarks values as thresholds or targets. The calculation of indicators is exhaustive, but the search for benchmark references is not. Thus, many maintenance managers read EN 15341 or SMRP Good Practices and extract valuable information, but they do not know the desired value of all parameters, either partially or fully applied to their respective fields. In world class maintenance, many figures have been

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proposed for many industries as a result of companies' experiences. Therefore, the success of WCM lays not only the proposal of common methods for parameter calculation, but in the establishment of real numbers as targets.

XI. Maintenance Audit

Converting forecasts into concrete real numeric values require 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 maintenance management is carrying out its mission, meeting its goals and objectives, following proper procedures and managing resources efficiently and effectively.

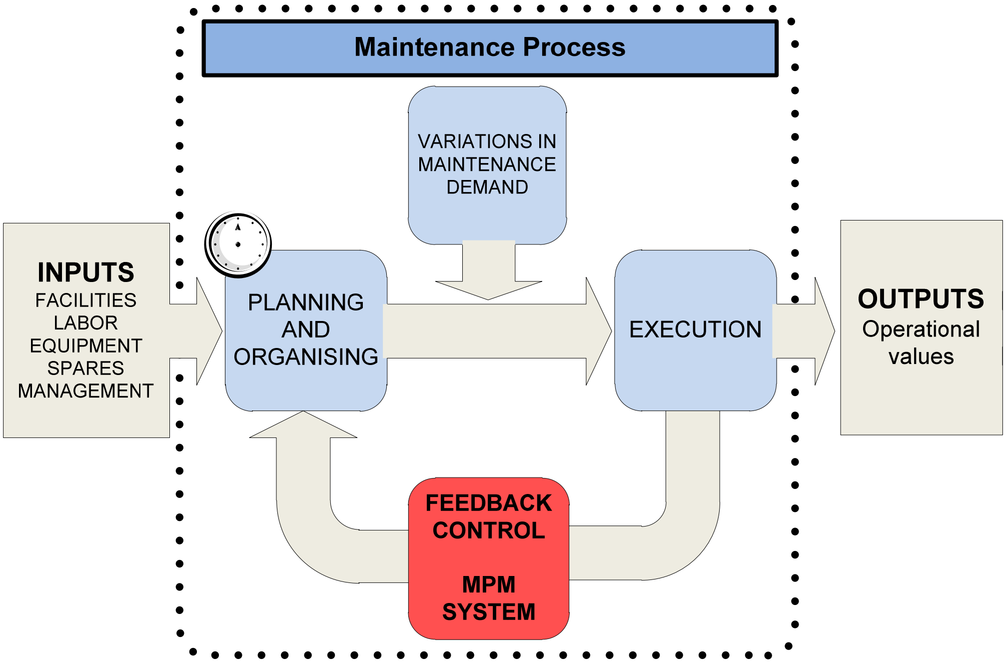

Fig. 9 Input-process-output model (IPO model) of the maintenance process.

This concentrates on the maintenance system itself, as opposed to quantifying its inputs and outputs (Fig. 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 utilizes general audits based on a common assumed standard designating what constitutes a good system. This is a popular tool for consultants since it allows them to have a consistent standard of 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 fact from one organization to another. This kind of 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 get unbiased findings, the reviewer should have no direct responsibility or accountability for the performance of the system under review. The audit is usually conducted by using a questionnaire designed to provide a profile of the maintenance system.

Typically, the questionnaire is structured to address specific key areas in the system to be audited. Responses to these questionnaires may take one of these forms:

- Either yes or no;
- Choose one or more of the available options; or
- On a Likert-type scale of, as an example, 1 to 5, to indicate different degrees of agreement or lack of it.

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, 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 the business success of the system elements that influence the relevant failures of assets. In this procedure, exhaustive failure attributes that contribute to business success have to be identified. 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, both in system design and execution. It is assumed that the standard can be universally applied to achieve superior performance. The maintenance system audit questionnaires by 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 in the specific operating environment. Sociotechnical Systems (STS) analysis provides a methodology to design 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 audit technique is initially concerned with the analysis of technology and business constraints. This allows the determination of the relative importance, and required attributes, of the various elements of a system. The actual system attributes can then be analyzed against the ideal system and tempered by the requirements for excellence in the particular activities making up the system. This second technique is pursued here. It tends to be qualitative in its methods, as it seeks to quantify the judgments of people with knowledge of the maintenance system, the organization's requirements and the system elements 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), DeGroote (1995), The Institute of Internal Auditors (1992), Mann, (1983) and Duffuaa and Raouf (1996), it helps management to achieve the following:

1. Ensure that 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 maintenance performance;
6. Increase the quality of the work;
7. Automate and recommend information systems to increase effectiveness and productivity;
8. Develop the culture of continuous improvement.

The audit process is usually done 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 of maintenance functions and control; reviewing relevant documentations; demonstrating systems applications; attending key meetings; obtaining answers to structured questionnaires; and validating plant, equipment and maintenance performance. The results of the interviews and the answers to the structured questionnaires are analyzed to formulate action plans for improvement.

Westerkamp (1987) has developed an audit scheme that covers fourteen factors contributing to maintenance productivity. He advocates automating the auditing process through: organization staffing and policy; management training; planner training; craft training; motivation; negotiation; management control; budget and cost; work order planning and scheduling; facilities, store, material and tool control; preventive maintenance and equipment history; engineering; work measurement; and data processing. He suggests obtaining information 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; 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.

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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; labor productivity; management training; planner training; craft training; motivation; management and budget control; work order planning and scheduling; facilities; supplies/stores, material and tool control; preventive maintenance and equipment history; engineering and condition monitoring; work measurement, incentives and information systems. They propose using the analytic hierarchy process (AHP) to determine factors' weight and to compute a maintenance audit index. They also suggest root cause analysis to develop an improvement action program.

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

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

Price Water House Coopers (1999) has developed a questionnaire to evaluate maintenance programs. 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 programs 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 programs for maintenance systems have been developed by Westerkamp (1987), Kaiser (1991), Duffuaa and Raouf (1996), Cooper (1999) and Al-Zahrani (2001). The audit programs 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 balanced scorecard technique, Tsang et al. (1999) presents a Systems Audit technique, based on socio-technical systems analysis (STS) for predicting the future maintenance performance and a DEA (Data Envelopment Analysis) technique, a non-parametric quantitative approach to benchmarking organizational maintenance performance in comparison with competitors. Using the four stage quality audit approach, Groote (1995) defines performance indicators in terms of ratios rather than absolute terms to develop a system for maintenance performance.

Many authors argue the necessity of obtaining both qualitative and quantitative results. Clarke [19] suggests an audit must contain maintenance radar (a spider Bells-Manson type of graphic) which imagines all the economic aspects, human etc. of maintenance. In his view, a product of the audit must be good operative and technical maintenance practices. Like many others, Tavares [20] makes use of radar maintenance 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 numeric data of the systems are not included in the radars; rather, they become subject to a strong human factor, Papazoglou and Aneziris (1999).

More recently Galar et al (2009) have 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 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 Quality function deployment (QFD) technique, using its ease of implementation, its alignment of performance indicators 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 maintenance performance measurement, i.e. a balanced view of a maintenance system, cross functional structure, vertical alignment of performance indicators etc. The introduction of performance indicators can:

- Clarify the strategic objective;
- Link maintenance department objectives to core business processes;
- Focus actions on critical success factors;
- Keep track of trends in development;
- Identify possible solutions to problems.

Varied industrial sectors have benefited from the introduction of indicators in their maintenance departments, Espinoza [53], in his work on the aluminum industry in England, says that in an effort to gain a competitive advantage over its main rivals, this industry is using a series of maintenance performance indicators through which its effectiveness can be monitored continuously (reliability, availability and use of equipment). Effective maintenance, according to the author, will vary the ratio from unplanned to planned activities. Espinoza says that increased scheduled jobs in this industry indicate that the maintenance strategy is effective. Other authors, like Racoceanu and Zerhouni [54] 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 [2], include the proper development, evolution and progression of the maintenance model. Wireman proposes a sequential implementation of steps to ensure all the functions necessary for the proper management of maintenance are in place: 1) preventive maintenance, 2) inventory and procurement, 3) the work order system, 4) CMMS system, 5) technical training and staff relationships, 6) staff involvement in operations, 7) predictive maintenance, 8) RCM, 9) TPM, 10) statistical optimization, and finally 11) continuous improvement. Wireman [2] considers that each of these activities is a section in the maintenance management process, as expressed in the pyramid shown in Fig. 10. Wireman [2] suggests that a preventive maintenance program should be implemented before moving to the next level of the pyramid – and so on, up the pyramid. Before considering the application of RCM, for example, predictive maintenance programs and involvement of staff in maintenance functions, appropriate work orders systems and management of maintenance resources are required. The involvement of operators and employees constitutes the next stage; TPM programs 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 who 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 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 Zaldivar [50] 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 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 cause 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. Zaldivar [50] says that with fewer managers, fewer administrative 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 Fig. 10.

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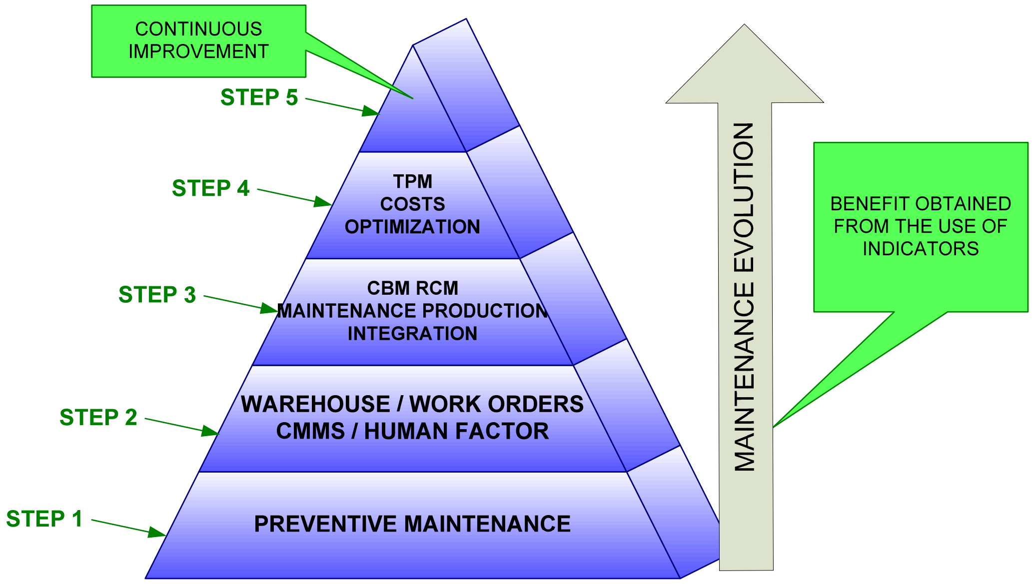

Fig. 10 Construction of the maintenance management process by Wireman [2].

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. The 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 [51]. Proper progression through the pyramid is essential (as in the sequential development pyramid of comprehensive maintenance program and the proposed hierarchy of KPIs).

In his investigation of the ability of a maintenance process to reach maturity by climbing the pyramid mentioned above, Schneidewind [52] 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 [52] 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 (LCC) 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 Internet, web-enabled wireless communication and technology. E-maintenance enables the companies with predictive intelligent/embedded sensors to monitor their assets through web-based wireless communication to prevent unexpected breakdown. This system can compare the performance of their product to others, using a global network system to focus on degradation monitoring and prognostics. Such information will greatly facilitate business decisions (Koc and Lee, 2004).

The main problem with performance measurement for decision-making is the non-availability of relevant data and information. However, the recent application of information and communication technology (ICT) and other emerging technologies facilitates easy and effective collection of data and information (Parida and Kumar, 2004). The two most important applications of the 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 machineries are monitored and managed by computer software, involving intelligent sensors, databases, wireless communication, Internet, online GUI etc. Levrat et al. 2008, Muller et al.2008, Thun 2008, Campos 2009, Cao et al. 2009,Emmanouilidis et al. 2009, Jantunen et al. 2010, Jeong et al. 2009, and Jun et al. 2009 have produced studies investigating the monitoring of manufacturing performance using wireless communication technologies and the impact on maintenance performance. Today, with the availability of unique e-maintenance solutions, the production and process industry can benefit from server-based software applications, the latest embedded Internet interface devices and state-of-the-art data security. E-maintenance creates a virtual knowledge centre by linking users, technicians/experts and manufacturers. It is useful for the process industry, as it can help to reduce overall costs, ensure savings in resources through OEE and yield a better return on maintenance investment (ROMI).

Some existing e-maintenance solutions provide server based software and equipment embedded internet interface devices (health management card). These e-maintenance solutions provide 24/7 (24 hours a day, 7 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 deal with the development and implementation of an effective MPM system that can create value for organizations. The issues considered include: 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 to 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.

The previous section 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;
- 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. 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 production, logistics, customers, employees and organizational goals.

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

A framework using the extended balance scorecard is more complete: it provides both qualitative and quantitative impacts of maintenance strategies; it can control different hierarchies of the organization; and it strives for both internal and external effectiveness. Similarly the multi-criteria multi-hierarchical framework for MPM is effective and efficient for MPM, as it incorporates the total maintenance effectiveness concept, as well as the characterization presented by Alsyouf (2006) and Kutucuoglu et al. (2001). In addition, it gives a causal relationship between performance indicators at different organizational levels and the 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 balance scorecard and multi-criteria 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.

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With respect to the first objective of this research, in the review of the literature, we identified a number of different techniques for formulating performance indicators to measure maintenance performance. However, as discussed previously, these MPM techniques can only help to determine the right set of performance indicators and are independent of the maintenance strategy. Therefore, we could not arrive at the optimal technique for evaluating condition based maintenance, remote-maintenance, RCM or 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 also showed what value is created when different frameworks are used. Through case studies, the literature demonstrated how and what value is created by using these MPM frameworks for organizations with condition based, vibration based and reliability centered maintenance. However, it failed to identify how and what value is created when these frameworks are employed by an organization through 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 like condition based maintenance, remote maintenance and e-maintenance.
- Comparing the effectiveness of different maintenance strategies (like CBM, remote maintenance and e-maintenance), using a particular framework, such as an extended balanced scorecard (Alsyouf, 2006) or a multi-criteria multi-hierarchy (Parida 2007)
- Combining a multi-hierarchical multi-criteria framework with an extended balanced scorecard framework, in order to consolidate their features in a single framework.
- Using the multi-criteria multi-hierarchical framework to evaluate the effectiveness of e-maintenance.

REFERENCES

[1] Muller, A., Crespo-Marquez, A., and Iung, B., 2008. On the concept of e-maintenance: review and current research. Reliability Engineering and System Safety, 93 (8), 1165–1187.
[2] Thun, J.-H., 2008. Supporting total productive maintenance by mobile devices. Production Planning and Control: The Management of Operations, 19 (4), 430–434
[3] Campos, J., 2009. Development in the application of ICT in condition monitoring and maintenance. Computers in Industry, 60, 1–20.
[4] Cao, H., et al., 2009. RFID in product lifecycle management: a case in automotive industry. International Journal of Computer Integrated Manufacturing, 22 (7), 616–637.
[5] Emmanouilidis, C., Liyanage, J.P., and Jantunen, E., 2009. Mobile solutions for engineering asset and maintenance management. Journal of Quality in Maintenance Engineering, 15 (1), 92–105
[6] Jantunen, E., Gilabert, E., Emmanouilidis, C., and Adgar, A., 2010. E-maintenance, a means to high overall efficiency. Engineering Asset Lifecycle Management, 20, 688–696.
[7] Jeong, S., Min-Hur, S., and Suh, S.H., 2009. A conceptual framework for computer-aided ubiquitous system engineering: architecture and prototype. International Journal of Computer Integrated Manufacturing, 22 (7), 671–685.
[8] Jun, H.B., et al., 2009. A framework for RFID applications in product lifecycle management. International Journal of Computer Integrated Manufacturing, 22 (7), 2009.
[9] Aditya Parida, Gopi Chattopadhyay, (2007) Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM), Journal of Quality in Maintenance Engineering, Vol. 13 Iss: 3, pp.241 – 258
[10] Aditya Parida, Uday Kumar ,(2009),Handbook of Maintenance Management and Engineering, Part I, 17-41,
[11] Aditya Parida, Uday Kumar, (2006) Maintenance performance measurement (MPM): issues and challenges, Journal of Quality in Maintenance Engineering, Vol. 12 Iss: 3, pp.239 – 251
[12] Ahlmann H (2002). From traditional practice to the new understanding: the significance of life cycle profit concept in the management of industrial enterprises, Proceedings of the International Foundation for Research in Maintenance, Maintenance Management and Modelling, 6–7 May, Växjö, Sweden.
[13] Albert H.C. Tsang, (2002) Strategic dimensions of maintenance management, Journal of Quality in Maintenance Engineering, Vol. 8 Iss: 1, pp.7 - 39
[14] Albert H.C. Tsang, Andrew K.S. Jardine, Harvey Kolodny, (1999) Measuring maintenance performance: a holistic approach, International Journal of Operations and Production Management, Vol. 19 Iss: 7, pp.691 – 715
[15] Al-Zahrani, A. (2001) Assessment of Factors Affecting Building Maintenance Management Auditing in Saudi Arabia. King Fahd University of Petroleum and Minerals, Saudi Arabia.
[16] APQC (1996), Corporate Performance Measurement Benchmarking Study Report, American Productivity and Quality Centre, Houston, TX.
[17] Armitage, W. and Jardine, A.K.S. (1968), ``Maintenance performance ± a decision problem'', International Journal of Production Research, Vol. 7 No. 1, pp. 15-22.

[18] Arts, R., Knapp, G. and Mann, L. (1998). *Some aspects of measuring maintenance performance in the process industry*. Journal of Quality in Maintenance Engineering, 4, No. 1, pp 6-11. 1998

[19] Atkinson, A.A., Waterhouse, J.H. and Wells, R.B. (1997), ``A stakeholder approach to strategic performance measurement'', Sloan Management Review, Vol. 38 No. 3, pp. 25-37.

[20] B Al-Najjar (2007) The lack of maintenance and not maintenance which costs: A model to describe and quantify the impact of vibration-based maintenance on company's business, International Journal of Production Economics, Volume 107, Issue 1, May 2007, Pages 260-273

[21] Barringer, P. and Weber, D. (1995). *Where Is My Data For Making Reliability Improvements?.* Fourth International Conference on Process Plant Reliability. November 14-17, 1995. Houston, Texas

[22] Besterfield, D., Besterfield-Michna, C., Besterfield, G. and Besterfield-Sacre, M. (2002). *Total quality management*. Third edition. Prentice-Hall International, Inc.

[23] Bifulco G., Capozzi S., Fortuna S., Mormile T. and Testa A. (2004). *Distributing the train traction power over cars: effects on dependability analyzed based on daily duty-cycle*. COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering Vol. 23 No. 1. 2004

[24] Bivona, E. and Montemaggiore, G. (2005). *Evaluating Fleet and Maintenance Management Strategies through System Dynamics Model in a City Bus Company*. International System Dynamics Conference - July 17 - 21, 2005 Boston.

[25] Blanchard B., Verma D. and Peterson E. (1995). *Maintainability: A Key to Effective Service ability and Maintenance Management.* Ed Wiley and Sons

[26] BSI, 1984.Glossary of maintenance terms in Terotechnology. British Standard Institution (BSI), London; BS3811.

[27] Cáceres, B. (2004). *Cómo Incrementar la Competitividad del Negocio mediante Estrategias para Gerenciar el Mantenimiento*. VI Congreso Panamericano de ingeniería de Mantenimiento. México, D.F.

[28] Cameron, K.S. (1986), ``A study of organizational effectiveness and its predictors'', Management Science, Vol. 32 No. 1, pp. 87-112.

[29] Campbell, J. D., (1995) Uptime Strategies for Excellence in Maintenance Management, Productivity Press, Portland, OR, U.S.A.

[30] Case, J. (1998). Using Measurement to Boost Your Unit's Performance. Harvard Management Update, Vol. 3, pp. 1-4.

[31] Castro, H. F. and Lucchesi, C. K. (2003). *Availability optimization with genetic algorithm*. International Journal of Quality Reliability Management Vol. 20 No. 7.

[32] Cea, R. (2002). *Programa Computacional de Apoyo al Análisis de la Seguridad de Funcionamiento en Equipos*

[33] Charnes, A., Clark, C.T., Cooper, W.W. and Golany, B.A. (1985), ``A developmental study of data envelopment analysis in measuring efficiency of maintenance units in the US Air Forces'', Annals of Operations Research, Vol. 2 No. 1, pp. 95-112.

[34] Clarke, P. (2002). Physical Asset Management Strategy Development and Implementation, Proceedings, ICOMS, 2002.

[35] Coelo, C. and Brito, G. (2007). *Proposta de modelo para controle de custos de manutençã com enfoque na aplicação de indicadores balanceados*. Boletim Técnico Organização and Estratégia 3 (2) 137-157.

[36] Coetzee, J.L. (1997), ``Towards a general maintenance model'', Martin, H.H. (Ed.), Proceedings of IFRIM '97, Hong Kong, paper 12, pp. 1-9.

[37] Coetzee, J.L. (1998), Maintenance, Maintenance Publishers, Republic of South Africa.

[38] Cross, M. (1988), ``Raising the value of maintenance in the corporate environment'', Management Research News, Vol. 11 No. 3, pp. 8-11.

[39] De Jong, E. (1997), Maintenance Practices in Small to Medium Sized Manufacturing Enterprises (SMEs), National Key Centre for Advanced Materials Technology, Monash University, Australia.

[40] De Lemos, L. (2003). *Metodología general para auditar programas de mantenimiento*. III congreso bolivariano de Ingeniería Mecánica. Lima, Perú.

[41] P. De Groote, (1995) Maintenance performance analysis: a practical approach, Journal of Quality in Maintenance Engineering, Vol. 1 Iss: 2, pp.4 – 24

[42] Dekker, R. (1996), ``Applications of maintenance optimization models: a review and analysis'', Reliability Engineering and System Safety, Vol. 51, pp. 229-40.

[43] Dixon, J.R., Nanni, A.J. Jr and Vollmann, T.E. (1990), The New Performance Challenge: Measuring Operations for World-Class Competition, Business One Irwin, Homewood, IL.

[44] Duffuaa, S. O., Raouf, A and Campbell,J. D. (1998), Planning and Control of Maintenance Systems : Modeling and Analysis,

[45] Duffuaa, S.O. and Ben-Daya, M. (1995). Improving Maintenance Quality Using SPC Tools. Journal of Quality in Maintenance Engineering, Vol. 1 no.2, pp. 25-33.

[46] Duffuaa, S.O. and Raauf, A. (1996). Continuous Maintenance Productivity Improvement Using Structured Audit. Internal Journal of Industrial Engineering 3(3), pp.151-166.

[47] Dwight, R.A. (1994), ``Performance indices: do they help with decision-making?'', Proceedings of ICOMS-94, Sydney, Paper 12, pp. 1-9.

[48] Dwight, R. (1999). Searching for real maintenance performance measures. Journal of Quality in Maintenance Engineering, Vol: 5 Issue: 3 pp 258 – 275

[49] Dwight, R.A. (1995), ``Concepts for measuring maintenance performance'', New Developments in Maintenance, Moret Ernst and Young Management Consultants, Netherlands, pp. 109-25.

[50] Eccles, R.G. (1995), ``The performance measurement manifesto'', in Holloway, J., Lewis, J. and Mallory, G. (Eds), Performance Measurement and Evaluation, Sage Publications, London, pp. 5-14.

[51] EEA (European Environment Agency). (1999). Enviromental indicators: Typology and overview. Technical Report No 25, Copenhagen.

[52] EN 13306, Maintenance Terminology, 2001

[53] EN 15341 (2007). *Maintenance Key Performance Indicators*.

[54] Espinoza, M. (2005). *Strategy to maximize maintenance operation*. Faculty of Business Administration. Simon Fraser University

[55] Fernández, F. and Salvador, R. (2005). *Medición y gestión del Capital Intelectual: aplicación del modelo Intelec al mantenimiento técnico.* IX Congreso de Ingeniería de Organización Gijón.

[56] GALAR-PASCUAL D, BERGES-MURO L, ROYO-SANCHEZ J. THE ISSUE OF PERFORMANCE MEASUREMENT IN THE MAINTENANCE FUNCTION DYNA Ingeniería e Industria. Junio 2010. Vol. 85-5 p.429-438

[57] Gelders, L., Mannaerts, P. and Maes, J. (1994), ``Manufacturing strategy, performance indicators and improvement programmes'', International Journal of production Research, Vol. 32 No. 4, pp. 797-805.

[58] Geraerds, W.M.J. (1990), ``The EUT-maintenance: model'', in Martin, H.H. (Ed.), New Developments in Maintenance, Moret Ernst and Young Management Consultants, Netherlands, pp. 1-15.

[59] González, F. J. (2005). *Proceso metodológico para reorganizar los Departamentos de Mantenimiento integrando nuevas técnicas*. Mantenimiento: ingeniería industrial y de edificios, Nº. 181, 2005, págs. 21-28

[60] Grenčík, J. and Legat, V. (2007). Maintenance audit and benchmarking - search for evaluation criteria on global scale. Eksploatacja i niezawodność. Nr. 3 (35) pp. 34 – 39. PNTTE, Warszawa.

[61] Hammer, M. and Champy, J. (1993), Reengineering the Corporation, Harper Business, New York, NY.

[62] Hansson, J. (2003). *Doctoral Thesis Total Quality Management - Aspects of Implementation and Performance*

ISBN 978-91-7439-379-8

[63] Hendricks, K. and Singhal, V. (1997). *Does implementing an effective TQM program actually improve operating*
[64] Hernández, E. (2000). *Sistema de Cálculo de Indicadores para el mantenimiento*. III Congreso cubano de Ingeniería y Reingeniería de Mantenimiento. http://www.columbia)
[65] Huang, S. and Dismukes, J.P., 2003. Manufacturing productivity improvement using effectiveness metrics and simulation analysis. International Journal of Production Research, 41 (3), 513–527.
[66] IEC 60050-191, International Electrotechnical Vocabulary, Chapter 191: Dependability and Quality of Service, 1990
[67] Alsyouf, I. (2006) Measuring maintenance performance using a balanced scorecard approach, Journal of Quality in Maintenance Engineering, Vol. 12 Iss: 2, pp.133 – 149
[68] Liyanage, J.P., Uday Kumar, (2003) Towards a value-based view on operations and maintenance performance management, Journal of Quality in Maintenance Engineering, Vol. 9 Iss: 4, pp.333 – 350
[69] Johnson, H. T and Kaplan, R. S (1987), Relevance Lost – The Rise and Fall of Management Accounting, Harvard Business School Press, Boston, MA.
[70] K.Y. Kutucuoglu, J. Hamali, Z. Irani, J.M. Sharp, (2001) A framework for managing maintenance using performance measurement systems, International Journal of Operations and Production Management, Vol. 21 Iss: 1/2, pp.173 – 195
[71] Kahn, J. and Olver, R. (2008). *EFNMS-SMRP Maintenance and Reliability indicator harmonization project*. TSMC Production and Maintenance Consultants
[72] Kahn, J. (2006). Applying Six Sigma to Plant Maintenance Improvement Programs. JK Consulting Fayetteville, Georgia: USA
[73] Kahn, Jerry and Gulati, Ramesh: SMRP Maintenance and Reliability Metrics Project, EuroMaintenance 2006,
[74] Kaiser, H. H., (1991), Maintenance Management Audit. Construction Consultants and Publishers.
[75] Kans M., Ingwald A., (2008), Common database for cost-effective improvement of maintenance performance ,International Journal of Production Economics, 113 (2), pp. 734-747.
[76] Kaplan, R, and Norton, D, (1996). *The Balanced Scorecard: Translating Strategy Into Action*. Harvard Business School Press. Boston, MA
[77] Kaplan, R.S. and Norton, D.P. (1992), ``The Balanced Scorecard ± measures that drive performance'', Harvard Business Review, Vol. 70 No. 1, pp. 71-9.
[78] Kaplan, R.S. and Norton, D.P. (1996a), ``Using the Balanced Scorecard as a strategic management system'', Harvard Business Review, Vol. 74 No. 1, pp. 75-85.
[79] Kaplan, R.S. and Norton, D.P. (1996b), The Balanced Scorecard, Harvard Business School Press, Boston, MA.
[80] Katsllometes, J. (2004). *How Good Is My Maintenance Program?.* Plant Operators Forum 2004: Denver, Colorado
[81] Kaydos, W. (1991). *Measuring, managing and maximizing performance*. First edition. Productivity Press, Inc. Portland
[82] Kearney Company, A T. The Seven Best of the Best Maintenance in North America. Chicago, Illinois, 1988
[83] Kelly, A., (1989), Maintenance and its Management, Conference Communications, Monks Hill, Surry.
[84] Kelly, A. ; Harris, M. J., (1998), Gestión del mantenimiento industrial Ed. Fundación REPSOL. Madrid
[85] Killet, G. (2001). Measuring Maintenance Performance:A Structured Approach. Elmina Associates Ltd
[86] Knezevic, J., Papic, L. and Vasic, B. (1997). *Sources of fuzziness in vehicle maintenance management*. Journal of Knoxville, Tennessee, USA 2007.
[87] Koc and Lee, 2004
[88] Kostic, S.B. and Arandjelovic, V.D. (1995). *Dependability, a key factor to the quality of products*. International
[89] Kumar, U.D. (1997). Analysis of fault tolerant systems operating under different stress levels during a mission. International Journal of Quality and Reliability Management. Vol. 14 Nº9
[90] Kumar, U. and Ellingsen, H. P. (2000) Design and development of maintenance performance indicators for the Norwegian oil and gas industry In proceedings of The 15th European Maintenance Congress: Euromaintenance 2000, The Swedish Maintenance Society (UTEK) and The European Federation of National Maintenance Societies (EFNMS), Gothenburg, Sweden, March, pp. 224-228.
[91] Lehtinen, E. and Wahlström, B. (1996). *Management of Safety through Performance Indicators for Operational Maintenance.* IAEA Specialist Meeting on Methodology for Nuclear Power Plant Performance and Statistical Analysis. Vienna, Austria.
[92] Levitt, J. (1997). *The handbook of maintenance management*. First edition. Industrial Press, Inc. NY.
[93] Levrat, E., Iung, B., Crespo Marquez, A.,(2008) , E-maintenance: review and conceptual framework, Production Planning and Control, Volume 19, Number 4, pp. 408-429(22)
[94] Pintelon, L., Frank Van Puyvelde, (1997) Maintenance performance reporting systems: some experiences, Journal of Quality in Maintenance Engineering, Vol. 3 Iss: 1, pp.4 – 15
[95] Mann, L. Jr. (1983), Maintenance Management. P.C. Heath and Company Publishers.
[96] Manoochehri, G. (1999). *Overcoming obstacles to developing effective performance measures*. Work Study, 48, Number 6, pp 223-229. http://www.emerald-library.com.
[97] Manuele, F.A. (2005). *Serious injury prevention*. Occupational Health and Safety; 74, 6; ABI/INFORM Global,
[98] Martorell, S., Sanchez, A., Muñoz, A., Pitarcha, J.L., Serradella, V. and Roldan, J. (1999). *The use of maintenance indicators to evaluate the effects of maintenance programs on NPP performance and safety*. Reliability Engineering and System Safety, Vol: 65, Issue: 2, pp 85-94.
[99] Maskell, B.H. (1991), Performance Measurement for World Class Manufacturing, Productivity Press, Portland, OR.
[100] Mata, D. and Aller J (2008). Análisis Probabilístico del Mantenimiento Predictivo y Correctivo de Máquinas Eléctricas.Rotativas en una Planta Siderúrgica. Revista Universidad, Ciencia y Tecnología de la Universidad Nacional Experimental Politécnica Antonio José de Sucre
[101] Mather, D. (2005). *The Maintenance Scorecard: Creating Strategic Advantage*. Industrial Press. New York
[102] MESA, 1995. Maintenance Engineering Society of Australia. Capability Assurance: A Generic Model of Maintenance.Maintenance Engineering Society of Australia (MESA), Australia.
[103] Mitchell, J.S. and Contributors. (2002). *Physical asset management handbook*. 3rd Edition. Gulf Publishing Company
[104] MOUBRAY John, Reliability Centred Maintenance RCM II, Butterworth-HeinnemannLtd., Oxford, 1991
[105] Muchiri, P.N., Pintelon, L., 2008. Performance measurement using overall equipment effectiveness (OEE): Literature review and practical application. International Journal of Production Research 46(13), 3517–3535.
[106] Murthy DNP, Atrens A, and Eccleston JA (2002) Strategic maintenance management. J of Qual in Maint Eng 8(4): 287–305.
[107] V. D. Noghin. Decision Making in Multicriteria Environment: a Quantitative Approach. Moscow: FIZMATLIT, 2nd edition, 2005 [in Russian] ISBN 5-9221-0274-5
[108] Nakajima, S., 1988 Introduction to TPM: Total Productive Maintenance. Productivity Press, Inc., 1988, pp. 129, 1988
[109] Papazoglou, I.A. and Aneziris O. (1999). On the quantification of the effects of organizational and management factors in chemical installations. Reliability Engineering and System Safety. Volume 63, Issue 1, January 1999, Pages 33-45
[110] Parida, A., Åhrén, T. and Kumar, U. (2003), Integrating maintenance performance with corporate balanced scorecard, COMADEM 2003, Proceedings of the 16th International Congress, Växjö , Sweden, 27-29 August, pp. 53-9.

[111] Parida, A; Phanse, K and Kumar, U (2004), An integrated approach to design and development of e-maintenance system. VETOMAC-3 and ACSIM-2004, New-Delhi, Dec 6-9, pp. 1141-1147.
[112] Pintelon, L., VanPuyvelde, F., (2006). Maintenance Decision Making. Leuven, Belgium, Acco.
[113] Muchiri, P. N., Pintelon, L., Martin, H., and Meyer, A. M. (2010). Empirical analysis of maintenance performance measurement in Belgian industries. International Journal of Production Research, 48(20), 5905-5924.
[114] Price Water House Coopers, (1999), Questionnaire of auditing, Toronto, Ontario Canada.
Productivos. Universidad de Talca. Facultad de Ingeniería. Escuela de Ingeniería E. Mecánica. Talca: Chile
[115] Raouf, A. (1994). Improving Capital Productivity through Maintenance, International Journal of Operations and Production Management, 14(7), 44-52.
[116] Raouf and M. Ben-Daya (1995). Total Maintenance Management : a systematic approach. Journal of Quality in Maintenance Engineering, Vol. 1, No.1, pp. 6-14.
[117] Racoceanu, D. and Zerhouni, N. (2002). *Modular Modelling and Analysis of a Distributed Production System with Distant Specialised Maintenance*. Proceedings of the 2002 international conference robotic and automation.
[118] Ray and Sahu 1990
[119] Rensen, E.J.K. (1995), ``Maintenance audits, a conceptual framework'', in Martin, H.H. (Ed.), New Developments in Maintenance, Moret Ernst and Young Management Consultants, Netherlands, pp. 83-94.
[120] Riis, J.O., Luxhøj, J.T. and Thorsteinsson, U. (1997), ``A situational maintenance model'', International Journal of Quality and Reliability Management, Vol. 14 No. 4, pp. 349-66.
[121] Sharp, J.M., Irani, Z., Wyant, T. and Firth, N. (1997), ``TQM in maintenance to improve manufacturing performance'', Proceedings of PICMET Conference, Portland, OH.
[122] Schneidewind, N. (1999). Measuring *and Evaluating Maintenance Process Using Reliability, Risk, and Test Metrics*. IEEE Transactions on Software Engineering, Vol. 25, No. 6, pp. 768-781.
[123] Shreve, D. W. (2003). *Integrated Condition Monitoring Technologies*. IRD Balancing LLC: USA
[124] Silter, G. (2003). *Life Cycle Management in the US Nuclear Power Industry*. Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17) Prague, Czech Republic.
[125] SMRP Best Practices Committee: SMRP Best Practice Metrics Glossary, Society for Maintenance and Reliability Professionals, McLean, Virginia, USA, 2006.October 2007
[126] SMRP Certifying Organization: Reference Guide for Certification in Maintenance and Reliability Management, 3rd Edition, Society for Maintenance and Reliability Professionals, McLean, Virginia, USA, 2006.
[127] SMRP Press Release: Global Indicators for Maintenance and Availability Performance, Society for Maintenance and Reliability Professionals, McLean, Virginia, USA, January 31, 2007. Published 2008
[128] Söderholm, P. (2005). *Doctoral Thesis. Maintenance and Continuous Improvement of Complex Systems Linking Stakeholder Requirements to the Use of Built-in Test Systems*. Department of Business Administration and Social Science. Luleå University of Technology
[129] Stephan, A. (1996), Measuring TPM performance, ICOMS Conference, Melbourne, May.
[130] Svantesson, T. (2008). *Benchmarking in Europe*. EFMS Workshops 2004-2005.
[131] Svantesson, Tom and Olver, Richard: SMRP-EFNMS Benchmarking Workshop, Euromaintenance 2008, Brussels, Belgium, 2008,
[132] Svantesson, Tom: Nordic Benchmarking Analysis and EFNMS Key Figures, Euromaintenance 2002, Helsinki,
[133] Swanson L. (2001), Linking maintenance strategies to performance, International Journal of Production Economics, 70 (3), pp. 237-244.
[134] Tavares, L. (2002). *Administración Moderna del Mantenimiento*. Datastream. 2002. http://www.datastream.net/latinamerica/libro/lourival.asp (libro digital)
[135] Taylor, J.C. and Felten, D.F. (1993), Performance By Design: Sociotechnical Systems in North America, Prentice Hall, Englewood Cliffs, NJ.
[136] The IIA's International Advanced Technology Committee (1994). Audit, Control and Security of Paperless Systems. The Institute of Internal Auditors Research Foundation, Orlando, Florida, USA.
[137] The Institute of Internal Auditors, (1992). A Common Body of Knowledge for Practice of Internal Auditing.
[138] Training Resources And Data Exchange TRADE and Performance-Based Management Special Interest Group.(1995) *. How to measure performance: a handbook of techniques and tools*. Prepared for the Special Project Group, Assistant Secretary for Defense Programs and the US Department of Energy.
[139] Tsang, A.H.C. (1998), ``A strategic approach to managing maintenance performance'', Journal of Quality in Maintenance Engineering, Vol. 4 No. 2, pp. 87-94.
[140] Vergara, E. (2007). Análisis de confiabilidad, disponibilidad y mantenibilidad del sistema de crudo diluido de petrozuata. Universidad Simón Bolívar Decanato de Estudios de Postgrado.
[141] Visser, J.K., Pretorious, M.W., 2003. The development of a performance measurement system for maintenance. SA Journal of Industrial Engineering1 4(1), 83–97.
[142] Weber and Thomas, 2006 A. Weber and R. Thomas, Key Performance Indicators: Measuring and Managing the Maintenance Function, Ivara Corporation (2006).
[143] Westerkamp, T.A. (1993), Maintenance Manager's Standard Manual, Prentice-Hall, Englewood Cliff, NJ, pp. 765-84.
[144] Westerkamp, T.A., (1987) Using Computers to Audit Maintenance Productivity. in Maintenance Management (Edited by E,. Hartmann), Industrial Engineering and Management Press, Atlanta, GA, U.S.A.
[145] Wireman, T. (1990), World Class Maintenance Management, Industrial Press, New York, NY.
[146] Wireman, T. (1998). *Developing performance indicators for managing maintenance*. Industrial Press (First edition): New York. USA
[147] Woodhouse, J. (2000). *Key Performance Indicators in Asset Management*. The Woodhouse Partnership Ltd.
[148] Woodhouse, J. 2004. Asset Management – An Introduction. Institute of Asset Management, http://www.iamuk.org/iam_publications.htm
[149] Zaldívar, S. (2006). *El Mantenimiento Técnico un reto histórico-lógico en el perfeccionamiento de la actividad gerencial*. Revista Tecnología en Marcha. Vol 19-1, pp 24-30.
[150] Zancolich, J., (2002), Auditing Maintenance Processes for Plant Efficiency, http://www.mt-online.com.

ISBN 978-91-7439-379-8