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Received 21 October 2013
Revised 9 June 2014
Accepted 8 November 2014

Performance measurement and management for maintenance: a literature review

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Abstract

Purpose – The purpose of this paper is to provide a literature review of the performance measurement (PM) in maintenance. The authors aim to discuss the background and development of the PM for maintenance, besides defining the concept of performance measures for maintenance and the frameworks developed.

Design/methodology/approach – A detailed and extensive literature search and study was undertaken by the authors on the concept and definition of PM, performance indicators (PIs), maintenance performance indicators and various performance frameworks. The history and theory of PM over different phases of business and technological developments have been critically examined and analysed in this review paper.

Findings – This paper reviews and presents the different PIs and PM frameworks like; balanced scorecard (BSC), performance prism, performance pyramid and performance matrix, etc., and identifies their characteristics and shortcomings. After considering related issues and challenges, frameworks and approaches for the maintenance performance measurement (MPM) are also presented, where the emerging techniques like; emaintenance have also been discussed amongst others. More and more industries are applying the balanced and integrated MPM frameworks for their competitive survivability and sustainability.

Practical implications – The concept, issues and approaches considered for the MPM frameworks can be adapted by the practicing managers, while trying to define and develop an MPM framework for the operation and maintenance activities. The considerations of the advantages and limitations of different frameworks can provide insights to the managers for implementation.

Originality/value – Some literature reviews on MPM and MPM frameworks are available today. This paper makes an attempt to provide a detailed and relevant literature review, besides adding value in this new and emerging area.

Keywords Issues and challenges, Maintenance performance measurement (MPM), Performance indicators (PIs), Performance measurement (PM)

Paper type Literature review

1. Introduction

Today's asset managers and asset owners need to know the relationship between the outputs of the maintenance process for assessing their contribution to the business goal. Effectiveness of maintenance and its quality need to be measured for the justification of investment in maintenance (Parida and Chattopadhyay, 2007). For many asset-intensive industries, the maintenance costs are a significant portion

The authors would like to acknowledge the support from the Reviewers and Prof. Salih O. Duffuaa for their comments and suggestions to improve this paper.

Journal of Quality in Maintenance Engineering
Vol. 21 No. 1, 2015
pp. 2-33

1355-2511
DOI 10.1108/JQME-10-2013-0067

of the operational cost. For example, the amount spent on maintenance budget for Europe is around 1,500 billion euros per year (Altmannshoffer, 2006) and for Sweden 20 billion euros per year (Ahlmann, 2002). In addition, breakdowns and downtime have an impact on the plant capacity, product quality and cost of production, as well as on health, safety and the environmental issues.

In manufacturing organizations, the maintenance-related costs are estimated to be 25 per cent of the overall operating cost (Cross, 1988; Komonen, 2002). In some industries, such as petrochemical, electrical power and mining, the maintenance related costs might surpass the operational costs (Raouf, 1993; De Groote, 1995; Eti *et al.*, 2005; Parida and Kumar, 2006). The process of maintenance performance measurement (MPM) development should be guided by the integration of critical success factors (CSF), which are derived from the overall organizational strategy (Leidecker and Bruno, 1984; Tsang *et al.*, 1999). This can realised by improved understanding of the operation and maintenance process, through identification, development and implementation of appropriate quantitative and qualitative performance indicators (PIs) for the MPM system.

Organizations are operating under a dynamic business environments, besides complicated intellectual work at all levels of the company, with a fast pace of information and communication technologies (ICT) renewal (Lönnqvist, 2004). Now manufacturing systems are operating more efficiently, effectively and economically to sustain competitiveness (Wang and Hwang, 2004). Under such challenging environment, to sustain and survive, implementing an appropriate performance measurement (PM) system in an organization can ensure that actions are aligned to the strategies and objectives (Lynch and Cross, 1991). Research evidences also show that companies that are managed using an integrated PM systems outperform (Lingle and Schiemann, 1996) and have superior stock prices (Gates, 1999) than to those not undertaking the PM.

PM forms a solid foundation for deciding where improvements are most pertinent at any given time. PM is also used as a basis for benchmarking internally and in comparison to other organizations. The measurement is entirely relative to indicate how good comparatively, the performance is. PM systems are used differently depending on their application, like financial reports, costing systems, performance appraisal and reward systems, customer satisfaction, competitor ranking and for measuring improvement of the organization (Feurer and Chaharbaghi, 1995), besides productivity improvement and optimization.

Maintenance provides critical support for heavy and capital-intensive industries by keeping the productivity performance of plants and machineries in a reliable and safe operating condition. Today, it is accepted that maintenance is a key function in sustaining long-term profitability for organizations (Al-Sultan and Duffuaa, 1995; Pintelon and Parodi-Herz, 2008). Maintenance is viewed as a value-adding activity, instead of a necessary evil (Ben-Daya and Duffuaa, 1995; Liyanage and Kumar, 2003)). Thus, the asset managers and owners need to measure and know the relationship between the outputs of the maintenance process in terms of its total contribution to the business goal. Besides the contribution, the efficiency and quality of the maintenance need to be measured through maintenance performance indicators (MPIs) and key performance indicators (KPIs), for justification of investment in maintenance (Parida and Chattopadhyay, 2007).

The development and publications in the area of MPM in the last decade have motivated the authors to systematically examine the literature dealing with the different aspects of the maintenance process, their related activities, measurements and management from an integrated and holistic perspective. For the purpose of this literature review, several electronic and printed databases were utilized. In the process, articles published in the last three decades are mostly identified, analysed and classified. This research effort looked for tracing the evolution of performance measures and measurement, in addition to the related maintenance organizational function, its resource utilization, activities and practices. These detailed examination resulted in articulating and identifying the various MPM issues and challenges, besides the frameworks and scope for further research in this area.

In this research review paper, besides the publications on historical development of PM and MPM, the recent development in the area of MPM, like MPM's use for benchmarking in the shape of harmonized indicators, data to decision though eMaintenance and identification of performance killers and drivers are considered and discussed. The organization of the paper is as follows: after a brief introduction, the literature review methodology is provided in Section 2. Section 3 discusses PM and their frameworks, including MPIs and shortcomings. Section 4, discusses MPIs, performance killers and drivers, besides benchmarking and harmonized indicators. The MPM frameworks with various emerging approaches and trends are discussed in Section 5, and Section 6 concludes the review paper.

2. Literature review

For this research purpose, a detailed and exhaustive search of literature pertaining to MPM and related areas were conducted. The time period of this literature review mostly covers the period from 1980 till 2012, though, MPM related publications covers the period mostly from 2000 onwards. The electronic databases used for this literature search and review were: Emerald (MCB Press/Emerald Group Publishing Limited), Science Direct (Elsavier), JSTOR, Google scholar, Scopus, and Ebesco (Academic search Elite). In addition, library based search was conducted in an attempt to include all possible related books and journals. The literature review was conducted with an aim to search all possible related works connected directly or indirectly with MPM, as well as reported projects, organizational systems, process and people.

As a result of the exhaustive literature search, papers published in the following journals, were short listed for this review paper on MPM, besides 53 books and doctoral theses, as well as conferences and other publications (Figure 1).

The number of journals and book published in MPM and its related areas also confirms the interest and importance of this subject for both the academia and industry.

3. PM, PIs and PM frameworks

This section starts with the definitions and current status for PM and its frameworks. These subject areas are continuously changing and expanding. This section also briefly deals with the overview of literature related to KPIs and PIs.

According to Amaratunga and Baldry (2002), the Procurement Executives' Association, described "performance management" as, "the use of PM information to effect positive change in organizational culture, systems and processes, by helping to set agreed-upon performance goals, allocating and prioritising resources, informing managers to either confirm or change current policy or programme directions to meet those goals, and sharing results of performance in pursuing those goals". Two key components need to be considered to move from PM to performance management: the right organizational structure, which facilitates the effective use of PM results; and the ability to use PM results to bring about change in the organization. A PM system can be described as the set of metrics used to quantify both the efficiency and effectiveness of actions (Neely *et al.*, 1995).

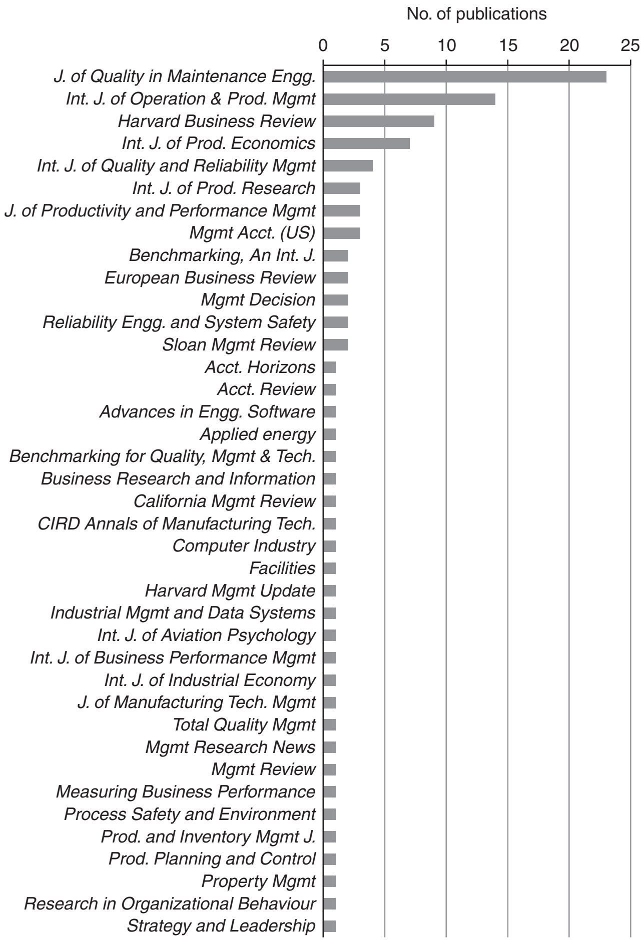

Figure 1.
Publications per journal

A PM system can acts similar to the instrument panel in the cockpit of an aircraft that is necessary to replace the rear-view mirror approach offered by the traditional accounting system based measurement. This instrument panel is used for strategic manoeuvring, day to day running of the organization, planning and implementing improvements and changes (Andersen and Fagerhaug, 2002). KPI can be defined for each element of a strategic plan, which is broken down to the PM at the basic process or shop floor/operational level through PIs. Metric, measure and PI, are terms often used interchangeably in the developing field of PM. Some authors say "metric" as the unit of measure, measures means specific observation characterizing performance and PI is a specifically defined variable. A performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of action (Neely *et al.*, 2005).

Vroom (1964) suggested that performance is a function of "ability and motivation". Porter and Lawler (1968) presented a model where performance consists of "efforts, ability and role perception". PM includes "hard" financial and non-financial metrics as well as "soft" metrics like employee attitudes, and covers both processes and results.

The basic concept of performance is function of ability, efforts and opportunity (Salminen, 2005). PM is also defined as the comparison of results against expectations with the implied objective of learning to do better (Rouse and Putterill, 2003). As per Neely *et al.* (2005), PM can be defined as the process of quantifying the efficiency and effectiveness of action. Thus, performance is the ability of an organization to implement a chosen strategy.

According to Ghalayini and Noble (1996), the literature pertaining to PM evolved through two phases. The first phase was started in late 1880s and known as cost accounting orientation phase; which helped the managers to evaluate the relevant costs of operation, and the second phase started after 1980, which attempted to present a balanced and integrated view of PM (Augusto *et al.*, 2005; Gomes *et al.*, 2004). During first phase with a financial focus, the approach was criticized for short-term measures and failing to measure and integrate all the factors critical to the business success (Banks and Wheelwright, 1979; Hayes and Garvin, 1982; Kaplan, 1983, 1984).

In the 1980s, the term "productivity" was replaced with "performance", as the criteria of productivity paradigm was unable to satisfy various stakeholders. A number of studies have pointed out the shortcomings of the prevailing PM systems, especially the ones based on the financial measures only (Johnson and Kaplan, 1987; Hall, 1983; Skinner, 1971; Dixon *et al.*, 1990). Traditional financial performance measures provide little indication of future performance and encourage short termism (Hayes and Abernathy, 1980; Kaplan, 1986); are internal rather than externally focused, with little regards for competitors or customers (Kaplan and Norton, 1992; Neely *et al.*, 1995); lack strategic focus and often inhibit innovation (Skinner, 1974; Richardson and Gordon, 1980). In order to overhaul the shortcomings in the existing traditional measures of the systems, organizations total competitive circumstances were taken in to consideration (Eccles, 1991; Neely, 1999). However, there is little evidence that organizations are ensuring full reflection of organizational context, thus leading to implementation of new measures to add on new priorities (Meyer and Gupta, 1994). It is often found that organizations are burdened with data overload (Kennerly and Neely, 2003; Karim *et al.*, 2009).

Organizations using integrated balanced performance management systems tend to perform better than their counterparts who do not (Parida and Kumar, 2006). However, studies have shown that 70 per cent of all those systems implementation initiatives have failed (Bourne *et al.*, 2002; Bourne, 2005). Some researchers advocate for the utilization of broader and innovative performance management approaches, such as the balance scorecard and new organizational improvement instruments (Garg and Deshmukh, 2006). In a comprehensive measurement system, the measures chosen should be aligned with business objectives derived from an organization's vision and strategy (Parida *et al.*, 2003). As a result, when the business objectives are changed, the measurement system should be changed accordingly. Failing this, the measurement system cannot be used to control the strategically important success factors (Kaplan and Norton, 1996).

3.1 PIs

PIs are used to highlight deficiencies in a company and to analyse it further to find the problem that is causing the indicator to be low. Ultimately, the indicator can then point to a solution of the problem. So, in implementation, there should be multi-level indicators, showing the hierarchical relationship of the PIs. For attributes of PIs, through which the organization seeks to improve performance relative to its strategic goals, see Kaplan and Norton (2001). PIs are used for the measurement of performance of any system or process. A PI compares actual conditions with a specific set of reference conditions (requirements), by measuring the distances between the current environmental situation and the desired situation (target), so called "distance to target" assessment (European Environment Agency (EEA), 1999). PIs should highlight opportunities for improvement within companies, when properly utilized (Wireman, 1998). PIs at the shop floor level or functional level when aggregated to the managerial or higher level are called KPIs. A KPI can indicate the performance measures of key result area (KRA) (Parida and Kumar, 2006). It is important for top management to satisfy the needs of all stakeholders/shareholders. These corporate PIs will vary from company to company depending on the current market conditions, business life cycle and the company's financial standing, etc.

PIs could be broadly classified as leading or lagging indicators. A leading indicator is one that warns the user about objectives beforehand. A leading indicator is one of a statistical series that fairly reliably turns up or down before the general economy does (Encyclopaedia Britannica, 2003). A leading indicator thus works as a performance driver and supports the concerned head of the specific organizational unit in ascertaining the present status with comparison to the reference one. Perceptual measures are often leading indicators in the sense that they are highly predictive of financial performance. When such measures are tracked today, this will lead to less worry about missing tomorrow's budgets (Case, 1998).

A lagging indicator normally changes direction after economy has. Lagging indicators indicate the condition after the performance has taken place; the value of construction completed for example, is outdated. The maintenance cost per unit or return on investment calculation, could be an example of a lagging indicator. The list of PIs is a long. But each organization's selection of PIs will vary according to their corporate strategy objectives and requirements. Pintelon and Puyvelde (1997) have categorized PIs as; global PI, set of PIs and structured PIs and mentions that introduction of a structured PM system is not an easy job. Kumar *et al.* (2011a) have discussed types of indicators, leading versus lagging and hard versus soft, besides their linkage to KPIs extensively.

3.2 PM frameworks

While reviewing the literature, one tends to notice that the terms, frameworks and models are often used interchangeably. There are several concepts and frameworks for measuring the business and maintenance performance. A conceptual framework explains, either graphically or in narrative form the main things to be studied; their key factors, constructions or variables and the presumed relationships among them. Frameworks can be rudimentary or elaborate, theory driven or common sensual, descriptive or casual. A framework specifies who and what will and will not be studied, and some relationship as indicated by arrows, which is based on logic (Miles and Huberman, 1994). Rouse and Putterill (2003) explains that frameworks assist in the holistic process by clarifying boundaries, specifying dimensions or views and may also provide initial intuitions about relationships among the dimensions. They should not be treated as models, but they form a good starting point for model building as part of theory development.

To restrict our literature review, the PM frameworks is divided into traditional accounting based, and multi-criteria frameworks. The multi-criteria PM frameworks are considered under balanced and multi-criteria, and, cause and effect relationship PM frameworks. These entire PM frameworks are relevant to the MPM framework conceptually as the MPM framework considers the integrated and holistic aspects of the organization, and forms part of the business measurement.

With the above mentioned back ground a large number of PM frameworks evolved for the companies world over under different organizational situations.

The genesis of the frameworks for PMs goes back to 1903, when three Du Pont cousins consolidated their small enterprises with many other small single-unit firms. They completely reorganized the Explosives industry and developed an organizational structure, and perfected these techniques in such a way that by 1910, they were following all the modern basic methods currently in use. This framework is known as Du Pont Pyramid of Financial Ratios and Du Pont ROI management accounting model (Chandler, 1977; Skousen *et al.*, 2001). Following the First World War, companies such as Du Pont, Sears Roebuck and General Motors were using sophisticated budgeting and management accounting techniques. By 1941, 50 per cent of established US companies were using budgetary control in one form or another (Bourne *et al.*, 2003). The post war phase saw a paradigm shift in organizations only for financial measures to both financial and non-financial measures in their objectives and PM. Though, General Electric first implemented a balanced set of performance measures in the 1950s (Bruns, 1998), PM grew by 1990s to follow a balanced approach. These lead to varieties of PM frameworks available for the implementation by the organizations (Kennerly and Neely, 2002).

Johnson and Kaplan (1987) pointed out the deficiencies in the management accounting information used for business management. These indicated the failures of the financial measures to consider changes in the competitive situations and strategies of the changing organizations. Du Pont pyramid's drawbacks were indicted by such studies, as its cost analysis relates to past and failed to indicate future performance, encouraging short-term measures (Bruns, 1998).

With these backgrounds, it is ideal to conclude that a well-developed PM system should have been used by the companies by now. But authors and researchers like; Neely *et al.* (1995, 1997), Kaplan (1984), Ashton (1997) and Geanuracos and Meiklejohn (1993) have confirmed it otherwise. Various authors discussed the problems with the performance measures used by organization today, and traditional financial measures are mostly criticized for:

- encouraging short termism, like delayed capital investment (Banks and Wheelwright, 1979; Hayes and Abernathy, 1980);
- lack of strategic focus and failure to provide data on quality, flexibility and responsiveness (Skinner, 1974);
- encouraging managers to minimize variance from standard than to improve continuously (Turney and Anderson, 1989; Schmenner, 1988);
- failure to provide information on customer's want and competitors' performance (Kaplan and Norton, 1992; Camp, 1989); and
- encourage local optimization, like, manufacturing inventory to keep the machine and people busy (Goldratt and Cox, 1986; Hall, 1983).

The first approach to PM was stated by Sink and Tuttle (1989), in their book *Planning and Measurement in your Organization of the Future*. Their theory explained that the performance of an organizational system is a complex interrelationship between seven different criteria, like efficient, effectiveness, quality, productivity, quality of work life and innovation, profitability/budgetability and excellence survival and growth. Subsequently, development of different PM frameworks created considerable interests in the industrial world. Different authors have modified, developed and suggested frameworks considering non-financial measurements and intangible assets to achieve competitive advantages by the organizations (Blair, 1995; Weber, 2000; Kaplan and Norton, 2001). Companies using integrated balanced PM system perform better than the companies not measuring their performance, as per Kennerly and Neely (2003). The financial measures were also criticized for being historically focused (Dixon *et al.*, 1990).

Throughout late 1980 and 1990s, other performance models were introduced to achieve better performance (Andersen and Fagerhaug, 2002). Some of the other known model/approaches are: the BSC approach (Kaplan and Norton, 1996), performance pyramid models (Lynch and Cross, 1991) and performance prism (Neely and Adams, 2002), etc. Besides, some other approaches were developed by various European research projects, like: AMBITE and ENAPS. For details, see, European Commission's research programmes web site: www.cordis.lu

The other PM systems and frameworks which evolved during this phase are: cause and effect relationship linking measures (macro process model of organization, (Brown, 1996); the consistent PM system, (Flapper *et al.*, 1996); the framework for small business PM, (Laitinen, 1996); the Cambridge PM or the performance prism, (Neely *et al.*, 1997); integrated dynamic PM, (Ghalayini *et al.*, 1997); integrated PM system (Bititci *et al.*, 1997); and the integrated measurement model, (Oliver and Palmer, 1998).

There are at least 21 PM frameworks that are specifically designed for measuring intellectual capital (Sveiby, 2004). They include the intellectual capital management model, the balanced PM system, the intangible Asset Monitor, and the Skandia navigator (Edvinsson and Malone, 1997; Knight, 1999; Sveiby, 1997). Many of them are basically similar to the PM frameworks, with the difference of their focus on measuring the intellectual assets (Lönnqvist, 2004). The compilations of the developed PM frameworks are given at Table I.

The development of the PM framework started in late 1970s and is still continuing to be studied, analysed and further developed by the researchers and professionals. It is interesting to see the development over the years, as shown in Figure 2. It is interesting to see that the decade of 1990s (1990-2000) contributes majority of the frameworks.

The PM frameworks can also be categorized under five types of PM frameworks as shown at Figure 3. All these frameworks have been explained and discussed in this section. The traditional accounting-based frameworks are the one prior to balanced and multi-criteria framework. Subsequently, multi-criteria hierarchical framework was developed to meet the expectation of the management from various industries. The function and business specific frameworks are the other means of categorizing the frameworks.

PM system design, as prepared by Kaplan and Norton (1992), consisted of eight steps and indicates the rules and guidelines for PM system design. Thereafter, as BSC grew in popularity and use, a large number of documentations are made for PM system and its design process. Unfortunately, most of them ended up in somehow open-ended system and vague statement (Feurer and Chaharbaghi, 1995). Prior to this, authors like Globerson (1985) suggested the process of designing a PM system. Maskell (1989), also suggested seven principles for PM system design with a focus on the output of the process.

Neely *et al.* (2000b) have mentioned the construction of a pilot process for PM system design. The aim of the process design phase is to establish a very practical PM

Model/framework	Measures/indicators/criteria	Reference
1. Sink and Tuttle (1989)	Efficiency, effectiveness, quality, productivity, quality of work life and innovation, profitability/budget ability, excellence, survival and growth,	Sink and Tuttle (1989)
2. Du Pont Pyramid	Financial ratios, ROI	Chandler (1977); Skousen *et al.* (2001)
3. PM matrix	Cost factors, non-cost factors, external factors, internal factors	Keegan *et al.* (1989)
4. Results and determinants matrix	Financial performance, competitiveness, quality, flexibility, resource utilization, innovation	Fitzgerald *et al.* (1991)
5. PM questionnaire	Strategies, actions and measures are assessed, extent to which they are supportive? Data analysis as per management position or function, range of response and level of disagreement	Dixon *et al.* (1990)
6. Brown's framework	Input measures, process measures, output measures, outcome measures	Brown (1996)
7. SMART pyramid (Performance pyramid)	Quality, delivery, process time, cost, customer satisfaction, flexibility, productivity, marketing measures, financial measures	Developed by Wang Laboratories. Lynch and Cross (1991)
8. Balanced Scorecard (BSC)	Financial, customer, internal processes, learning and growth	Kaplan and Norton (1992)
9. Consistent PM system	Derived from strategy, continuous improvement, fast and accurate feedback, explicit purpose, relevance	Flapper *et al.* (1996)
10. PM framework for small businesses	Flexibility, timeliness, quality, finance, customer satisfaction, human factors	Laitinen (1996)
11. Cambridge PM process	Quality, flexibility, timeliness, finance, customer satisfaction, human factors	Neely *et al.* (1997)
12. Integrated dynamic PM System	Timeliness, finance, customer satisfaction, human factors , quality, flexibility	Ghalayini *et al.* (1997)
13. Integrated PM framework	Quality, flexibility, timeliness, finance, customer satisfaction	Medori and Steeple (2000)
14. Integrated PM system	Finance, customer satisfaction, human factors, quality, flexibility, timeliness	Bititci (1994)
15. Dynamic PM systems	External and internal monitoring system, review system, internal deployment system, IT platform needs	Bititci *et al.* (2000)
16. Integrated measurement model	Customer satisfaction, human factors, quality, flexibility, timeliness, finance	Oliver and Palmer (1998)
17. Comparative business scorecard	Stakeholder value, delight the stakeholder, organizational learning, process excellence	Kanji (1998)
18. Skandia navigator	Financial focus, customer focus, human focus, process focus, renewal and development focus	Edvinsson and Malone (1997); Sveiby (1997)
19. Balanced IT scorecard (BITS)	Financial perspective, customer satisfaction, internal processes, infrastructure and innovation, people perspective	ESI (1998) as mentioned in Abran and Buglione (2003)

(*continued*)

Table I.
Performance measurement frameworks

Model/framework	Measures/indicators/criteria	Reference
20. BSC of advanced information. Services Inc (AISBSC)	Financial perspective, customer perspectiveprocesses, people, infrastructure and innovation	Abran and Buglione (2003)
21. Intangible Asset-monitor (IAM)	Internal structure: *growth, *renewal, *efficiency, *stability, risk (concept models, computers, administrative systems); external structure: *customer, *supplier, *brand names, *trademark and image; individual competence: * skills, *education*experience, *values, *social skill	Sveiby (1997)
22. QUEST	Quality, economic, social and technical factors	Abran and Buglione (2003)
23. European Foundation for Quality Management (EFQM)	Leadership, enablers: people management, policy and strategy, resources; processes, results: people and customer satisfaction, impact on society; and business results	www.efqm.org/ as mentioned in Wongrassamee *et al.* (2003)
24. EN 15341	Maintenance key performance indicators	CEN (2007)
25. Multi-criteria hierarchical framework for MPM	Balanced and considering the strategic, tactical and operational perspectives	Parida and Chattopadhyay (2007)
26. Link and effect model	Technical indicators, like; availability, capacity utilization, etc., at the operational level is linked to strategic level through the tactical level and vice versa	Stenström (2012)
27. Venezuela Norma Covenin 2500-93	Manual for evaluation of maintenance systems through questionnaire and scoresheet	Norma Venezolana (1993)

Note: *Indicates the different internal and external structures
Source: Adapted from Parida and Chattopadhyay (2007)

Table I.

system design process, built on the basis of the best of academic theory and industrial practice, which could be implemented and tested. This process consisted of the 12 phases. Neely *et al.* (1997) applied the pilot PM system design process in three UK manufacturing companies.

4. MPIs, performance killers and drivers, benchmarking and harmonized indicators

The MPIs are used for the measurement of performance of any maintenance system or process. A PI is a product of several measures (metrics), when used for measurement of maintenance performance in an area or activity; is called the MPIs (Wireman, 1998; Parida *et al.*, 2003). MPIs are applied in order to find ways to reduce down time, costs and waste, operate more efficiently, and get more capacity from the operational lines (Parida and Kumar, 2004b). MPIs are utilized to evaluate the effectiveness of maintenance carried out (Wireman, 1998). MPIs compare the actual conditions with a specific set of reference conditions (requirements/targets) (EEA, 1999). MPIs can also be defined as "the means to measure the efficiency and effectiveness of maintenance and related performance." Liyanage and Kumar (2003) define a PI of maintenance as "a measure equipped with baselines and realistic targets to facilitate prognostic and/or diagnostic processes and justify associated decisions and subsequent actions at

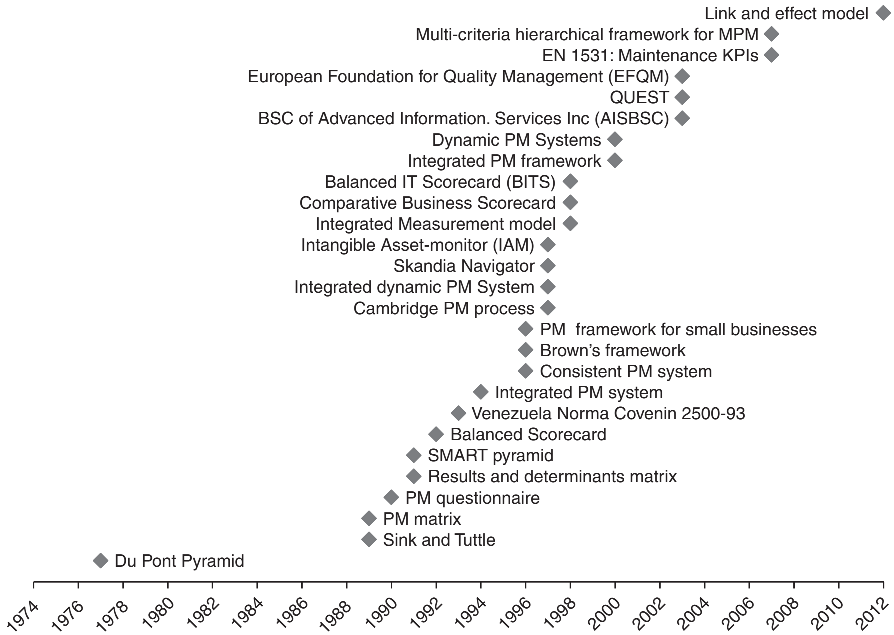

Figure 2.
PM frameworks development

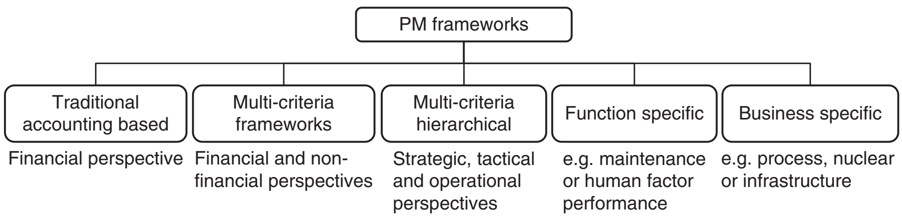

Figure 3.
PM frameworks categorization

appropriate levels in the organization to create value in the business process". One way of measuring the maintenance performance is to develop MPIs and implement them with a total involvement of the entire organization. MPIs are linked to the reduction of downtime, costs and wastes, and the enhancement of capacity utilization, productivity, quality, health and safety. MPIs also need to be different for different industries and the difference causes a need for other PIs (Arts *et al.*, 1998). Duffuaa *et al.* (1999) have classified the MPIs into two categories as: economic indicators and technical indicators. Campbell and Jardine (2001) have assigned these indices into six classes as; maintenance productivity, maintenance organization, maintenance costs, maintenance efficiency, maintenance quality and overall maintenance results.

MPIs could be used for financial reports, for monitoring the performance of employees, customer satisfaction, the health, safety and environmental (HSE) rating, and overall equipment effectiveness (OEE), as well as many other applications, when considering the PM issues holistically. Maintenance budget, plant or system's availability targets, meantime, between failures and repair (MTBF and MTTR), maintenance reliability and downtime, are some of the examples of MPIs.

The establishment of a link between the lagging and the leading indicators helps to monitor and control the performance of the process, and the indicators to be linked are selected in line with the chosen maintenance strategy (Kumar and Ellingsen, 2000).

It is relevant to note that, the full list of indicators could be very long, but the number should be kept as low as possible in an organization, as it is not possible to monitor and control a large number of indicators (Schneiderman, 1999; Smith, 2001). A logical scenario for process PI essentially looks at the shareholders' value at a macro level especially, in oil and gas (O&M) process. In one of the project: PI-TEC-T5/REV0 for the O&G project of Norway, task 5 deals with development of indicators (PI-TEC-T5/REV0 (Task 5 Development of indicators), 2000).

The measurement of the performance in the maintenance function can be grouped in different subsets lately, emphasizing the set of financial indicators. The generation of these indicators demands data collection of high reliability through a model of costs adapted to the maintenance function, characterized by the occultism of these costs (Galar *et al.*, 2012).

PIs to support the railway infrastructure managers (IMs) in decision making have been mapped and compared with indicators of European Standards. The listed indicators form a basis for constructing a MPM system for railway infrastructures (Stenström *et al.*, 2013a).

The total productive maintenance (TPM) concept (Nakajima, 1988) provides a quantitative MPI called OEE for measuring productivity of manufacturing equipment, which identifies and measures losses in availability, performance/speed and quality. OEE supports the improvement of equipment effectiveness and its productivity. The OEE concept has become quite popular and is widely used as a quantitative tool to measure production performance of industries (Huang and Dismukes, 2003; Muchiri and Pintelon, 2008).

Campbell (1995) classifies the MPIs into three categories like; equipment performance (e.g. availability, reliability, etc.), cost performance (e.g. maintenance, labour and material cost) and process performance (e.g. ratio of planned and unplanned work, schedule compliance, etc.). Coetzee (1997) outlines four categories of MPIs; maintenance results (availability, mean time to failure (MTTF), breakdown frequency, mean time to repair (MTTR) and production rate); maintenance productivity (manpower utilization, manpower efficiency and maintenance cost component over total production cost); and maintenance operational purposefulness (scheduling intensity, breakdown intensity, breakdown severity, work order turnover, schedule compliance and task backlog) and maintenance cost justification (maintenance cost per unit production, stock turnover and maintenance cost over replacement value).

4.1 Maintenance performance killers, performance drivers and cost drivers

For any industry or organization, the list of MPIs is quite large due to historical and heterogeneous reasons. To reassure the management that maintenance budget can create value addition; researchers are further classifying the MPIs as performance drivers, performance killers and cost drivers. A number of European Union research projects are considering these aspects of MPIs to reduce the maintenance possession time or delays and optimize productivity, besides resource and capacity utilization (Automain, 2012).

Kaplan and Norton (1992, 1996) used the term performance driver in their BSC framework, complementing the financial measures of past performance which can act as the driver of future. Performance drivers are viewed as the inputs within a process which drives the performance to deliver the objectives. The inputs in a process, which performs negatively, can be termed as performance killers. (Tsang, 1998, 2000; Parida and Kumar, 2009) described performance drivers as equivalent to lead indicators, which have the ability to predict future outcome. Several authors mentioned that a lead indicator can be a performance driver which acts like an early warning system (Parida, 2006; Parida and Chattopadhyay, 2007; Patra *et al.*, 2009).

As per Markeset and Kumar (2005) performance killers are factors/issues that reduce performance without being strong enough to stop a process and the authors have given a number of examples of performance killers like; equipment with critical uptime, health, safety and environment; bottlenecks in capacity, administration and inventory; incompetence; lack of proper tools and facilities; faulty procedures and checklists; and inadequate information, communication flow and systems, etc. Furthermore, Parida and Kumar (2006) have discussed a number of performance killers, which are unavailability of resources, materials, spares, personnel, IT support, project support, time, etc. According to maintenance strategies, and EN 13306, the excessive or non-optimized corrective maintenance tasks are considered as performance killers; while the preventive or predictive activities can be termed as performance drivers or cost drivers as per their application and achieved results.

4.2 Benchmarking and harmonized MPIs

Benchmarking of PIs were undertaken by the benchmarking committee (now known as European Maintenance assessment Committee) of the European Federation of National Maintenance Societies (EFNMS), from 1998 and the best practices committee of Society for Maintenance and Reliability Professionals, USA (SMRP) from 2004. Since 2006, these two organizations have been working on a harmonized process, comparing the existing indicators for formulas and term definitions. The basis for the terms are; EN 13306 Standard of "Maintenance Terminology", EN 15341 Standard of "Maintenance Key Performance Indicators" and IEC 60050-191-1990 Dependability and Quality of Service (Svantesson, 2011). Further details can be seen at Galar *et al.* (2011a) and Svantesson (2011).

It is difficult to compare ratios of different plants or, for that matter, different organizations. In this context, meaningful comparisons of maintenance performance efficiency between various plants cannot be carried out in the absence of maintenance performance efficiency standards (Raouf, 1993; Yam *et al.*, 2000; Åhrén and Parida, 2009). Benchmarking is critical towards achieving world-class maintenance performance levels (Chen, 1994; Raouf and Ben-Daya, 1995; Madu, 2000). It is to be noted that benchmarking is one of the key elements for the continuous improvement process (Åhrén and Parida, 2009). The CEN-European Committee for Standardization (2007), through the framework of the EN 15341 standard, presented the maintenance performance measures' classification in terms of economic, technical, and organizational indicators. More recently, Cabral (2009) classified economical and technical measures in four groups, namely, time-related factors, human effort-related factors, number of events and cost-related factors.

5. MPM and MPM frameworks

Maintenance for today's advanced manufacturing technologies are becoming very critical for the organizations ability to compete and in this context, operations management, especially maintenance management, is taking on a broader organizational strategic role (Simoes *et al.*, 2011). The scope of maintenance has shifted from a narrowly defined manufacturing or operational perspective, to the corporate strategic perspective. Some authors attribute this shift to the utilization of more advanced technologies (Swanson, 1997), increased emphasis on safety, and new environmental legislations (Cooke, 2003). Thus, the role of maintenance managers are becoming critical and they are being called on to integrate and direct the maintenance efforts to meet organizational strategic goals efficiently and effectively (Alsyouf, 2007; Al-Najjar, 2007).

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, to 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).

It is important to have an organizational systematic maintenance strategy to guide the strategic use of maintenance resources, models and techniques (Jonsson, 1999). There are many models, techniques, systems and approaches available to facilitate and support maintenance management of activities, resources and decisions (Garg and Deshmukh, 2006). There are several new approaches and strategies/tactics/technologies like; web-based maintenance, integration of product and maintenance design, proactive maintenance based on intelligent units, life cycle simulation for maintenance strategy planning, model-based maintenance, TPM, Reliability-Centered Maintenance (RCM), Preventive Maintenance (PM), Condition Based Maintenance (CBM), and Continuous Maintenance (CM) (Takata *et al.*, 2004). Therefore, approaching maintenance management strategically and systematically has become essential to make the right decisions, especially in capital-intensive industries. The literature points to strong linkages between business strategy and manufacturing maintenance strategies (Madu, 2000; Pinjala *et al.*, 2006; Rosqvist *et al.*, 2009).

More and more studies are carried out to ascertain and establish the relationship between maintenance performance and reliability of the productive and operative system, as PM provides a base for improvement and without measurement there can be no certainty of improvement (Parida *et al.*, 2003). MPM can be used as a powerful methodology, which allows maintenance engineer/managers to plan, monitor and control their operation/business. The purpose of measuring maintenance performance is designed to help and predict future action and performance based on past data. Some of the important factors behind demands on MPMs are; measuring value created by the maintenance, justifying investment, revising resource allocations, HSE issues, focus on knowledge management, and adapting to new trends in operation and maintenance strategy, besides organizational structural changes, (Parida and Kumar, 2006). More and more research works are undertaken to develop models and simulations linking MPIs and MPM framework with business objectives and strategies. Duffuaa *et al.* (2001), have discussed a generic conceptual simulation model for the maintenance systems.

Various issues and challenges associated with development and implementation of a MPM system were highlighted and discussed by Parida and Kumar (2006). Multinational companies like Mobil, DHL, TNT, Shell, ABB and General Motors, have successfully implemented PMs as mentioned in their business conferences (Lewis, 1996; Morris, 1996; Business Intelligence, 2000).

Various MPM approaches as used for developing the organizational specific MPM frameworks are classified and discussed here after.

5.1 Value-driven Performance (VDM) measure for MPM

VDM is a methodology developed on four value drivers in maintenance, like; asset utilization, resource allocation, cost control and HSE (Haarman and Delahay, 2006). These four drivers are used to calculate the value of maintenance strategies using the formula of discounted present value (Stenström *et al.*, 2013a). Advanced operational manufacturing technologies are blended with modern ICT to integrate and coordinate operational resources, processes and activities in order to generate a stream of value-added operations aimed at capturing and sustaining a competitive advantage (Simoes *et al.*, 2011). Maintenance activities are undertaken to meet the future operation/production demand. The readiness to deal with uncertain events, such as equipment breakdown, is also influenced by the maintenance management decisions. Dwight (1995) identified the shortcomings of performance measures as prevalent in industry (Tsang *et al.*, 1999); and suggested a "Incident Evaluation Approach" for determining the expected residual value of an action policy. This approach considers the possible primal incidents and their related actions leading to secondary incidents (failure mode), which will reduce the potential output of the system (Dwight, 1995).

5.2 The BSC approach-based MPM system

As discussed, under PM framework, BSC approach is a holistic approach, which considers both financial and non-financial measures for measuring performance (Kaplan and Norton, 1992, 1996). Parida *et al.* (2003) and Tsang *et al.* (1999) suggested BSC approach-based MPM system. Alsyouf (2006) suggested a BSC framework to assess the contribution of maintenance to strategic business objectives, which was tested for validation at a Swedish paper mill. The results confirmed the possibility to measure and identify the cause-and-effect relationship using an effective maintenance strategy to assess its impact on the company's competitive advantages. Alsyouf (2006) criticized the balance scorecard technique presented by Tsang (1998) as the performance measures, based on the four non-hierarchical perspectives only, focusing on a top-down PM, which does not consider the extended value chain i.e. it ignores the suppliers, employees, other competitors . The extended balance scorecard presented by Alsyouf (2006) incorporates performance measures based on seven perspectives: Corporate business (financial), society, consumer, production, support functions, human resources and supplier perspectives. Galar *et al.* (2011a) have discussed a hierarchical model of different maintenance metrics under a BSC approach to reach a good conclusion for decision making. This premise implies a hierarchy of indicators needed according to the areas of influence for the rest of the organization, posed by interactions with finance department, human resources, purchasing, and, of course, with production in the seeking of compliance with corporate objectives. Besides, BSC approach can be applied for maintenance audit and maturity model (Kumar *et al.*, 2011a).

5.3 Integrated MPM system corporate strategy and BSC

Corporate BSC forms part of the corporate strategy to measure the performance and compare the same with corporate objectives. This forms the reference/bench mark to compare the activities/indicators with the actual. These balance scorecards of the corporate strategy are translated to different divisions, departments and down to employee level so that it can be judged and evaluated at various level. Similarly, MPIs can be translated from different BSC perspectives down to the divisions, department, section and employee level. While considering the BSC perspectives, it is important to introduce HSE perspectives, additional to Kaplan and Norton's basic four-BSC perspectives. HSE has been considered and included, as this forms a very critical and mandatory requirement for the process industries like, oil and gas and mining industries today (Parida *et al.*, 2003). Once this linkage and integration is achieved by an organization, in all possibility, the organization can achieve maintenance excellence, which could support the organization to achieve its corporate objectives.

Since maintenance is identified as a critical and strategic process by many oil and gas (O&G) operators, it must be managed effectively in line with corporate objective (Kumar and Ellingsen, 2000). A research project "development and implementation of operation and maintenance (O&M) for PIs" (Kumar, 1998; Kumar and Ellingsen, 1999), was initiated by the Centre for Maintenance and Asset Management at the Stavanger University Norway, for strategic nature of maintenance. Critical lead indicators (performance drivers) were developed and implemented at the level of the maintenance process or at the team/individual level.

The indicators of maintenance performance are sustained in three pillars, i.e.: RAMS parameters, a cost model and the human factor. An agreed cost model in maintenance is formed as the base necessary to compose the corpus of the financial indicators, in addition form an excellent group in the general set of indicators of the performance of a company (Galar *et al.*, 2010).

5.4 Multi-criteria hierarchical framework for MPM

Parida and Chattopadhyay (2007), have developed a balanced, holistic and integrated multi-criteria hierarchical MPM framework, for various levels of the organization. The proposed framework for MPM is a relevant, timely, reliable, cost and time-effective and user-friendly system for stakeholders at various levels. The indicators at the subsystem/component level, plant level and corporate level are linked with the MPIs for the organizational objectives and strategy. The proposed framework has been evaluated with a mining process industry and also with an energy sector industry successfully (Parida, 2006, 2007). The link and effect concept inherent to this framework is also developed into a model and being evaluated with positive results at Swedish Railway (Åhrén, 2008; Stenström, 2012).

5.5 Audits for MPM

Audit of the maintenance system confirms the maintenance capability of an organization. The audit undertakes a comprehensive review of maintenance system's dimensions like; organization, personnel, training, planning and scheduling, data collection and analysis, control mechanism, measurement and reward system, etc. (Tsang *et al.*, 1999). Questionnaire are structured and used for specific areas for the system to be audited, with different weightage assigned to know their relative contributions to the system performance. Dwight (1994) suggested "feedback from operation" to audit the contribution to the system's overall performance. Maintenance system questionnaire were developed by Westerkamps (1993) and Wireman (1990). For alignment of strategy, actions and PIs of an organization's PM system, Dixon *et al.* (1990) have developed and specific questionnaire, called Performance Management Questionnaire (PMQ). Moreover, for auditing the maintenance function specifically, Venezuelan Commission for Industrial Standards (COVENIN) has developed a questionnaire; COVENIN 2500-93 (COVENIN, 1993). Kumar *et al.* (2011a) have discussed various issues related to maintenance audits using BSC and maturity model.

5.6 eMaintenance frameworks for MPM

The role of an integrated information system is critical to ensure data availability for true reliability-based maintenance schedule optimization (Sherwin and Jonsson, 1995). Information sharing practices, their attributes, information technology (IT) use, collaborative foundation, time-related issues, processes and activities are all considered as critical elements of information integration (Uusipaavalniemi and Juga, 2009). IT can be beneficial in reducing costs, and assisting in providing services, which were infeasible before (Concetti *et al.*, 2009). Thus, it is essential that the software design of the maintenance performance management system incorporates the culture and resources of the organization for which it is intended (Davies, 1990; Pinjala *et al.*, 2006; Hwang *et al.*, 2007; Kans, 2008). The literature reviewed for computerized maintenance management systems (CMMS) included many of the features needed to support the maintenance management and PM system (Labib, 1998, 2004).

Development of IT has contributed to the emergence of eMaintenance concept, since early 2000, which has become a common term in the maintenance related literature today (Muller *et al.*, 2007). eMaintenance can be defined as a maintenance strategy where tasks are managed electronically using real time equipment data obtained through digital technologies (i.e. mobile devices, remote sensing, condition monitoring, knowledge engineering, tele-communications and internet technologies (Tsang, 2002). eMaintenance is also considered as a maintenance plan to meet the productivity through condition monitoring, proactive maintenance and remote maintenance through real time information for decision making. Koc and Lee (2001) referred eMaintenance as predictive maintenance system which provides only monitoring and predictive prognostics functions.

The main problem with PM for decision making is the non-availability of relevant data and information. In an emaintenance virtual connectivity basic model, the real time connectivity amongst all concerned stakeholders facilitates collection of system health and performance information (Parida and Kumar, 2004a, b). ITEA (IT for European Advancement), established in 1999, conducted PROTEUS project (ITEA 01011) to provide a fully integrated platform to support any broad emaintenance strategy. A broad emaintenance model indicating different stakeholders and their role is discussed by Parida and Kumar (2004c, d), where, emaintenance creates a virtual knowledge centre with users, technicians/experts and the manufacturers, specializing in operation and maintenance of process industries like mining and paper amongst others. This model indicates the feasibilities of organizing the maintenance activities and competence into a virtual centre called maintenance control centre, which can predict and control all maintenance-related information.

5.7 Plant/equipment health management system (PHMS) for MPM

PHMS can be defined as an approach used for corrective, preventive and predictive maintenance besides other supportive activities. With a need to achieve zero down time, zero defect, instantaneous response and decision making, and world-class OEE performance; prognostics and diagnostics are used through embedded sensors and device to business tool (D2B). The largest problems as exist in the industry today, is a low OEE, which is 15-25 per cent below the target level. All these needs have led to e-health card for equipment's degradation assessment, which forms part of emaintenance. PHMS thus, consisting of e-condition monitoring (CM) diagnostics and prognostics, and condition based operation and support, which can improve the dependability and safety of the technical systems, besides decreasing life cycle cost of operation and support (Mobley, 1990; Campbell and Jardine, 2001; Soderholm and Akersten, 2002). This system delivers data and information, which indicates the health condition of the system. The stakeholders of the system are the receivers of the data and information (Lyytinnen and Hirschheim, 1987, ISO/IEC 1528.2002). The problem today in a health management system is the existing information islands, i.e. the different specialized systems, with in an organization speaking a different data and information language.

5.8 Strategic asset performance approach for MPM

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). 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. Assessing the asset performance is a complex issue as it involves multiple inputs and outputs; and various stakeholders' dynamic requirements. Lack of integration among various stakeholders and their changing requirements in strategic asset performance assessment is still a problem for the companies. It is a challenge to integrate a whole organization, where free flow and transparency of information is possible; and each process is linked to integrate to achieve the company's business goals. Parida and Kumar (2009) discussed various issues associated with integrated strategic asset performance and have suggested a framework linking the integrated enterprise asset management's (EAM) measuring criteria with condition monitoring, IT and hierarchical levels for effective decision making. Parida (2012), after discussing strategic aspects, issues and challenges for asset performance, has suggested an asset performance assessment framework in line with multi-criteria hierarchical MPM framework (Parida and Chattopadhyay, 2007).

5.9 Human factors in MPM

Maintenance is a logistic organizational function, which is typically integrated into a production process involving soft and human factors. Therefore, its efficiency and effectiveness tend to be difficult to measure in absolute terms. Simões *et al.* (2011) have reviewed the occurrence and types of MPM measures and found human factor measures to be the most lacking. Consequently, performance measures have been defined in relative terms (values), in form of ratios of economic, technical or organizational measures (De Groote, 1995). The human factor represented by maintenance technicians and other related staff is the backbone of the maintenance system in any organization. As such, the effectiveness of the different facets of the performance system is very much dependent on the competency, training, and motivation of the overall human factor in charge of the maintenance system (Ljungberg, 1998). In this context, factors such as, years of relevant work experience on a specific machine, personal disposition, operator reliability, work environment, motivational management, training and continuing education, are all relevant factors, which tend to impact the effectiveness of the performance of the maintenance system (Cabahug *et al.*, 2004). Operators are in direct contact with the maintenance activities and efforts. The relationship between the maintenance technicians and machine operators is very critical, as it influences service quality and user satisfaction level. In this context, repeated visits to repair equipment for the same problem result in operator dissatisfaction (Ardalan *et al.*, 1992). For quality oriented management programmes, employee participation is critical for success. The attitude, conduct and personality of maintenance personnel are critical to the effectiveness of the maintenance effort (Goh and Tay, 1995; Arca and Prado, 2008). The human resources aspect of maintenance has been playing an increasing role in relation to operational environment safety (Rankin *et al.*, 2000; Patankar and Taylor, 2000). Moreover, maintenance accidents are higher in number compared to normal operation accidents due to the non-standardized intervention in machines with lowered barriers (Galar *et al.*, 2011b). For a review on human error in maintenance, see work by Dhillon and Liu, (2006).

6. Issues and challenges in the implementation of MPM systems

PM systems have shown to increase the performance and competiveness of organizations through their use of more balanced metrics but there are some implementation issues. In a literature review, Bourne *et al.* (2003) list the issues noted by researchers in the implementation of PM initiatives, including the following:

- lack of leadership and resistance to change;
- vision and mission may not be actionable if there are difficulties evaluating the relative importance of measures and problems identifying true "drivers";
- goals may be negotiated rather than based on stakeholder requirements;
- striving for perfection can undermine success;
- strategy may not be linked to department, team and individual goals;
- a large number of measures dilutes the overall impact;
- metrics can be poorly defined;
- a highly developed information system is required and data may be hard to access;
- consequences of measurement; and
- time and expense.

Leadership support may be the most important factor in the success of MPM implementations. It is therefore essential to be able to stress and justify the advantages of MPM systems. Parida and Kumar (2006) identified the following key factors for justifying a MPM implementation:

- measuring value created by the maintenance;
- justifying investment;
- revising resource allocations;
- HSE issues;
- focus on knowledge management;
- adapting to new trends in operation and maintenance strategy; and
- organizational structural changes.

Difficulties regarding poorly defined and large numbers of indicators and databases have been specifically recognized in the planning and PM of railway infrastructure in several studies (Åhren, 2008; Stenström, 2012).

Kaplan and Norton (1996) list several of the issues as recorded by Bourne *et al.* (2002) and stress the problem of overlooking the strategy planning and instead introducing a rigorous data collecting computer system. A major concern in the information age is that companies are not turning data into knowledge and results as the gap between data processing and knowledge management is too large. In traditional PM systems, PIs give quantitative numbers of something and omit the underlying factors responsible for the performance of the PIs. The link and effect model aims at providing the user with knowledge of the underlying performance drivers and killers.

Concerning the problem of a large number of measures, it is noticed that companies report a large number of measures to senior management each month, which is manyfold of the recommended number of measures on a scorecard, thereby confusing detail with accuracy. The number of strategic level indicators depends on the number of senior managers, but identification of the most important indicators and data aggregation is needed since there can be several hundreds of indicators at the operational level. Aggregation of data, e.g. total delay or OEE, is a weakness of traditional PM systems since it can make the indicators abstract as the underlying factors can be unknown. The link and effect model tries to solve this by complementing indicators with the underlying factors responsible for the performance.

IMs have grown with the expansion of railways; thus, operation and maintenance practices have grown with respect to the specific needs of each IM. However, harmonization and increased use of standards have come with the globalization, especially with in the EU, considering increasing interoperability and building of a trans-European railway network . Another important element in PM is the fast development of new technologies, including computers (hardware and software) and condition monitoring. Changes in the enterprise resource planning (ERP) system or a CMMS within an organization can alter the PM practices and monitoring of historical asset condition data. Organizational changes can also affect the success of measuring performance. Overall, PM systems need to be proactive and dynamic to handle changes like the following:

- change in business goals, objectives, strategy, policies, etc.;
- change in technology and communication, e.g. maintenance procedures and ERP;
- organizational changes;
- evolving regulations, e.g. health, safety, security and environment;
- stakeholder requirements; and
- fluctuations in economy, i.e. the business cycle.

6.1 Case studies in MPM

Numerous MPM case studies of various kinds can be found throughout the literature. Simões *et al.* (2011) have listed the occurrence of MPM applications and case studies per industrial sectors. However, reviewing the methods and results of present case studies is an area of further research, but out of the scope of this study. Nevertheless, authors' experiences have been summarized in Table II. Case study observations are to a large extent in line with previous section on implementation issues:

- databases and PIs are seldom documented or regulated;
- key components of strategic planning practices are often poorly developed, i.e. vision/mission, goals, objectives, KRAs, CSFs, KPIs, as well as the difference between policies, strategies, philosophies and tools;

Table II.
Case studies in MPM

Area and industry	Case study and method	Comments
Mining balling area – LKAB mining company (Parida, 2007)	Top-down approach and multi-criteria hierarchical framework of seven criteria and three levels	38 MPIs set-up in seven criteria and three levels Specific case of plant operation. Extended to Scania truck manufacturer, using three criteria, three levels and 21 MPIs (Bernspång and Kali, 2011)
Hydropower – Vattenfall power company (Parida, 2006)	Top-down approach and multi-criteria framework of seven criteria	15 MPIs in seven criteria. General business operation
Oil and gas – Norwegian oil and gas companies (Liyanage and Kumar, 2003)	Linking results to performance drivers of operation and maintenance	
Railway infrastructure – Trafikverket infrastructure manager	Overall railway infrastructure effectiveness (ORIE) ORIE = APQ (availability × performance × quality) (Åhrén and Parida, 2009)	Specific formulation of equipment effectiveness for railway infrastructure operation and maintenance
	Link and effect model for breaking down objectives to analysis and simulation of asset performance data	110 MPIs grouped into managerial and condition based with sub-groups according to asset structure and European Standards (Stenström *et al.*, 2012a) Breakdown methodology and analysis (Stenström, 2013b)
	Maintenance performance measurement taking into account cold climate effects on failures	Failures as a function of temperature for planning maintenance (Stenström *et al.*, 2012b)

- the data to information to knowledge is lacking in automation, resulting in the need for ordering analysis which can take days to months; and
- continuous improvement and training practice is often not fully practiced or on routine, leading to ad hoc management.

The main disadvantages that can be concluded are risk of: inefficiency and poor effectiveness; new KPIs are continuously developed at the same time as old KPIs are forgotten; trend tracking is missing, long lead times and poor quantitative decision support.

7. Future trends and conclusions

The literature review undertaken attempted to include all the relevant PM and MPM frameworks in this paper, which are analysed from MPM context. In this paper, various developed and emerging PM and MPM frameworks are presented. However, not much work has been carried out on the process of actually designing the measurement systems. From the research projects, which have sought results in the design of measurement systems, and as stated by Neely *et al.* (2000a), it has become apparent that much of the writing about PM to date has been too superficial, in that it ignores the complexities involved in the actual design of measurement systems. These issues and aspects are applicable for the MPM frameworks also. The implementation of the MPM framework and the measures designed for the organization are the real challenges for the managers.

The future trends will be related to increase in the availability and capacity utilization of the operational system as per the objectives of the management. Besides, the future trends in MPM are to map the maintenance process and activities, collection and analysing the data to identify the performance killers and drivers, which forms part of the balanced and integrated MPM system. Besides, the MPM framework needs to assess the contribution of maintenance function to achieve the strategic business objectives using qualitative and quantitative data applying RAMS, LCC and eMaintenance approach for correct decision making and benchmarking for achieving the business performance.

References

Abran, A. and Buglione, L. (2003), "A multidimensional performance model for consolidating balanced scorecards", *Advances in Engineering Software*, Vol. 34 No. 6, pp. 339-349.

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 & Modelling, Växjö, 6-7 May*.

Åhrén, T. (2008), "Maintenance performance indicators (MPIs) for railway infrastructure", doctoral thesis, Luleå University of Technology.

Åhrén, T. and Parida, A. (2009), "Maintenance performance indicators (MPIs) for benchmarking the railway infrastructure: a case study", *Benchmarking – An International Journal*, Vol. 16 No. 2, pp. 247-258.

Al-Najjar, B. (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*, Vol. 107 No. 1, pp. 260-273.

Al-Sultan, K.S. and Duffuaa, S.O. (1995), "Maintenance control via mathematical programming", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 3, pp. 36-46.

Alsyouf, I. (2006), "Measuring maintenance performance using a balanced scorecard approach", *Journal of Quality in Maintenance Engineering*, Vol. 12 No. 2, pp. 133-149.

Alsyouf, I. (2007), "The role of maintenance in improving companies' productivity and profitability", *International Journal of Production Economics*, Vol. 105 No. 1, pp. 70-78.

Altmannshoffer, R. (2006), "Der facility manager", *Industrielles FM*, April, pp. 12-13 (in German).

Amaratunga, D. and Baldry, D. (2002), "Moving from performance measurement to performance management", *Facilities*, Vol. 20 Nos 5/6, pp. 217-223.

Andersen, B. and Fagerhaug, T. (2002), *Performance Measurement Explained*, ASQ Quality Press, Milwaukee, WI.

Arca, J.G. and Prado, J.C.P. (2008), "Personnel participation as a key factor for success in maintenance program implementation", *International Journal of Productivity and Performance Management*, Vol. 57 No. 3, pp. 247-258.

Ardalan, A., Hammesfahr, J. and Pope, J. (1992), "Total quality control: the repair facility", *Industrial Management & Data Systems*, Vol. 92 No. 8, pp. 7-10.

Arts, R.H.P.M., Knapp, G.M. and Mann, L. Jr (1998), "Some aspects of measuring maintenance performance in the process industry", *Journal of Quality in Maintenance Engineering*, Vol. 4 No. 1, pp. 6-11.

Ashton, C. (1997), *Strategic Performance Measurement; Transforming Corporate Performance by Measuring and Managing the Drivers of Business Success*, Business Intelligence Ltd, Wimbledon.

Augusto, M., Figueira, J. and Lisboa, J. (2005), "An application of a multi-criteria approach to assessing the performance of Portugal's economic sectors", *European Business Review*, Vol. 17 No. 2, pp. 113-132.

Automain (2012), "Augmented usage of track by optimization of maintenance allocation and inspection of railway networks", EU FP-7 project Automain, available at: www.automain.eu/public-deliverables (accessed 30 August 2012).

Banks, R.L. and Wheelwright, S.C. (1979), "Operations versus strategy – trading tomorrow for today", *Harvard Business Review*, May/June, pp. 112-120.

Ben-Daya, M. and Duffuaa, S.O. (1995), "Maintenance and quality: the missing link", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 1, pp. 20-26.

Bernspång, A. and Kali, J. (2011), "Measuring the performance of a preventive maintenance programme for heavy trucks – from a life cycle profit perspective", available at: www.pm.lth.se (accessed 6 September 2013).

Bititci, U. (1994), "Measuring your way to profit", *Management Decision*, Vol. 32 No. 6.

Bititci, U.S., Carrie, A.S. and McDevitt, L. (1997), "Integrated performance measurement systems: a development guide", *International Journal of Operation & Production Management*, Vol. 17 No. 5, pp. 522-534.

Bititci, U.S., Turner, T. and Begemann, C. (2000), "Dynamics of performance measurement systems", *International Journal of Operations and Production Management*, Vol. 20 No. 6, pp. 692-704.

Blair, M.B. (1995), *Ownership and Control: Rethinking Corporate Governance for the Twenty-first Century*, Brookings Institute, Washington, DC.

Bourne, M. (2005), "Researching performance measurement system implementation: the dynamics of success and failure", *Production Planning & Control*, Vol. 16 No. 2, pp. 101-113.

Bourne, M., Neely, A., Mills, J. and Platts, K. (2003), "Implementing performance measurement systems: a literature review", *International Journal of Business Performance Management*, Vol. 5 No. 1, pp. 1-24.

Bourne, M., Neely, A., Platts, K. and Mills, J. (2002), "The success and failure of performance measurement initiatives perceptions of participating managers", *International Journal of Operations & Production Management*, Vol. 22 No. 11, pp. 1288-1310.

Brown, M. (1996), *Keeping Score: Using the Right Metrics to Drive World Class Performance*, Quality Resources, New York, NY.

Bruns, W. (1998), "Profit as a performance measure: powerful concept, insufficient measure, performance measurement – theory and practise", *The First International Conference on Performance Measurement, Cambridge, 14-17 July*.

Business Intelligence (2000), *Business Intelligence Conference, London, 3-5 May*, Chaired by Kaplan and Norton.

Cabahug, R.R., Edwards, D.J. and Nicholas, J. (2004), "Classifying plant operator maintenance proficiency: examining personal variables", *Building Research & Information*, Vol. 32 No. 2, pp. 119-127.

Cabral, J.P.S. (2009), *Gestã o da Manutenc, ã o de Equipamentos, Instalac, õ es e edificios*, Biblioteca Industria & Servic, os, LIDEL, Lisboa.

Camp, R.C. (1989), *Benchmarking – the Search for Industry Best Practices that Lead to Superior Performance*, ASQS Quality Press, Milwaukee, WI.

Campbell, J.D. (1995), *Uptime Strategies for Excellence in Maintenance Management*, Productivity Press, Portland, OR.

Campbell, J.D. and Jardine, A.K.S. (2001), *Maintenance Excellence: Optimizing Equipment Life-Cycle Decisions*, Marcel Dekker, New York, NY.

Case, J. (1998), "Using measurement to boost your unit's performance". *Harvard Management Update*, Vol. 3, pp. 1-4.

CEN-European Committee for Standardization (2007), "EN 15341 – European Standard – maintenance key performance indicators", Ref. no. EN 15341:2007:E, March.

Chandler, A.D. (1977), *The Visible Hand – Managerial Revolution in American Business*, Harvard University Press, Boston, MA, pp. 417.

Chen, F. (1994), "Benchmarking: preventive maintenance practices at Japanese transplants", *International Journal of Quality & Reliability Management*, Vol. 11 No. 8, pp. 19-26.

Coetzee, J.L. (1997), "Towards a general maintenance model", in Martin, H.H. (Ed.), *Paper No. 12 Proceedings of IFRIM '97*, Maintenance Publishers, Hong Kong, pp. 1-9.

Concetti, M., Cuccioletta, R., Fedele, L. and Mercuri, G. (2009), "Tele-maintenance 'intelligent', system for technical plants result management", *Reliability Engineering and System Safety*, Vol. 94 No. 1, pp. 63-77.

Cooke, F.L. (2003), "Plant maintenance strategy: evidence from four British manufacturing firms", *Journal of Quality in Maintenance Engineering*, Vol. 9 No. 3, pp. 239-249.

COVENIN (1993), *Manual para evaluarlos sistemas de mantenimiento en la industria (Manual For Evaluating Maintenance Systems Industry)*, Venezuelan Commission for Industrial Standards (COVENIN), Venezuela.

Cross, M. (1988), "Engineering maintenance organization performance an assessment of the evidence from over 200 sites", *Management Research News*, Vol. 11 Nos 1/2, pp. 20-23.

Davies, C.R. (1990), "Computer-based planned maintenance programmes", *Property Management*, Vol. 8 No. 1, pp. 40-60.

De Groote, P. (1995), "Maintenance performance analysis: a practical approach", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 2, pp. 4-24.

Dhillon, B.S. and Liu, Y. (2006), "Human error in maintenance: a review", *Journal of Quality in Maintenance Engineering*, Vol. 12 No. 1, pp. 21-36.

Dixon, J.R., Nanni, A.J. and Vollmann, T.E. (1990), *The New Performance Challenge- Measuring Operations for World-class Competition*, Dow Jones- Irwin, Homewood, IL.

Duffuaa, S.O., Raouf, A. and Campbell, J.D. (1999), *Planning and Control of Maintenance Systems: Modeling and Analysis*, John Wiley and Sons, New York, NY.

Duffuaa, S.O., Ben-Daya, M., Al-Sultan, K.S. and Andijani, A.A. (2001), "A generic conceptual simulation model for maintenance systems", *Journal of Quality in Maintenance*, Vol. 7 No. 3, pp. 207-219.

Dwight, R.A. (1994), "Performance indices: do they help in decision making?", *Proceedings of ICOMES-94, Sydney*, pp. 1-9.

Dwight, R.A. (1995), *Concepts of Measuring Maintenance Performance, New Developments in Maintenance*, Moret Ernst & Young Management Consultants, Amsterdam, pp. 109-125.

Eccles, R.G. (1991), "The performance measurement manifesto", *Harvard Business Review*, January-February, pp. 131-137.

Edvinsson, L. and Malone, M.S. (1997), *Intellectual Capital: Realizing your Company's True Value by Finding its Hidden Brainpower*, Harper Business, New York, NY.

Encyclopedia Britannica (2003), "Economic indicator", available at: http://search.eb.com/ (accessed 20 May 2004).

European Environment Agency (EEA) (1999), "Enviromental indicators: typology and overview", Technical Report No 25, Copenhagen.

Eti, M.C., Ogaji, S.O.T. and Probert, S.D. (2005), "Maintenance schemes and their implementation for the Afam thermal-power station", *Applied Energy*, Vol. 82 No. 3, pp. 255-265.

Feurer, R. and Chaharbaghi, K. (1995), "Strategy formulation: a learning methodology", *Benchmarking for Quality, Management & Technology*, Vol. 2 No. 1, pp. 38-55.

Fitzgerald, L., Johnson, R., Brignall, S., Silvestro, R. and Voss, C. (1991), *Performance Measurement in Service Businesses*, CIMA, London.

Flapper, S., Fortuin, L. and Stoop, P. (1996), "Towards consistent performance management systems", *International Journal of Operation & Production Management*, Vol. 16 No. 7, pp. 27-37.

Galar, D., Berges, L., Lamban, P. and Royo. J. (2010a), *La jerarquía de los KPIs de la función mantenimiento y el nuevo rol de los parámetros RAMS*, XII Jornadas de Confiabilidad, Cadiz.

Galar, D., Parida, A., Kumar, U., Baglee, D. and Morant, A. (2012), "The measurement of maintenance function efficiency through financial KPIs", *Proceedings of 25th International Congress on Condition Monitoring and Diagnostic Engineering (COMADEM 2012), IOP Publishing Ltd, Huddersfield, 18-20 June*.

Galar, D., Parida, A., Kumar, U., Stenström, C. and Berger, L. (2011b), "Maintenance metrics: a hierarchical model of balanced scorecard", *IEEE International Conference on Quality and Reliability (IEEQR), Piscataway, NJ*, pp. 67-74.

Galar, D., Stenström, C., Parida, A., Kumar, R. and Berges, L. (2011b), "Human factor in maintenance performance measurement", *2011 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), 6-9 December*, pp. 1569-1576.

Garg, A. and Deshmukh, S.G. (2006), "Maintenance management: literature review and directions", *Journal of Quality in Maintenance Engineering*, Vol. 12 No. 3, pp. 205-238.

Gates, S. (1999), *Aligning Strategic Performance Measures and Results*, The Conference Board, New York, NY.

Geanuracos, J. and Meiklejohn, I. (1993), *Performance Measurement: the New Agenda*, Business Intelligence, London.

Ghalayini, A., Noble, J. and Crowe, T. (1997), "An integrated dynamic performance measurement system for improving manufacturing competitiveness", *International Journal of Production Economics*, Vol. 48 No. 8, pp. 207-225.

Ghalayini, A.M. and Noble, J.S. (1996), "The changing basis of performance measurement", *International Journal of Operations & Production Management*, Vol. 16 No. 8, pp. 63-80.

Globerson, S. (1985), "Issues in developing a performance criteria system for an organization", *International Journal of Production Research*, Vol. 23 No. 4, pp. 639-646.

Goh, M. and Tay, G.-H. (1995), "Implementing a quality maintenance system in a military organization", *International Journal of Quality & Reliability Management*, Vol. 12 No. 4, pp. 26-39.

Goldratt, E.M. and Cox, J. (1986), *The Goal: Beating the Competition*, Creative Output Books, Hounslow.

Gomes, C.F., Yasin, M.M. and Lisboa, J.V. (2004), "A literature review of manufacturing performance measures in an organizational context: a framework and direction for future research", *Journal of manufacturing Technology Management*, Vol. 15 No. 6, pp. 511-530.

Haarman, M. and Delahay, G. (2006), *Value Driven Maintenance: What is the Actual Added Value of Maintenance*?, Mainnovation, Dordrecht.

Hall, R.W. (1983), *Zero Inventories*, Dow-Jones Irwin, Homewood, IL.

Hayes, R.H. and Abernathy, W.J. (1980), "Managing our way to economic decline", *Harvard Business Review*, Vol. 58 No. 4, pp. 67-77.

Hayes, R.H. and Garvin, D.A. (1982), "Managing as if tomorrow mattered", *Harvard Business Review*, Vol. 60 No. 3, pp. 70-79.

Huang, S. and Dismukes, J.P. (2003), "Manufacturing productivity improvement using effectiveness metrics and simulation analysis", *International Journal of Production Research*, Vol. 41 No. 3, pp. 513-527.

Hwang, W.T., Tien, S.W. and Shu, C.M. (2007), "Building an executive information system for maintenance efficiency in petrochemical plants – an evaluation", *Process Safety and Environmental Protection*, Vol. 85 No. B2, pp. 139-146.

Johnson, H.T. and Kaplan, R.S. (1987), *Relevance Lost – The Rise and Fall of Management Accounting*, Harvard Business School Press, Boston, MA.

Jonsson, P. (1999), "Company-wide integration of strategic maintenance: an empirical analysis", *International Journal of Production Economics*, Vols 60/61 No. 20, pp. 155-164.

Kanji, G.K. (1998), "Measurement of business excellence", *Total Quality Management*, Vol. 9 No. 1, pp. 633-643.

Kans, M. (2008), "An approach for determining the requirements of computerised maintenance management systems", *Computers in Industry*, Vol. 59 No. 1, pp. 32-40.

Kaplan, R.S. (1983), "Measuring manufacturing performance: a new challenge for managerial accounting research", *Accounting Review*, Vol. 58 No. 4, pp. 686-703.

Kaplan, R.S. (1984), "Yesterday's accounting undermines production", *Harvard Business Review*, Vol. 62, July, pp. 95-101.

Kaplan, R.S. (1986), "Accounting lag – the obsolescence of cost accounting systems", *California Management Review*, Vol. 28 No. 2, pp. 174-199.

Kaplan, R.S. and Norton, D.P. (1992), "The balanced scorecard – measures that drive performance", *Harvard Business Review*, Vol. 70 No. 1, pp. 71-79.

Kaplan, R.S. and Norton, D.P. (1996), *The Balanced Scorecard: Translating Strategy into Action*, Harvard Business School Press, Boston, MA, pp. 322.

Kaplan, R.S. and Norton, D.P. (2001), "Transforming the balanced scorecard from performance measurement to strategic management part I", *Accounting Horizons*, Vol. 15 No. 1, pp. 87-104.

Karim, R., Candell, O. and Soderholm, P. (2009), "E-maintenance and information logistics: aspects of content format", *Journal of Quality in Maintenance Engineering*, Vol. 15 No. 3, pp. 308-324.

Keegan, D.P., Eiler, R.G. and Jones, C.R. (1989), "Are your performance obsolete?", *Management Accounting (US)*, Vol. 70 No. 12, pp. 45-50.

Kennerly, M. and Neely, A. (2002), "Performance measurement frameworks: a review", in Neely, A. (Ed.), *Business Performance Measurement*, Cambridge University Press, Cambridge, pp. 145-156.

Kennerly, M. and Neely, A. (2003), "Measuring performance in a changing business environment", *International Journal of Operation & Production Management*, Vol. 23 No. 2, pp. 213-229.

Knight, D.J. (1999), "Performance measure for increasing intellectual capital", *Strategy and Leadership*, 1999, pp. 71-78.

Koc, M. and Lee, J. (2001), "A system framework for next-generation E-maintenance systems", *Proceedings of the 2nd international Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, 11-15 December*.

Komonen, K. (2002), "A cost model of industrial maintenance for profitability analysis and benchmarking", *International Journal of Production Economics*, Vol. 79 No. 1, pp. 15-31.

Kumar, U. (1998), "Design and development of maintenance performance indicators for the Norwegian Oil and Gas companies", research project plan, Stavanger, available at: www.his.no/SDV (accessed 11 November 2009).

Kumar, U. and Ellingsen, H.P. (1999), "The maintenance management process", Technical report PI-TEC-T4/REV1, Project: Development & Implementation of Operation & Maintenance Performance Indicators, Stavanger.

Kumar, U. and Ellingsen, H.P. (2000), "Development and implementation of maintenance performance indicators for the norwegian oil and gas industry", *Proceedings of the 14th International Maintenance Congress (Euro Maintenance 2000), Gothenburg, 7-10 March*, pp. 221-228.

Kumar, U., Galar, D., Parida, A. and Stenström, C. (2011a), "Maintenance audits using balanced scorecard and maturity model", *Maintworld*, No. 3, pp. 34-40.

Kumar, U., Galar, D., Parida, A., Stenström, C. and Berges, L. (2011b), "Maintenance performance metrics: a state of the art review", *Proceedings of MPMM 2011: (Maintenance Performance Measurement & Management), Luleå : Luleå tekniska universitet, 13-15 December, Lulea*, ISBN 78-91-7439-379-8, pp. 3-34.

Labib, A.W. (1998), "World-class maintenance using a computerized maintenance management system", *Journal of Quality in Maintenance Engineering*, Vol. 4 No. 1, pp. 66-75.

Labib, A.W. (2004), "A decision analysis model for maintenance policy selection using a CMMS", *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 3, pp. 191-202.

Laitinen, E. (1996), *Framework for Small Business Performance Measurement*, Vaasan yliopisto (University of Vaasa), Vasa.

Leidecker, J.K. and Bruno, A.V. (1984) "Identifying and using critical success factors", *Long Range Planning*, Vol. 17 No. 1, pp. 23-32.

Lewis, M. (1996), "Translating strategy into action at mobil", *Business Performance Measurement Conference, Business Intelligence, London, 22-23 October*.

Lingle, J.H. and Schiemann, W.A. (1996), "From balanced scorecard to strategy gauge: is measurement worth it?", *Management Review*, pp. 56-62.

Liyanage, J.P. and Kumar, U. (2003), "Towards a value-based view on operations and maintenance performance management", *Journal of Quality in Maintenance Engineering*, Vol. 9 No. 4, pp. 333-350.

Ljungberg, O. (1998), "Measurement of overall equipment effectiveness as a basis for TPM activities", *International Journal of Operations & Production Management*, Vol. 18 No. 5, pp. 495-507.

Lönnqvist, A. (2004), "Business performance measurement for knowledge-intensive organizations", available at: www.pmteam.tut.fi/julkaisut/HK.pdf (accessed 22 August 2004).

Lynch, R.L. and Cross, K.F. (1991), *Measure Up! The Essential Guide to Measuring Business Performance*, Mandarin, London.

Lyytinen, K. and Hirschheim, R. (1987), "Information system failures: a survey and classification of the empirical literature", *Oxford Surveys in Information Technology*, Oxford University Press, Oxford, pp. 257-309.

Madu, C.N. (2000), "Competing through maintenance strategies", *International Journal of Quality & Reliability Management*, Vol. 17 No. 9, pp. 937-948.

Markeset, T. and Kumar, U. (2005), "Product support strategy: conventional versus functional products", *Journal of Quality in Maintenance Engineering*, Vol. 11 No. 1, pp. 53-67.

Maskell, B. (1989), "Performance measures for world class manufacturing", *Management Accounting*, pp. 32-33.

Medori, D. and Steeple, D. (2000), "A framework for auditing and enhancing performance measurement systems", *International Journal of Operation & Production Management*, Vol. 20 No. 5, pp. 520-533.

Meyer, M.W. and Gupta, V. (1994), "The performance paradox", in Straw, B.M. and Cummings, L.L. (Eds), *Research in Organizational Behavior*, Vol. 16, JAI Press, Greenwich, CT, pp. 309-369.

Miles, M.B. and Huberman, A.M. (1994), *Qualitative Data Analysis*, Sage Publication, CA.

Mobley, R.K. (1990), *An Introduction to Predictive Maintenance*, Van Nostrand Reinhold, New York, NY.

Morris, D. (1996), "Integrating improvement programmes to harness and direct company wide initiatives", *Business Performance Measurement Conference, Business Intelligence, London, 22-23 October*.

Muchiri, P.N. and Pintelon, L. (2008), "Performance measurement using overall equipment effectiveness (OEE): literature review and practical application", *International Journal of Production Research*, Vol. 46 No. 13, pp. 3517-3535.

Muller, A., Marquez, A.C. and Iung, B. (2007), "On the concept of emaintenance: review and current research", *Journal of Reliability Engineering and System Safety*, Vol. 93 No. 8, pp. 1165-1187.

Nakajima, S. (1988), *Introduction to TPM: Total Productive Maintenance*, Productivity Press, Cambridge, MA.

Neely, A., Mills, J., Platts. K., Richards, H., Gregory, M., Bourne, M. and Kennerley, M. (2000a), "Performance measurement system design: developing and testing a process-based approach", *International Journal of Operations & Production Management*, Vol. 20 No. 10, pp. 1119-1145.

Neely, A.D. (1999), "The performance measurement revolution: why now and what next?", *International Journal of Operations and Production Management*, Vol. 19 No. 2, pp. 205-228.

Neely, A.D. and Adams, C. (2002), *Perspective on Performance: The Performance Prism*, Crane field University, Cranfield, available at: www.cranefield.ac.uk/som/cbp/prism.htm

Neely, A.D., Gregory, M. and Platts, K. (1995), "Performance measurement system design – a literature review and research agenda", *International Journal of Operations and Production Management*, Vol. 15 No. 4, pp. 80-116.

Neely, A.D., Gregory, M. and Platts, K. (2005), "Performance measurement research development in the last decade and a research agenda for the next", *International Journal of Operations and Production Management*, Vol. 25 No. 12, pp. 1264-1277.

Neely, A.D., Kennerley, M.P. and Adams, C.A. (2000b), *The New Measurement Crisis: The Performance Prism as a Solution*, Cranfield School of Management, Cranfield.

Neely, A.D., Richards, A.H., Mills, J.F., Platts, K.W. and Bourne, M.C.S. (1997), "Designing performance measures: a structured approach", *International Journal of Operation & Production Management*, Vol. 17 No. 11, pp. 1131-1153.

Norma Venezolana (1993), "Manual para evaluarlos sistemas de mantenimiento en la industria", *Covenin*, No. 2500, pp. 2500-2593.

Oliver, L. and Palmer, E. (1998), "Integrated model for infrastructural implementation of performance measurement", *Performance Measurement – Theory and Practice (Conference Proceedings), Vol. 2, Cambridge, Cambridge University*, pp. 695-702.

Parida, A. (2006), "Development of a multi-criteria hierarchical framework for maintenance performance measurement concepts, issues and challenges", doctoral thesis Number 2006:37, Luleå University of Technology, Luleå, ISSN: 1402-1544.

Parida, A. (2007), "Study and analysis of maintenance performance indicators (MPIs) for LKAB", *Journal of Quality in Maintenance Engineering*, Vol. 13 No. 4, pp. 325-337.

Parida, A. (2012), "Asset performance assessment", *Asset Management Chapter 7*, Springer Science Publications, Dordrecht.

Parida, A. and Chattopadhyay, G. (2007), "Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM)", *Journal of Quality in Maintenance Engineering*, Vol. 13 No. 3, pp. 241-258.

Parida, A. and Kumar, U. (2004a), "Measurement of environmental management system's effectiveness", *Proceedings of 8th SWEMP 2004, Antalya, 17-20 May*, pp. 33-38.

Parida, A. and Kumar, U. (2004b), "Application of overall equipment effectiveness (OEE) as a process performance indicator: a case study from Kiruna mines", *Proceedings of ENTMS Aneswar, Bhubaneswar, 11-12 May* .

Parida, A. and Kumar, U. (2004c), "Managing information is key to maintenance effectiveness", *e-Proceedings of the IMS' 2004, Arles, 15-17 July*.

Parida, A. and Kumar, U. (2004d), "E-maintenance for equipments effectiveness in mining and mineral based industry", *Proceedings of MPES 2004, Wroclow, 1-3 September*.

Parida, A. and Kumar, U. (2006), "Maintenance performance measurement (MPM): issues and challenges", *Journal of Quality in Maintenance Engineering*, Vol. 12 No. 3, pp. 239-251.

Parida, A. and Kumar, U. (2009), "Maintenance productivity and performance measurement", in Ben-Daya, M., Duffuaa, S.O., Raouf, A., Knezevic, J. and Aitkadi, D. (Eds), *Handbook of Maintenance Management and Engineering*, 1st ed., Springer, London, pp. 17-41.

Parida, A., Åhrén, T. and Kumar, U. (2003), "Integrating maintenance performance with corporate balanced scorecard", *COMADEM 2003, Proceedings of the 16th International Congress, Växjö, 27-29 August*, pp. 53-59.

Patankar, M.S. and Taylor, J.C. (2000), "MRM training, evaluation, and safety management", *The International Journal of Aviation Psychology*, Vol. 18 No. 1, pp. 61-71.

Patra, A.P., Kumar, U. and Larsson-Kråik, P.-O. (2009), "Assessment and improvement of railway track safety", *Proceedings of 9th International Heavy Haul Conference (IHHA), Shanghai, 22-24 June*.

Pinjala, S.K., Pintelon, L. and Vereecke, A. (2006), "An empirical investigation on the relationship between business and maintenance strategies", *International Journal of Production Economics*, Vol. 104 No. 1, pp. 214-229.

Pintelon, L. and Parodi-Herz, A. (2008), "Maintenance: an evolutionary perspective", in Kobbacy, K.A.H. and Murthy, D.N.P. (Eds), *Complex System Maintenance Handbook*, 1st ed., Springer, London, pp. 21-48.

Pintelon, L. and Puyvelde, F.V. (1997), "Maintenance performance reporting systems: some experiences", *Journal of Quality in Maintenance Engineering*, Vol. 3 No. 1, pp. 4-15.

PI-TEC-T5/REV0 (Task 5 Development of indicators) (2000), *Development & Implementation of Operation & Maintenance Performance Indicators*, PI-TEC-T5/REV0 (Task 5 Development of indicators), Oslo.

Porter, L.W. and Lawler, E.E. (1968), *Managerial Attitudes and Performance*, Dorsey, Homewood, IL.

Rankin, W., Hibit, R., Allen, J. and Sargent, R. (2000), "Development and evaluation of the maintenance error decision aid (MEDA) process", *International Journal of Industrial Ergonomics*, Vol. 26 No. 2 , pp. 261-276.

Raouf, A. (1993), "On evaluating maintenance performance", *International Journal of Quality & Reliability Management*, Vol. 10 No. 3, pp. 33-36.

Raouf, A. and Ben-Daya, M. (1995), "Total maintenance management: a systematic approach", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 1, pp. 6-14.

Richardson, P.R. and Gordon, J.R.M. (1980), "Measuring total manufacturing performance", *Sloan Management Review*, pp. 47-58.

Rosqvist, T., Laakso, K. and Reunanen, M. (2009), "Value-driven maintenance planning for a production plant", *Reliability Engineering & System Safety*, Vol. 94 No. 1, pp. 97-110.

Rouse, P. and Putterill, L. (2003), "An integral framework for performance measurement", *Management Decision*, Vol. 41 No. 8, pp. 791-805.

Salminen, J. (2005), "Measuring performance and determining success factor of construction sites", doctoral dissertation, Helsinki University of Technology, Helsinki, ISBN 951-22-7493-0.

Schmenner, R.W. (1988), "Escaping the black holes of cost accounting", *Business Horizons*, January-February, pp. 66-72.

Schneiderman, A. (1999), "Why balanced scorecards fail", *Journal of Strategic Performance Measurement*, Special Issue, pp. 6-11.

Sherwin, D.J. and Jonsson, P. (1995), "TQM, maintenance and plant availability", *Journal of Quality in Maintenance Engineering*, Vol. 1 No. 1, pp. 15-19.

Simões, J.M., Gomes, C.F. and Yasin, M.M. (2011), "A literature review of maintenance performance measurement", *Journal of Quality in Maintenance Engineering*, Vol. 17 No. 2, pp. 116-137.

Sink, D. and Tuttle, T.C. (1989), *Planning and Measurement in your Organization of the Future*, Industrial Engineering and Management Press, Norcross, GA.

Skinner, W. (1971), "The anachronistic factory", *Harvard Business Review*, pp. 61-70.

Skinner, W. (1974), "The decline, fall and renewal of manufacturing", *Industrial Engineering*, October, pp. 32-38.

Skousen, K., Albrecht, J., Stice, E. and Swain, M. (2001), *Management Accounting*, Volume 2, South-Western, Cincinnati, OH.

Smith, R. (2001), "Key Performance Indicators- leading or lagging and when to use them", available at: www.reliabilityweb.com (accessed 12 March 2003).

Söderholm, P. and Akersten, P.A. (2002), "Aerospace diagnostics and prognostics in a TQM perspective", *Proceedings of the 15th International Congress of COMADEM 2002, Birmingham, 2-4 September*, pp. 80-89.

Stenström, C. (2012), "Link and effect model for performance improvement of railway infrastructure", Licentiate thesis, Luleå University of Technology, Luleå, ISBN 1402-1757.

Stenström, C., Parida, A. and Galar, D. (2012a), "Maintenance performance indicators for railway infrastructure management", in Pombo, J. (Ed.), *Proceedings of the First International Conference on Railway Technology: Research, Development and Maintenance*, Civil-Comp Press, Stirlingshire, p. 85.

Stenström, C., Parida, A., Kumar, U. and Galar, D. (2013a), "Performance indicators and terminology for value driven maintenance", *Journal of Quality in Maintenance Engineering*, Vol. 19 No. 3.

Stenström, C., Parida, A., Galar, D. andKumar, U. (2013b), "Link and effect model for performance improvement of railway infrastructure", *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, Vol. 227 No. 4, pp. 392-402.

Stenström, C., Famurewa, S., Parida, A. and Galar, D. (2012b), "Impact of cold climate on failures in railway infrastructure", *Proceedings of the 2nd International Conference on Maintenance Performance Measurement & Management, Sunderland, 12-13 September*.

Svantesson, T. (2011), "EFNMS-SMRP maintenance and reliability indicator harmonization project", *Proceedings of (MPMM 2011): Maintenance Performance Measurement & Management, Luleå tekniska universitet*, pp. 191-200.

Sveiby, K.E. (1997), *The New Organisational Wealth: Managing and Measuring Knowledge Based Assets*, Berett Koehler, San Francisco, CA.

Sveiby, K.E. (2004), "Methods for measuring intangible assets", avialable at: www.sveiby.com.au/IntangibleMethods.html (accessed 22 August 2004).

Swanson, L. (1997), "An empirical study of the relationship between production technology and maintenance management", *International Journal of Production Economics*, Vol. 53 No. 2, pp. 191-207.

Takata, S., Kimura, F., van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ceglarek, D. and Lee, J. (2004), "Maintenance: changing role in life cycle management", *CIRP Annals –Manufacturing Technology*, Vol. 53 No. 2, pp. 643-655.

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.

Tsang, A.H.C. (2000), *Maintenance Performance Management in Capital Intensive Organizations*, University of Toronto, Toronto.

Tsang, A.H.C. (2002), "Strategic dimensions of maintenance management", *Journal of Quality in Maintenance Engineering*, Vol. 8 No. 1, pp. 7-39.

Tsang, A.H.C., Jardine, A.K.S. and Kolodny, H. (1999), "Measuring maintenance performance: a holistic approach", *International Journal of Operation & Production Management*, Vol. 19 No. 7, pp. 691-715.

Turney, P.B.B. and Anderson, B. (1989), "Accounting for continuous improvement", *Sloan Management Review*, Vol. 30 No. 2, pp. 37-48.

Uusipaavalniemi, S. and Juga, J. (2009), "Information integration in maintenance services", *International Journal of Productivity and Performance Management*, Vol. 58 No. 1, pp. 92-110.

Vroom, V.H. (1964), *Work and Motivation*, John Wiley & Sons, New York, NY.

Wang, C. and Hwang, S. (2004), "A stochastic maintenance management model with recovery factor", *Journal of Quality in Maintenance Engineering*, Vol. 10 No. 2, pp. 154-165.

Weber, A.M. (2000), "New math for a new economy", *Fast Company*, No. 31.

Westerkamp, T.A. (1993), *Maintenance Manager's Standard Manual*, Prentice-Hall, Englewood Cliff, NJ, pp. 765-784.

Wireman, T. (1990), *World Class Maintenance Management*, Industrial Press, New York, NY.

Wireman, T. (1998), *Developing Performance Indicators for Managing Maintenance*, Industrial Press Inc., New York, NY, p. 1998.

Wongrassamee, S., Gardiner, P.D. and Simmons, J.E.L. (2003), "Performance measurement tools: the balanced scorecard and the EFQM excellence model", *Measuring Business Performance*, Vol. 7 No. 1, pp. 14-29.

Yam, R.C.M., Tse, P., Ling, L. and Fung, F. (2000), "Enhancement of maintenance management through benchmarking", *Journal of Quality in Maintenance Engineering*, Vol. 6 No. 4, pp. 224-240.

Further reading

Downing, L. (2001), "The Global BSC community: a special report on implementation experience from scorecard users worldwide", European Summit on Balanced Scorecard, Nice, May.

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.

Haarman, M. and Delahay, G. (2004), *Value Driven Maintenance – New Faith in Maintenance*, Mainnovation, Dordrecht.

Ittner, C.D. and Larcker, D.F. (2003), "Coming up short on nonfinancial", *Performance Measurement, Harvard Business Review*, Vol. 81 No. 11, pp. 88-95.

Kahn, J.D. and Klemme-Wolff, H. (2004), "Overview of MIMOSA and the open system architecture for enterprise application integration", *Proceedings of the 17th European Congress, Barcelona, 11-13 May*, pp. 333-341.

Kutucuoglu, K.Y., Hamali, J., Irani, J. and Sharp, J.M. (2001), "A framework for managing maintenance using performance measurement systems", *International Journal of Operation and Production Management*, Vol. 21 Nos 1/2, pp. 173-194.

Medori, D. (1998), *Integrated Performance Measure Framework*, Coventry University, Coventry.

Mitchell, J. (2002), *Physical Asset Management Handbook*, Clarion Technical Publishers, Houston, TX.

Moubray, J. (1997), *Reliability–Centered Maintenance*, Published by Butterworth Heinemann, Oxford.

Neely, A.D. (1998), *Measuring Business Performance: Why, Why and How*, Economist Books, London.

Parida, A., Johansson, D. and Edelman, M. (2004), "Success of reliability centered maintenance (RCM) lies in its implementation: a case study", *Workshop Proceedings of 17th European Maintenance Congress 2004, Barcelona, 11-13 May*, pp. 229-236.

PROTEUS (2004), "A generic platform for e-maintenance", available at: www.itea2.org; www.eurekanetwork.org (accessed 22 July 2007).

Söderholm, P. and Parida, A. (2004), "Health management of complex technical systems", *COMADEM 2004, Proceedings of the 17th International Congress, Cambridge, 23-25 August.*

Stenström, C., Parida, A., Kumar, U. and Galar, D. (2011), "Maintenance value drivers, killers and their indicators", *Proceedings of (MPMM 2011): Maintenance Performance Measurement & Management, Luleå tekniska universitet*, pp. 125-130.

Wealleans, D. (2000), *Organizational Measurement Manual*, Abingdon, Oxon.

Wisner, J.D. and Fawcett, S.E. (1991), "Link firm strategy to operate decisions through performance measurement", *Production and Inventory Management Journal*, pp. 5-11.

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