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Emerald Article: Maintenance management: literature review and directions

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APPLICATIONS AND CASE STUDIES

Maintenance management: literature review and directions

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Abstract

Purpose – The purpose of this paper is to review the literature on maintenance management and suggest possible gaps from the point of view of researchers and practitioners.

Design/methodology/approach – The paper systematically categorizes the published literature and then analyzes and reviews it methodically.

Findings – The paper finds that important issues in maintenance management range from various optimization models, maintenance techniques, scheduling, and information systems etc. Within each category, gaps have been identified. A new shift in maintenance paradigm is also highlighted.

Practical implications – Literature on classification of maintenance management has so far been very limited. This paper reviews a large number of papers in this field and suggests a classification in to various areas and sub areas. Subsequently, various emerging trends in the field of maintenance management are identified to help researchers specifying gaps in the literature and direct research efforts suitably.

Originality/value – The paper contains a comprehensive listing of publications on the field in question and their classification according to various attributes. The paper will be useful to researchers, maintenance professionals and others concerned with maintenance to understand the importance of maintenance management

Keywords Maintenance, Optimization techniques, Production scheduling, Performance measures, Information systems

Paper type Literature review

Introductions

Throughout the years, the importance of the maintenance function and therefore of maintenance management has grown. The widespread mechanization and automation has reduced the number of production personnel and increased the capital employed in the production equipment and civil structures. As a result, the fraction of employees working in the area of maintenance as well as the fraction of maintenance spending on the total operational costs has grown over the years. In refineries, for instance, it is not uncommon that the maintenance and operations departments are the largest, and each comprises 30 percent of the total manpower. Furthermore, next to the energy costs, maintenance costs can be the largest part of any operational budget. Yet, the main question faced by the maintenance management, whether its output is produced more effectively, in terms of contribution to company profits and efficiently, in terms of manpower and materials employed, is very difficult to answer.

A lot of literature is available from various resources in the field of maintenance management. Dekker and Scarf (1998) have presented various classifications of maintenance optimization models by analyzing 112 papers. In the area of maintenance

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performance measurement an overview of various performance measurement systems (PMS), including indicators, reference numbers and surveys, has been discussed in detail (Pintelon and Puyvelde, 1997). Various approaches for measuring maintenance performance have also been reviewed (Tsang *et al.*, 1999). In another invited review, Wang (2002) has undertaken a survey of maintenance policies of deteriorating systems and has finally summarized, classified and compared various existing maintenance policies for both single- and multi-unit systems with emphasis on single unit systems.

The specific objectives of this paper are:

(1) To suggest a classification of available literature in the field of maintenance management.

(2) To identify critical observations on each classification.

(3) To identify emerging trends in the field of maintenance management.

(4) Based on above, to suggest directions for future researchers in this field.

(5) As far as possible to consolidate all available literature on maintenance management.

The organization of this paper is as follows:

(1) After a brief introduction, in the next section existing literature on maintenance has been classified in to a number of areas and sub areas.

(2) Detailed discussion on these areas/sub areas along with critical observations on each is undertaken in the next section.

(3) In the final section, changing trends in the area of maintenance management have been identified along with recommendations for the future research work.

Outcome of the literature survey

A total of 142 papers were collected and analyzed. A broad classification of this literature in to six areas giving year wise distribution is given at Table I. These areas are:

(1) (A) maintenance optimization models;

(2) (B) maintenance techniques;

(3) (C) maintenance scheduling;

(4) (D) maintenance performance measurement;

(5) (E) maintenance information systems; and

(6) (F) maintenance policies.

Maintenance optimization models can be both qualitative and quantitative. The former includes techniques like total productive maintenance (TPM), reliability centered maintenance (RCM), etc. while the later incorporates various deterministic/ stochastic models like Markov Decision, Bayesian models, etc. There has been a long journey of maintenance techniques evolution from corrective maintenance (CM) in 1940 to various operation research (OR) models for maintenance as on today. A number of latest techniques have been analyzed under this broad area. Unlike scheduling in production, the maintenance schedule becomes immediately out of place as soon as an emergency job is received. Maintenance scheduling is therefore another challenging area, which merits

	Area	2004-2006	2003	2002	2001	2000	1999	1998	1997	1996	1995	Others	Total
A	Maintenance optimization models	3	5	6	2	4	2	3	1	–	–	1 (1992)	27
B	Maintenance techniques	6	8	9	15	5	6	4	3	2	–	–	58
C	Maintenance scheduling	1	1	2	2	2	1	–	–	–	–	–	9
D	Maintenance performance measurement	3	4	1	3	1	3	3	2	1	2	–	23
E	Maintenance information system	1	–	1	–	–	3	–	–	1	–	–	6
F	Maintenance policies	2	1	5	4	1	1	2	1	1	–	1 (1992)	19
	Total	16	19	24	26	13	16	12	7	5	2	2	142

Table I.
Classifications of research areas

separate investigation. An effective performance measurement system is essential for effective functioning of any organization as whatever gets measured has a higher probability of its completion. The first maintenance management information system (MMIS) appeared in the 1980s due to the full recognition of maintenance as an important business function. The same has now become an essential component of any maintenance organization and thus merits investigation also under a separate area. Similarly, the various maintenance policies can be classified as age replacement policy, periodic repair policy, block repair policy, failure limit policy, etc. each of which has different characteristics, advantages and disadvantages and requires extensive research.

Further sub classification of these areas in to several sub areas has also been attempted after critical scrutiny. The detailed classification of the same is represented in Figure 1 and year-wise distribution tabulated in Table II.

Analysis of research areas with observations

Each of the above six areas and sub areas have been discussed in detail with critical observations in this section.

(A) Maintenance optimization models

The quantitative approach to maintenance optimization is covered in detail in the literature with a total of 24 papers in past few years. During the past few decades widespread mechanization and automation has reduced the number of production personnel while capital employed in production equipment has increased manifold (Dekker and Scarf, 1998). In general, maintenance optimization models cover four aspects:

(1) a description of a technical system, its function and importance;

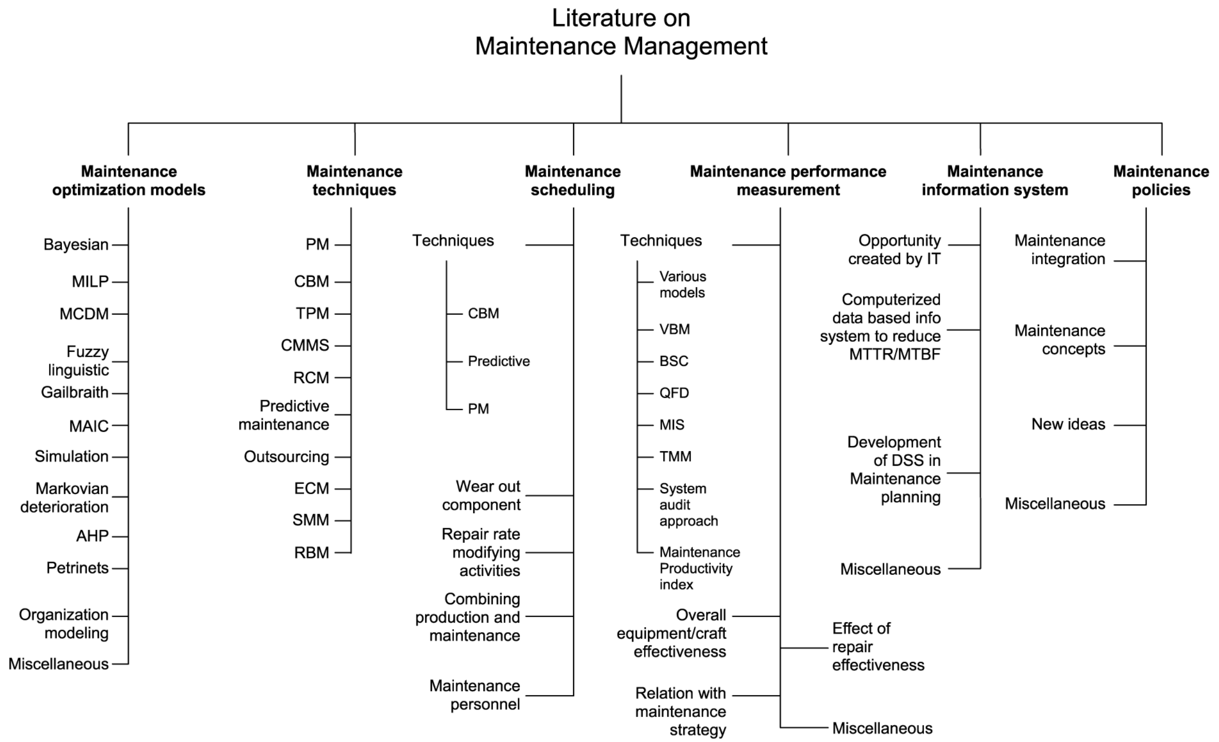
(2) a modeling of the deterioration of the system in time and possible consequences for this system;

(3) a description of the available information about the system and actions open to management; and

(4) an objective function and an optimization technique which helps in finding the best balance.

The models have been classified according to the modeling of the deterioration as deterministic or stochastic models. The later is further classified as stochastic models under risk or under warranty.

Dekker and Scarf (1998) also present another classification of these models as age and block replacement models, Markov decision models and delay time models. They have further identified a total of 112 papers containing applications and classified them as case studies if models have been used with real data to provide advice on real problems to the management, or classified as in which a new model is put central and in which indications are given about applications of the model, or classified as in which model focuses on an application tool, like a decision support system or expert system and which mentions applications of the tool. They also brought out that equipment overhauls comprised the largest group of applications (about 30) followed by the area of vehicle replacements (about ten). A suggested sub classification of this area in to 12 sub areas is discussed as follows.



Notes: MILP: Mixed Integer Linear Programming; MCDM: Multiple Criteria Decision Making; MAIC: Materially per Apparecchiature de Impiariti Chemiei; AHP: Analytic Hierarchy Process; PM: Preventive Maintenance; CBM: Condition Based Maintenance; TPM: Total Productive Maintenance; CMMS: Computerized Maintenance Management Systems; RCM: Reliability Centered Maintenance; ECM: Effectiveness Centered Maintenance; SMM: Strategic Maintenance Management; RBM: Risk Based Maintenance; VBM: Vibration Based Maintenance; BSC: Balanced Score Card; MTTR: Mean Time to Repair; MTBF: Mean Time Between Failure; QFD: Quality Function Deployment; MIS: Maintenance Information Systems; TMM: Total Maintenance Management; DSS: Decision Support Systems; ECM: Electronic Counter Measures

Figure 1.
Maintenance management classification tree showing various sub areas

Table II.
Sub-classification of areas

Area	Sub area	2004-2006	2003	2002	2001	2000	1999	1998	1997	1996	1995	Others	Sub-area total	Total
A Maintenance optimization models														27
	A.1 Bayesian	1	1	–	–	–	–	–	–	–	–	–	2	
	A.2 MILP	–	1	–	–	–	–	–	–	–	–	–	1	
	A.3 MCDM	–	1	–	–	–	–	–	1	–	–	–	2	
	A.4 Fuzzy linguistic	–	1	–	1	–	–	–	–	–	–	–	2	
	A.5 Galbraith	–	1	–	–	–	–	–	–	–	–	–	1	
	A.6 MAIC	–	–	1	–	–	–	–	–	–	–	–	1	
	A.7 Simulation	–	–	2	–	1	–	–	–	–	–	1(1992)	4	
	A.8 Markovian deterioration	–	2	1	–	1	–	–	–	–	–	4	–	
	A.9 AHP	–	–	–	–	1	–	1	–	–	–	–	2	
	A.10 Petri nets	–	–	–	–	–	1	–	–	–	–	–	1	
	A.11 Maintenance organization modeling	1	–	–	–	1	–	–	–	–	–	–	2	
	A.12 Miscellaneous(includes review paper)	1	–	1	–	1	–	2	–	–	–	–	5	
	Sub total	3	5	6	2	4	2	3	1	–	–	1	27	
B Maintenance techniques														58
	B.1 PM	3	4	4	5	2	1	1	1	–	–	–	21	
	B.2 CBM	1	–	2	1	–	2	–	–	–	–	–	6	
	B.3 TPM	1	–	–	7	2	1	–	–	–	–	–	11	
	B.4 CMMS	–	1	–	1	–	1	1	1	2	–	–	7	
	B.5 RCM	–	2	–	1	1	–	1	–	–	–	–	5	
	B.6 Predictive maintenance	–	1	–	–	–	1	–	–	–	–	2	–	
	B.7 Outsourcing	1	–	–	–	–	1	–	1	–	–	–	3	
	B.8 ECM	–	–	1	–	–	–	–	–	–	–	–	1	
	B.9 SMM	–	–	1	–	–	–	–	–	–	–	–	1	
	B.10 RBM	–	1	–	–	–	–	–	–	–	–	–	1	
	Sub total	8	8	9	15	5	6	4	3	2	–	–	58	
C Maintenance scheduling														9
	C.1 Techniques													
	C.1.1 CBM	1	1	–	–	–	–	–	–	–	–	–	21	
	C.1.2 Predictive	–	–	1	–	–	–	–	–	–	–	–	1	
	C.1.3 PM	–	–	–	1	1	–	–	–	–	–	–	2	

(continued)

Table II.

Area	Sub area	2004-2006	2003	2002	2001	2000	1999	1998	1997	1996	1995	Others	Sub-area total	Total
	C.2 Wear out components	–	–	1	–	–	–	–	–	–	–	–	1	
	C.3 Repair rate modifying activities	–	–	–	1	–	–	–	–	–	–	–	1	
	C.4 Combining production and maintenance	–	–	–	–	1	–	–	–	–	–	–	1	
	C.5 Maintenance personnel	–	–	–	–	–	1	–	–	–	–	–	1	
	Sub total	1	1	2	2	2	1	–	–	–	–	–	9	
D Maintenance performance measurement					–									
	D.1 Techniques													23
	D.1.1 Various models	–	–	–	–	–	1	–	1	–	–	–	2	
	D.1.2 VBM	1	–	–	–	–	–	–	–	–	–	–	1	
	D.1.3 BSC	–	1	–	–	–	–	1	–	–	–	–	2	
	D.1.4 QFD	–	–	–	1	–	–	–	–	–	–	–	1	
	D.1.5 MIS	–	–	–	–	–	–	1	–	–	–	–	1	
	D.1.6 TMM	–	–	–	–	–	–	–	–	–	1	–	1	
	D.1.7 System audit approach	–	–	–	–	–	1	–	–	–	1	–	2	
	D.1.8 Maintenance productivity index	–	–	–	–	1	–	–	–	–	–	–	1	
	D.2 Overall equipment/craft effectiveness	–	2	–	1	–	–	1	–	–	–	–	4	
	D.3 Relation with maintenance strategy	2	–	–	1	–	–	–	–	–	–	–	3	
	D.4 Effect of failure on effectiveness	–	–	–	–	–	1	–	–	–	–	–	1	
	D.5 Miscellaneous	–	1	1	–	–	–	–	1	1	–	–	4	
	Sub total	3	4	1	3	1	3	3	2	1	2	–	23	
E Maintenance information system														6
	E.1 Opportunity created by IT	–	–	–	–	–	1	–	–	–	–	–	1	
	E.2 Computerized data based info system to reduce MTTR/MTBF	–	–	–	–	–	–	–	–	1	–	–	1	
	E.3 Development of DSS in maintenance planning	–	–	–	–	–	1	–	–	–	–	–	1	
	E.4 Miscellaneous	1	–	1	–	–	1	–	–	–	–	–	3	
	Sub total	1	–	1	–	–	3	–	–	1	–	–	6	

(*continued*)

Table II.

Area	Sub area	2004-2006	2003	2002	2001	2000	1999	1998	1997	1996	1995	Others	Sub-area total	Total
F Maintenance policies														19
	F.1 Maintenance integration	–	–	1	2	1	1	–	–	–	–	–	5	
	F.2 Emerging maintenance concepts													
	F.2.1 EMQ determination in imperfect PM	–	–	–	1	–	–	1	–	–	–	–	2	
	F.2.2 Simulation in maintenance	1	–	1	–	–	–	–	–	–	–	–	2	
	F.2.3 Customized maintenance concept	–	–	1	–	–	–	–	–	–	–	–	1	
	F.2.4 Object-oriented maintenance management	–	1	–	–	–	–	–	–	–	–	–	1	
	F.3 New ideas	1	–	–	1	–	–	1	–	–	–	–	3	
	F.4 Miscellaneous (includes review papers)	–	–	2	–	–	–	–	1	1	–	1 (1992)	5	
	Sub total	2	1	5	4	1	1	2	1	1	–	1	19	
	Total	16	19	24	26	13	16	12	7	5	2	2	–	142

Notes: MILP: mixed integer linear programming; MCDM: multiple criteria decision making; MAIC: *Materially per Apparecchiature de Impiariti Chemiei*; AHP: analytic hierarchy process; PM: preventive maintenance; CBM: condition-based maintenance; TPM: total productive maintenance; CMMS: computerized maintenance management systems; RCM: reliability centered maintenance; ECM: effectiveness-centered maintenance; SMM: strategic maintenance management; RBM: risk-based maintenance; VBM: vibration-based maintenance; BSC: balanced score card; MTTR: mean time to repair; MTBF: mean time between failure; QFD: quality function deployment; MIS: maintenance information systems; TMM: total maintenance management; DSS: decision support systems; ECM: electronic counter measures; EMQ: economic manufacturing quantity

(A.1) Bayesian approach. A fully Bayesian i.e. subjective approach towards straightforward means of presenting uncertainty related to future events to decision makers in the context of an inspection maintenance decision problem has also been optimally discussed (Apeland and Scarf, 2003). This approach is in contrast with the classical probabilistic approach (for example: Ho and Silva (2006) have used unbiased estimators for MTTF) that assumes the existence of true probabilities and probability distributions.

(A.2) Mixed integer linear programming (MILP) formulation. Goel *et al.* (2003) present a new mathematical formulation i.e. MILP for the integrated design, production and maintenance planning for a multi-process plant. A reliability allocation model at the design stage is coupled with the existing optimization framework to identify the optimal size and initial reliability for each unit of equipment at the design stage. In contrast to earlier approaches, which focus mainly on deriving an effective maintenance policy at the operational stage, the proposed integrated approach provides a designer with an opportunity to improve the operational availability at the design stage itself.

(A.3 to A.6) Maintenance approach using fuzzy multiple criteria decision making (MCDM) and linguistic approaches. Al-Najjar and Alsyouf (2003) assess and select most informative (efficient) maintenance approach using fuzzy MCDM evaluation methodology. Triantaphyllou *et al.* (1997) earlier reported similar approach. Mechefske and Wang (2003, 2001) have used a fuzzy linguistic approach to achieve subjective assessments of maintenance strategies and practices in an objective manner. Swanson (2003) has applied Galbraith's information processing model to study how the maintenance function applies different strategies to cope with the environmental complexity. Pieri *et al.* (2002) have presented a knowledge-based decision support system, *Materially per Apparecchiature de Impiariti Chemiei* (MAIC) for maintenance of a chemical plant.

(A.7 and A.8) Simulation and Markovian probabilistic models. Chen and Popova (2002) and Barata *et al.* (2002) use Monte Carlo simulation to determine optimum maintenance policy (i.e. minimizing total service cost) and for modeling of continuously monitored deteriorating systems. A simulation model (Sarker and Haque, 2000) has also been developed to reduce maintenance and inventory costs for a manufacturing system with stochastic item failure, replacement and order lead times. Balakrishnan (1992) demonstrates application of simulation models to evaluate maintenance policies (i.e. selected out of opportunistic, failure and block) for an automated production line in a steel rolling mill. Markovian probabilistic models for optimizing maintenance policy have also been discussed by Bruns (2002), Marquez and Heguedas (2002), Chiang and Yuan (2001) and Lam (1999) in great detail.

(A.9 to A.11) Analytic hierarchy process (AHP), Petri nets and maintenance organization modeling. Bevilacqua and Braglia (2000) describe an application of AHP for selecting the best maintenance strategy for an oil refinery. Similar attempts were made earlier by Labib *et al.* (1998). Rochdi *et al.* (1999) utilize Petri nets for maintenance modeling of industrial systems. Sherwin (2000) reviews maintenance organization models, e.g. advanced terotechnological model (ATM), Eindhoven University of Technology model (EUT), total quality management (TQM)/TPM/RCM model etc. and suggests maintenance can be a contributor to profits by use of information technology (IT) and showed that integrated IT permits co-planning of production with

maintenance. Bevilacqua *et al.* (2005) have used an artificial neural network (ANN) framework for failure rate prediction.

(A.12) Miscellaneous. The rest of the papers (Hsieh and Chiu, 2002; Sander and Wang, 2000; Anderson *et al.*, 1998) were distributed in the areas of road maintenance, scheduling of overhauls of electric power stations, manpower requirement planning, inspection in nuclear industry, lighting maintenance, etc. Recently, Dhillon and Liu (2006) have reviewed extensively on human-related errors in maintenance.

Some observations

- There are few problems in applying quantitative optimization models like: DSSs are needed to optimize maintenance; data problems; and the gap between theory and practice. Thus applications of these models are very limited in industry.
- It seems that a number of papers have been published in the last five years in this area. This sudden rise is due to the fact that IT (both soft and hardware) is now becoming available at low cost and is rapidly developing. However, limited work is directed towards developing an operational decision support system.
- These models have flourished only as a mathematical discipline with in operations research (OR). The applications of the same have been very limited so far as virtually no case studies have been published. It can be said that its impact on decision making within a maintenance organization has so far been limited.
- More application will be seen if models are developed in conjunction with the problem owner. Limited application is also attributed to inadequate definition of a problem by its owners and lack of training in education of engineers, which presently focuses on the design of systems and not on maintenance. Engineers need to be taught economics of maintenance and principles of optimization.
- No attempts have been made to integrate these quantitative approaches with qualitative ones, like RCM, etc.
- Presently, many researchers are pursuing the development of various mathematical maintenance models to estimate the reliability measures and determine the optimum maintenance policies. However, these models may be useful to maintenance engineers if they are capable of incorporating information about the repair and maintenance strategy, the engineering management policies, the methods of failure detection, failure mechanisms, etc. that justify reasonableness of assumptions, and the applicability of model in a given system environment that can give greater confidence in estimates based on small numbers of production data.

(B) Maintenance techniques

Another classification of the work done on maintenance is on various techniques. A total of 54 papers are identified under this broad area. These techniques have been further sub classified in to ten areas, each of which has been discussed in detail as follows.

(B.1) Preventive maintenance (PM). A series of tasks performed at a frequency dictated by the passage of time, the amount of production, machine condition that either extend the life of an asset or detect that an asset had critical wear and is going to fail or break down constitute PM. A total of 20 papers have been published under this

category in the last seven years. The recent ones include a paper by Chelbi and Ait-Kadi (2004) that presents a mathematical model for joint strategy of buffer stock production and PM for a randomly failing production unit operating in an environment where repair and PM durations are random. Charles *et al.* (2003) demonstrate usefulness of simulation tool (simulator MELISSA C^{++}) for optimizing PM cost in a semiconductor-manufacturing environment. Breakdowns occurring in combined corrective/PM context have been modeled and also both direct and indirect maintenance costs estimated. Qian *et al.* (2005) discuss about optimal preventive policies for a shock model with pre-specified damage levels.

Chen *et al.* (2003) propose a state and time dependent PM policy for a multistage Markovian deteriorating system. Bloch-Mercier (2002) also proposes a PM policy with sequential checking procedure for a Markov deteriorating system. Sheu *et al.* (2001) consider a Bayesian theoretic approach to determine an optimal adaptive PM policy with minimal repair. In a more recent work Juang and Anderson (2004) consider a Bayesian theoretic approach to determine an optimal adaptive PM policy with minimum repair.

Zhao (2003) has introduced degradation ratio to represent the imperfect effect assuming that the system after PM action starts a new failure process. PM policy has also been suggested for a degradation system with an acceptable reliability level. Bris *et al.* (2003) have shown the efficiency of an optimization method to minimize the PM cost of series parallel systems based on the time dependent Birnbaum importance factor and using Monte Carlo simulation (applied with programming tool APLAB) and genetic algorithm. Badía *et al.* (2002) demonstrate development of a model for minimizing the cost per unit time of inspection and PM through selection of a unique interval. Gürler and Kaya (2002) suggest a control policy where the system is replaced when a component enters a PM due or down state (life time of each component is described by various stages (O, −−−−−-, S) which are further classified as good, doubtful, PM due and down). Motta *et al.* (2002) present a statistical approach of analysis and decision that uses reliability techniques to define the best periodicity for PM of power system protective relays.

In the literature reported for the period 2001-1997, Salameh and Ghattas (2001) determine the just-in-time (JIT) buffer level by trading off the holding cost per unit time and the shortage cost per unit time such that their sum is minimum. This is demonstrated for a production unit subjected to regular PM. Tsai *et al.* (2001) present the periodic PM of a system with deteriorated components. An age reduction model models degraded behavior of components and genetic algorithm is used for deciding the optimal activity combination at each PM.

Gupta *et al.* (2001a, b) present an easy-to-implement state dependent PM policy consistent with the production environment. It is shown that increased PM activity can lower total expected work-in-process (WIP) inventory on its own i.e. without accounting for the lower unplanned downtime. Dohi *et al.* (2001) derive optimal PM strategies under intermittently used environment. Lai *et al.* (2000) has discussed application of the sequel method to determine the optimal policy as when to carry out PM action for an engine/replace the engine. Ben-Daya and Alghamdi (2000) present two sequential PM models. In first, age reduction of the system is assumed to depend on the level of PM activities. In second, PM intervals are defined in such a way that hazard rate is same for all. Hsu (1999) addresses the joints effects of PM and replacement policies on a queue-like production system with minimum repair at failures. Gupta and Al-Turki (1998) discuss adapting JIT manufacturing systems to PM interruptions. Gopalakrishnan *et al.* (1997) present an approach to generate an adaptive PM schedule, which maximizes the net savings from PM subject to workforce constraints.

(B.2) Condition-based maintenance. The PM service is based on some reading, measurement going beyond a predetermined limit. If a machine cannot hold a tolerance, a condition-based maintenance is initiated. A total of six papers have been published in the last five years. In the recent works, Grall *et al.* (2002) focus on the mathematical modeling of a condition based inspection/replacement policy for a stochastically and continuously deteriorating single unit system. Chen and Trivedi (2002) explain condition-based maintenance in detail and also derive a closed form expression of system availability when device undergoes both deterioration as well as Poisson type failures. Marseguerra *et al.* (2002) consider a continuously monitored multi-component system and use a generic algorithm for determining the optimal degradation level beyond which PM is to be performed; within this level condition-based maintenance policy can be implemented. Jamali *et al.* (2005) evolve joint optimal periodic and conditional maintenance strategy.

Saranga and Knezevic (2001) use reliability condition predictor (RCP) for reliability prediction of condition-based maintenance systems. The methodology uses Markov models for reliability prediction. Barbera *et al.* (1999) discuss a condition-based maintenance model with exponential failures and fixed inspection intervals for a two-unit system in series. Luce (1999) selects the best maintenance method using Weibull Law by comparing CM, systematic PM and conditional PM.

(B.3) TPM. TPM, originating from Japan centers on solving maintenance problems using quality circles method. Some of the advantages of implementing TPM in an organization are better understanding of the equipment performance, improved teamwork, less adversarial approach between production and maintenance, etc. Wang and Lee (2001) discuss an application of TPM, which uses an approach to determine the appropriate time for checking the performance of implementing TPM. McKone *et al.* (2001) investigate the relationship between TPM and manufacturing performance (MP) through structural equation modeling (SEM). It is shown that there is a significant and positive indirect relationship between TPM and MP through JIT practices. Ireland and Dale (2001) discuss study of TPM in three companies. These companies had followed Nakajima's seven steps of autonomous maintenance. Das (2001) presents a case study where TPM is implemented in a step-by-step manner and also develops some parameters for measuring the effectiveness of TPM.

Gupta *et al.* (2001a, b) address basics of TPM and its key issue overall equipment effectiveness (OEE). It is shown that maximization of OEE requires reduction of six big losses. These are ineffective maintenance resulting in breakdowns, set up and adjustment time loss, idling and minor stoppages of equipment, operation at reduced speed, poor raw material/processing defects and quality losses during machine starting. Finally, TPM benefits were modeled using AHP by Kodali and Chandra (2001) and Kodali (2001). In a little older work, Finlow-Bates *et al.* (2000) show that in order to implement TPM successfully, three strong tools i.e. " seven simple tools of TQM", four thinking models of "Kepner-Tregoe" and "Root cause analysis" are to be navigated as all three are complementary to each other. Cooke (2000) presents case studies in implementing TPM in four manufacturing companies. In the still older works McKone *et al.* (1999) propose a theoretical framework for understanding the use of TPM and how it depends on managerial factors such as JIT, TQM, employee involvement (EI) and environmental/organizational factors such as country, industry/company characteristics, etc. This framework is also tested for 97 plants. Shamsuddin *et al.* (2005) argue that TPM can go much beyond much maintenance and may encompass a host of business functions within an organization.

(B.4) Computerized maintenance management systems (CMMS). CMMS provide capabilities to store retrieve and analyze information. A total of seven papers have been published in the last eight years. Fernandez *et al.* (2003) propose a maintenance maturity grid to support the CMMS implementation. Leger and Movel (2001) deal with computer-aided integration of maintenance in an enterprise. Older works include a paper by Singer (1999) that discusses a seven-step plan for using all the features of the CMMS package.

Two important papers in the area of CMMS include a paper by Labib (1998) that uses a formalized decision analysis approach based on multiple criteria and rule-based system for finding the worst machines. This policy emphasizes the fact that the best policy is the one, which improves the life cycle profit. Swanson (1997) provides information regarding the characteristics and use of CMMS. The paper also includes literature review of CMMS. Jones and Collis (1996) present findings of a questionnaire survey examining use of computers in maintenance management and concludes that computers are still not optimally utilized and there is considerable potential for future development. Wickers (1996) presents a method called "Front end maintenance analysis" which has widely been applied in industry and proved to be an effective method of identifying parameters for condition monitoring and clearly shows the link between these parameters and a maintenance management system.

(B.5) RCM. Reliability centered approach was founded in the 1960s and initially oriented towards aircraft maintenance. It is now only in the past ten years or so that this concept has started coming to the industry. It directs maintenance efforts at those parts and units where reliability is critical. A total of five papers have been published in the last few years. Gabbar *et al.* (2003) present an improved RCM (automated environment) process as integrated with CMMS. The major components of the enhanced RCM process are identified and a prototype as integrated with the various modules of the adopted CMMS is implemented. Wessels (2003) proposes a cost optimized scheduled maintenance interval that uses costs as the constraint and overcomes quantitative complexity by use of computer/software technology. This interval enables an organization to implement a comprehensive RCM program effectively.

Eisinger and Rakowsky (2001) discuss a probabilistic approach in the modeling of uncertainties in RCM. They conclude by saying that these uncertainties in the decision making of RCM might be unacceptable in many practical applications, leading to non-optimum maintenance strategies. An alternative approach for some specified uncertainties are also discussed. Hipkin and Cock (2000) discuss implementation of RCM and TPM with respect to TQM and business process re-engineering (BPR) and show as to how maintenance implementation follows the path of other interventions. Finally, Rausand (1998) present a structured approach to RCM and discuss its various steps at length.

(B.6) Predictive maintenance. Predictive maintenance consists in deciding whether or not to maintain a system according to its state. A total of two papers were found on

this type of maintenance. McKone and Weiss (2002) have presented detailed guidelines for implementing predictive maintenance in manufacturing industry. They recommended that practitioners should not abandon the traditional maintenance methods but follow given guidelines for utilizing periodic maintenance with the new technologies. In an older work by Chu *et al.* (1998) a general predictive replacement model based on dynamic programming is presented.

(B.7) Maintenance outsourcing. This refers to transferring workload to outsiders with the goals of getting higher quality maintenance at faster, safer and lower costs. The other goals are to reduce the number of full-time equivalents (FTEs) and concentrate organization's talent, energy and resources in to areas called core competencies. Two papers are published in this area. Murthy and Asgharizadeh (1999) deal with game theoretic formulation model to determine outsourcing agent's optimal strategy with regards to the price structure, the number of customers to service and the number of service channels. Martin (1997) discusses in detail the various facets of maintenance outsourcing. Paper also discusses various research issues from an industrial engineering point of view. It is also shown that various scientific disciplines such as management accounting, operations management, computer science and socio technology all need to be involved at different stages as the issues of selecting suitable maintenance contracts, determination of contractor capabilities, contract portfolio management and the design of a contractor's maintenance function are all very much related to one another. Buczkowski *et al.* (2005) discuss the prioritized warranty repairs for an outsourcing context.

(B.8) Effectiveness centered maintenance. Effectiveness centered maintenance (ECM) stresses "doing the right things" instead of "doing things right". This approach focuses on system functions and customer service, and has several features that are practical to enhance the performance of maintenance practices and encompasses core concepts of quality management, TPM and RCM. The ECM approach is more comprehensive as compared with TPM and RCM. It is composed of people participation, quality improvement, and maintenance strategy development and performance measurement. Pun *et al.* (2002) review in detail various basic concepts of maintenance and discuss need of ECM approach. Determination of ECM performance indices has also been attempted in this paper.

(B.9) Strategic maintenance management. In the strategic maintenance management (SMM) approach, maintenance is viewed as a multi disciplinary activity. This approach overcomes some of the deficiencies of RCM and TPM approaches as these do not deal with issues like operating load on the equipment and its effect on the degradation process, long-term strategic issues and outsourcing of maintenance, etc. In addition, these approaches to a large extent are qualitative or at the most semi-quantitative. The SMM approach in contrast, is more quantitative, involving the use of mathematical models that integrate technical, commercial and operational aspects from business viewpoint. As a result SMM views maintenance from a perspective that is broader than that of RCM or TPM. Murthy *et al.* (2002) in a recent work outline this approach in detail with presentation of few case studies.

(B.10) Risk-based maintenance. Risk-based maintenance ensures a sound maintenance strategy meeting the dual objectives of minimization of hazards caused by unexpected failure of equipment and a cost effective strategy. Khan and Haddara (2003) outline this approach in detail and contrast it with the current approaches. The

proposed methodology is comprehensive and quantitative. It comprises of three main modules i.e. risk estimation module, risk evaluation module and maintenance planning module. A case study using this methodology is also presented.

Some observations

- Up to about 1940, maintenance cost was considered as an unavoidable cost and the only maintenance carried out was CM. The evolution of OR and its applications during the Second World War led to the widespread use of PM. Since the 1950s, OR models for maintenance have appeared at an ever-increasing rate.
- In the 1970s, a more integrated approach to maintenance involving a close linkage to reliability (R) and maintainability (M) was recognized. The term "R & M" became very popular, which gave birth to RCM. At the same time the Japanese gave birth to TPM in the context of manufacturing.
- Preventive and condition-based maintenance continue to be the areas where the maximum number of papers have been published. Various simulation tools and mathematical models are attempted in recent past for minimizing the PM cost. Similarly, various models for optimum PM policy determination have been attempted using selection of unique inspection interval, introduction of degradation ratio, etc. However, not many applications have been published.
- CMMS appears to be used less often as a device for analysis and coordination. The uses so far appear to be only a storehouse for equipment information, as a PM tool and a maintenance work-planning tool.
- While it might be expected that maintenance personnel would be the primary users of CMMS, an opportunity exists for a more broad use of CMMS by production personnel. Increased use of analysis and coordination capabilities and greater use of CMMS by personnel outside maintenance function have the potential to improve maintenance responsiveness and equipment condition. As a future scope, more work needs to be done to link CMMS design and use with actual maintenance performance.
- RCM has the potential to be utilized in an automated environment i.e. more work on its integration with CMMS can be attempted.
- The area of maintenance outsourcing has tremendous potential for future work as more and more clients are becoming interested in contracting out maintenance and contractors take great interest in solving current problem areas.
- Maintenance is increasingly viewed as a multi disciplinary activity involving integration of existing techniques like TPM, RCM, etc. as is evident from the emergence of the new approaches like ECM, SMM and RBM.

(C) Maintenance scheduling

Scheduling means bringing together in the precise timing the six elements of a successful maintenance job i.e. the mechanic(s), tools, materials/parts, availability of unit to be serviced, information needed to complete the job and the necessary permissions. A total of eight papers are published in the last few years. Dieulle *et al.* (2003) discuss development of a new probabilistic method based on the semi sequential property in a condition-based maintenance environment for scheduling. Inspection random time is chosen with the help of a maintenance scheduling function and a gamma process models deterioration. Grall *et al.* (2002) discuss a predictive maintenance scheduling structure for a gradually deteriorating single unit system, which is based on regenerative, and semi-regenerative process theory. In the area of PM scheduling, two works have been reported. Gopalakrishnan *et al.* (2001) present a tabu search heuristic for PM scheduling while Greenwood and Gupta (2000) present workforce constrained PM scheduling using evolution strategies. Tsang *et al.* (2006) use data management techniques for optimization in CBM.

Artana and Ishida (2002) address a method for determining the optimum maintenance schedule for components in wear out phase. The interval between maintenance for the components is optimized by minimizing the total cost. Most papers in the maintenance field are based on the assumption that machines are always available at constant speed. However, in applications it is very common for a machine to be in a subnormal condition after running for a certain period of time. Motivated by this, Lee and Lin (2001) discuss scheduling problems involving repair and maintenance rate modifying activities for a problem commonly found in the surface mounted technology of electronic assembly lines. Sloan and Shanthikumar (2000) deal with combined production and maintenance scheduling for a multiple product single machine production system. Duffuaa and Al-Sultan (1999) deal with scheduling maintenance personnel using a stochastic programming model that is a stochastic version of the Robert and Escudero model for scheduling maintenance personnel.

Some observations

- It is this stochastic nature that makes maintenance scheduling a challenging problem and distinguishes with production scheduling.
- Integration of various scheduling models in to MMISs may be investigated as a future research area to ensure effective planning and scheduling of maintenance jobs.

(D) Maintenance performance measurement

In the past, maintenance performance reporting was limited to minimum budget reporting. Another reason is that maintenance performance reporting is difficult. The maintenance performance perceived also depends on the perspective applied i.e. accountants will think of maintenance in terms of costs, top management is interested in budget performance, engineers will focus on techniques, production on equipment availability and support responsiveness, etc. Maintenance managers often have access to many data, but seldom receive the information they need. This means that processing the data to obtain useful management information, e.g. a few typical performance indicators is a time-consuming business.

(D.1) Measurement techniques. In this section various maintenance performance measurement techniques have been identified from the literature. These have been sub-classified as follows:

- *(D.1.1) Review of various models*. Pintelon and Puyvelde (1997) present an overview of various PMS including indicators, reference numbers and surveys. Elaborate models like Hibi, Luck and the maintenance management tool (MMT) have been presented along with case studies on MMT. This model is considered to be more proactive, than other scientific approaches for maintenance performance reporting. MMT consists of a control board (CB) which allows a quick evaluation of maintenance performance during a fixed duration, e.g. in past one month and a network of detailed reports (DR). Tsang *et al.* (1999) discuss pitfalls relating to indiscriminate use of common maintenance performance measures. Various approaches to measuring maintenance performance have been reviewed. Value-based performance measure attempts to assess the impact of maintenance activities on the future value of the associated assets. The balance scorecard (BSC) provides an alternative and holistic approach to measurement that is developed on the notion that no single measure is sufficient to indicate the total performance of a system. Systems audit and data envelopment analysis (DEA) are the other two approaches covered in detail. Applying BSC for managing maintenance performance is potential research area that may be explored.

- *(D.1.2) Balanced scorecard*. In a recent work Liyanage and Kumar (2003) have applied BSC to develop operations and maintenance performance (O&M) management process in the oil and gas industry. The paper emphasizes on the value rather than the cost of operations and maintenance in the emerging business environment, and stresses that there is a need to move from a plant-based policy to a more or less long-term business oriented approach. Tsang (1998) also discusses the concept of BSC as a SMM tool for performance measurement in industry.
- *(D.1.3) Performance measures based on VBM model*. A model is developed by Al-Najjar and Alsyouf (2004) for economic impact of vibration-based maintenance (VBM (part of condition-based maintenance)) and further utilized to develop relevant maintenance performance measures. The model has utilized life cycle costs (LCC) as monitoring parameters to provide the required information for decision making, to ensure cost effective actions and enhance continual improvement efforts cost effectively.
- *(D.1.4) PMS using quality function deployment (QFD) technique*. Kutucuoglu *et al.* (2001) look at the role of PMS in maintenance with particular reference to developing a new PMS using QFD technique. QFD uses a type of three-stage matrix diagram to present data and information and is also referred to as "a house of quality". The reason is that the matrix in QFD fits together to form a house-shaped diagram. The paper also highlights that although the framework might be complicated and may demand extra resources for small and medium-sized companies, the application showed that it could easily be adapted for the needs of the company.
- *(D.1.5) PMS using maintenance information systems*. Arts *et al.* (1998) describe that MMIS is required to measure performance. A number of performance indices have been listed for maintenance performance measurement. Similarly, an extensive list of indices for the maintenance manager with benchmarks for these indices has also been published in a paper of National Petroleum Refiners Association cited in the above work.
- *(D.1.6 and D.1.7) PMS using total maintenance management (TMM) and systems audit approach*. Raouf and Ben-Daya (1995) propose a systematic

approach to TMM and discuss various issues pertaining to TMM along with presentation of a methodology to measure the effectiveness of the current status of maintenance management. In the area of systems audit approach, Groote (1995) presents a maintenance evaluation approach based on a quality audit and quantifiable maintenance performance indicators. Results of a study of performance ratios from three industries are also presented. Another work on systems approach by Dwight (1999) argues that an absolute definition of maintenance performance in terms of changes in value presents difficult practical problems. The paper further suggests that the systems audit approach for performance measurement can potentially overcome some of these problems.

- *(D.1.8) Maintenance productivity index*. A partial maintenance productivity goal is that the firm should seek to maximize its maintenance productivity in economic terms, and should aim at producing any level of output which is decided on at minimum maintenance cost with respect to the production system's state (Löfsten, 2000). In the discussed partial productivity model, the output prices of the produced products and input prices (maintenance costs) are shown to change over time. Expected changes in the prices of outputs and of current inputs are built into the model.

(D.2) Overall equipment/craft effectiveness. OEE can be said to be a measure of progress of TPM in an organization. Presently, definition of OEE includes six big losses, including downtime and other production losses that reduce output/machine hour or capacity utilization and does not include factors that reduce capacity utilization, e.g. planned downtime, lack of material input, lack of labor, etc. Ljungberg (1998) argues that it should be beneficial to change focus and use a comprehensive model for losses and proposes a TPM model with eight equipment losses. The author also says that the data collection problem has not been sufficiently treated in the literature and has suggested a method for collecting disturbance data where computerized systems are combined with manual recording. Jeong and Phillips (2001) highlight that accurate estimation of equipment utilization is very essential. They present a new loss classification scheme for computing OEE for a capital-intensive industry and provide justification for this scheme. They also present the methodology for designing the necessary data collection system that can serve as a template for any industry.

In a recent work, Bamber *et al.* (2003) explore the purpose of the OEE concept in modern operations. This paper has discussed that in order to effectively address all six big losses and hence improve OEE, cross-functional team (CFT) is necessary. CFT accordingly has the combined necessary skills and knowledge of entire system of manufacture to identify correctly the practices and activities that relate to the six big losses. Additionally, through the use of CFT, it is more likely that the responsibility ad authority to carry out improvements is gained from management. In another work, Peters (2003) has introduced overall craft effectiveness (OCE) like the concept of OEE. OCE deals with the productivity of labor resources (OEE $=$ Availability $\times$ Performance $\times$ Quality, OCE $=$ Craft utilization $\times$ Craft efficiency $\times$ Craft service quality).

(D.3) Performance measurement relationship with maintenance strategy. Swanson (2001) reports results of a study of the relationship between maintenance strategies and performance. The analysis has demonstrated a strong positive relationship between proactive (preventive and predictive) and aggressive (TPM) maintenance strategies

and performance. The paper concludes by saying that through demonstration of impact these strategies can have on plant performance, managers may be more comfortable in making these investments in maintenance. Pintelon *et al.* (2006) have evaluated the effectiveness of various maintenance strategies. Pongpech *et al.* (2006) discuss various maintenance strategies for equipment under lease.

(D.4) Effect of maintenance induced failures on operational effectiveness. Crocker (1999) pays attention to three areas – inspection effectiveness, repair effectiveness and maintenance-induced failures. These areas are usually ignored during the design of the system and also during its operations. It is therefore important to understand how they affect operational effectiveness of the system and what steps can be taken to avoid their effects.

(D.5) Miscellaneous. The rest of the papers deal with various areas such as machine tools (Aronson, 2002), software maintenance (Bandi *et al.*, 2003), mill performance (Lamb, 1996) and space (Cooke and Paulsen, 1997).

Some observations

- In the past, maintenance performance reporting was limited to minimum budget reporting. Data accuracy and report timeliness are other problems in maintenance performance reporting. The maintenance manager also lacks the tools, e.g. query or time to draw required reports.
- Popular PIs are indicators, reference numbers, surveys and various models (Hibi, Luck and MMT) out of which MMT has gained lots of popularity in the recent past.
- Performance measures can also be classified as value-based performance measure, balance scorecard, systems audit approach and data envelopment analysis. A DEA approach will be appropriate for quantitative comparison of operational efficiencies of multiple maintenance organizations; the remaining three approaches are useful for measuring the maintenance performance of an organization. Examining case studies on MMT can be a potential research area.
- Feasibility of applying BSC model for managing performance is still an unexplored area that needs further research.
- Problems and factors associated with implementation of PMS using QFD technique are also important and require further research. So far, work has only been directed in the design of such a system.
- Integration of PMS with an effective MMIS is presently lacking.

(E) Maintenance information systems

The impact of IT on maintenance management is still relatively young in the business arena. In addition, sound maintenance management requires a lot of interaction with other business functions as the era of enterprise-wide information management and business planning becomes a norm rather than an exception. Pintelon *et al.* (1999) address some important opportunities created by the IT (r)evolution for maintenance management. He has indicated how IT is actively used in a number of normal working situations and has pointed to new uses. Three possible applications suggested in the paper are BPR through workgroup computing technology for better performance, organizational transformations, e.g. decentralized maintenance, repair and operating supplies (MRO) stores utilizing integrated systems technology resulting in an integrated business function approach and redefining external relationships, e.g. outsourcing through inter-enterprise technology resulting to extended business partnerships.

Satyanarayana and Prasad (1996) have attempted to introduce maintenance information system for the maintenance department of a Fishing Fleet Company in order to reduce MTTR and increase MTBF. The system is menu-driven and user friendly and with little modifications can be used for any industry. Nagarur and Kaewplang (1999) present a computerized decision support system to assist in maintenance planning. The system design and analysis and the decision support system design and development are all developed in an object-oriented environment. The whole system was developed for a powder coating factory. In the implementation stages, it was found that the users found the system easy to operate because of the object-oriented style of using the icons for operating the system.

Westerkamp (2002) measures information engineered performance standards (EPS). The paper, however, is not specific to maintenance management information. Fitzgerald *et al.* (1999) report findings from a study of systems development and maintenance issues conducted in the UK. Paper relates to information system maintenance in general rather being on maintenance information systems.

Bardey *et al.* (2005) deliberate on the fundamental issues related to maintaining or not to maintain equipment with reference to the information needs of a decision maker.

Some observations

- In the early 1980s the first MMIS appeared due to full recognition of maintenance as an important business function. The initial MMIS, supporting mainly mainframe applications, were mostly administratively oriented.
- Progressively, more specific maintenance software containing modules, e.g. equipment data, work order planning etc. became available. Recently, these became even more user friendly with the use of graphical user interface (GUI) and multimedia applications. For spare parts management GUI-MMIS offers inventory administration in addition to inventory control models.
- There are very promising developments in IT which can help to improve maintenance practice and create better competitiveness. Buying sophisticated hardware or software is not the complete answer.
- Maintenance software is commercially available either as a standalone package or as a module in integrated systems, e.g. SAP. Some of the packages are R/5, Rimes, Maximo, etc.
- Evolution in middleware software is a recent trend that is much broader than MMIS. This software should manage the communications between corporate (e.g. ERP) and plant-floor (e.g. management execution systems).
- Problems relating to application and development of an object-oriented decision support system for maintenance management is another potential field for future.

(F) Maintenance policies

Two invited reviews are worth discussing under this sub section. In the first, Wang (2002) has undertaken a survey of maintenance policies of deteriorating systems. He has said that in the past decades, maintenance and replacement problems of deteriorating systems have been extensively studied in literature. Thousands of maintenance and replacement models have been created which can fall in to some categories of maintenance policies like age replacement policy, random age replacement policy, block replacement policy, periodic PM policy, failure limit policy, etc.; each kind of policy has different characteristics, advantages and disadvantages. Author has finally summarized, classified and compared various existing maintenance policies for both single-unit and multi-unit systems with emphasis on single unit systems.

Another important review was by Pham and Wang (1996) in which imperfect maintenance has been discussed in detail. The authors have said that the maintenance of deteriorating systems is often imperfect i.e. the system after maintenance will not be as good as new, but younger. Imperfect maintenance study has indicated a significant breakthrough in reliability and maintenance theory. Research activities in maintenance engineering have been conducted over the past 30 years and more than 40 mathematical imperfect maintenance models have been proposed for estimating the reliability measures and determining the optimum maintenance policies. The authors have summarized various treatment methods and optimal policies on the imperfect maintenance in the paper along with a few important results.

(F.1) Maintenance integration. Iravani and Duenyas (2002) indicate that the common practice of making maintenance and production decisions separately can be rather costly and that there are significant benefits for making these decisions in an integrated fashion. The same was demonstrated for a make-to-stock production system consisting of a single deteriorating machine, which produces a single item. The performance of maintenance and production system integrated using a Markov decision process and evaluated with help of approximate methods was found to work extremely well. Tu *et al.* (2001) present a case study of an electronic manufacturing company that was lacking a sound maintenance management system. A such integrated system has been shown to be developed and implemented in this paper using methods and principles of maintenance performance auditing, cost recording and tracing, RCM planning and control, condition monitoring and on-line feedback control and integrated planning and control. Jonsson (1999) re-emphasizes that integration of maintenance produces better results. Data gathered and analyzed from 293 Swedish maintenance managers in manufacturing firms showed that integration and long-term planning of maintenance both affect prevention, quality improvement and manufacturing capabilities.

Many companies using MRPII very often appear to be isolated from maintenance management activities. Strategy for integration of these two computerization areas in to logistics management is essential to take advantage of both modern maintenance strategy and production planning strategy. Ip *et al.* (2000) suggest designing an enhanced MRPII system that incorporates systematic integration of maintenance management with the use of the integration definition method (IDEF) model. In order to illustrate the methodology, paper has also describes a lamp manufacturing company with highly sophisticated equipment that depends on modern maintenance strategies as well as MRPII type production and planning.

Research on TQM, JIT and TPM generally investigates the implementation and impact of these programs in isolation. However, many researchers believe and argue conceptually the value of understanding the joint implementation of these manufacturing programs. Cua *et al.* (2001) investigate the practices of the three programs simultaneously. It is shown that there is evidence showing the compatibility of the practices in the three programs. A variety of future research studies are also possible in this area.

(F.2) Emerging maintenance concepts. A number of maintenance concepts have emerged in recent past. These are as follows:

- *(F.2.1) Economic manufacturing quantity (EMQ) determination in an imperfect PM*. Tseng *et al.* (1998) investigate imperfect maintenance policies for deteriorating production systems such that the EMQ can be obtained. A case in which maintenance action is imperfect and may lead a production system to a worse condition has been considered. A case has been examined for two commonly used maintenance strategies and it is shown that for both optimal maintenance policies can be obtained. Emerging maintenance concepts are: neural management maintenance. ANNs embody computational networks based on biological metaphor to simulate the brain action. It is an interconnection of computational elements known as neurons. The main capabilities of ANN include superb pattern classification, matching and completion, trend prediction, capability to generalize and reliability, efficiency and fast responses. Application of ANN in maintenance management would certainly utilize all the above knowledge and methods. Polimac and Polimac (2001) highlight the above aspects and state that maintenance methods applied at present should be combined in a comprehensive neural management maintenance system, which would permanently monitor the system and suggest the most appropriate actions and strategies. This should add quality in the decision-making process and consequently reduce the overall maintenance costs.
- *(F.2.2) Simulation in maintenance*. Andijani and Duffuaa (2002) review the literature on the use of simulation in maintenance. The reviewed literature has been evaluated with respect to the elements of sound simulation study and it is observed that many of the simulation studies on maintenance systems ignored model validation, proper design of experiments and sound ways of output analysis. They opined that the available models in the literature could be enhanced by focusing more on model validation and design of the experiment for the simulation study.

  El Hayek *et al.* (2005) discuss performance of maintenance based on life cycle costs of complex machinery using simulation as a technique.
- *(F.2.3) Customized maintenance concept*. A maintenance concept can be defined as the set of various maintenance interventions (corrective, preventive, condition-based, etc.) and the general structure in which these interventions are foreseen. Waeyenbergh and Pintelon (2002) intimate that more and more companies are searching for a customized maintenance concept. The framework described in this paper offers some guidelines to develop such a concept and borrows some ideas from maintenance concepts in the literature. An important feature of the framework is that it allows incorporating all information available in the company, ranging from experience of maintenance workers to data captured by modern information and communication technology (ICT) means.

The proposed framework can be seen as built out of five modules, which are start-up module, identification of most important systems (MISs) and most critical components (MCCs) module, maintenance policy decision step module, performance measurement module and the continuous improvement module.

- *(F.2.4) Object-oriented maintenance management*. During the last decade, many companies have made large investments in the development and implementation of enterprise resource planning (ERP) systems. However, only few of these systems developed or installed have actually considered maintenance strategies. Nikolopoulos *et al.* (2003) highlight proper design and integration of maintenance management in to ERP systems enable enterprises to effectively manage their production, planning and scheduling. This work presents the design of an object oriented maintenance management model and its integration in to an ERP system.

(F.3) New ideas. Most maintenance optimization models need an estimate of the so-called "naked" failure rate function as input. In practice it is difficult to estimate the "naked" failure rate, because overhauls and other PM actions tend to corrupt the recorded life lengths. Oien (1998) stresses the importance of utilizing the knowledge of maintenance engineer (i.e. expert judgment) to get credible input data. The author has recommended including a simple question about the mean remaining life length on the work-order forms. By this approach the knowledge of maintenance engineers may be incorporated in a simple and cost-effective way.

Extensive literature on change over and maintenance as a separate subjects has been published, yet relatively little consideration has been given to the impact that each discipline can have on the other. Despite the manifest similarities in some changeover and maintenance tasks, well-documented improvement techniques that are used to enhance change over performance do not seem to be widely applied, where appropriate, to the discipline of maintenance. McIntosh *et al.* (2001) highlight these aspects and assert that the maintenance community might give greater attention to what has occurred in the improvement of change over performance. Cheung *et al.* (2005) have used a novel concept of expert system for aircraft maintenance that is viewed as service industry.

(F.4) Miscellaneous. The rest of the papers not directly relevant are on maintenance strategy assessment (Jonsson, 1997), value of change in maintenance (Call, 2002) and nuclear environment maintenance (Chockie and Bjorkelo, 1992).

Some observations

- Maintenance management must be integrated with other functional departments like production and quality control. computer aided integrated maintenance management (CIMM) is needed by manufacturing companies to integrate, schedule and control production and maintenance.
- Limited research has been attempted to consider maintenance strategy in design of MRPII. Integration of maintenance management in to MRPII using appropriate system design is invaluable. Further research can be done using this approach to enhance MRPII system and improve logistics management and physical distribution functions of any organization.

- Future studies in the joint implementation of TQM, JIT and TPM are possible. Studies could help examining the close linkage among functions and also pinpoint exact nature of interactions among them, which will give a full understanding of relationship between TQM, JIT and TPM.
- A new technique neural management maintenance is yet to be developed which will combine the already applied methods in maintenance and which should reduce involvement of analysts/ engineers in processing the data and thus add quality in decision-making process. Further work in this direction is a potential research area.
- In future development of the customized maintenance concept framework, more modules, e.g. material selection, data management, maintenance policy, standardization etc. should be added and the content of each module be carefully elaborated on. This modular approach should allow selection of modules for which a decision support module is foreseen. Design of this module has a future scope of research.
- Problems related to implementation of an object-oriented maintenance management model and its integration to ERP may be taken as a future work.
- Knowledge of maintenance engineers i.e. the expert judgment may be useful in the design of customized maintenance concept.
- There appears to be similarities between changeover and maintenance tasks. Well-documented improvement techniques that are used to enhance changeover performance do not seem to be widely applied. The correlation between the two will be an interesting area for research.

Consolidated summary

A consolidated summary highlighting emerging trends of various attributes is given in Table III. The same will assist future researchers in the field of maintenance management to identify literature gaps and direct research efforts suitably. A glaring change in attitude towards maintenance from a necessary evil to "external and internal partnerships" is noticed. During the 1950s only CM was undertaken i.e. "fix it when it breaks". This was gradually translated to PM and its various forms like predictive maintenance, condition-based maintenance, etc. Concept of reliability came during 1980s in the form of RCM, which directed maintenance efforts at those parts and units where reliability is critical followed by TPM, which revolved around solving maintenance problems using quality circles method. Emerging tend is towards integration of these various approaches in the form of ECM or SMM. Similarly, there have been developments in the area of maintenance outsourcing. More and more organizations are resorting to this form of vertical contracting to further build up their core competency levels. In the areas of performance measurement and information systems also, very interested trends have been noticed.

Directions for future work are as follows:

(1) *Modeling and optimization oriented*:
   - Limited work is directed towards developing an operational decision support system utilizing a suitable maintenance optimization model.
   - Developing optimization models for maintenance engineers, which are capable of incorporating information about the repair and maintenance

Attribute	Earlier	Emerging
Attitude towards maintenance	Necessary evil	Technical matter – profit contributor – partnership
Maintenance strategy	CM-PM-RCM-TPM	Integration of various approaches, e.g. ECM, SMM, etc.
Maintenance optimization models (quantitative)	Mathematical discipline with limited applications	Application oriented, integration with qualitative approaches
Maintenance outsourcing	Not existed	Part of vertical contracting
Maintenance scheduling	Models in isolation	Integration with MMIS
Performance indicators	Reference numbers, surveys, indicators, models – Hibi and Luck	Maintenance management tool (MMT) model
Performance measurement approaches	Value based approach, systems audit approach, data envelopment analysis (DEA)	Balance score card (BSC) approach, quality function deployment (QFD)
PMS integration with information system	Poor	Developing
Data collection in measurement of OEE	Not sufficiently treated	Designing of data collection system
Evolution of MMIS	Mainframe applications and mostly administration oriented	Evolution in middleware software (e.g. communication between corporate and plant floor), work group computing, integrated system technology, inter-enterprise technology
Spare parts management	Inventory administration	Graphical user interface (GUI) – maintenance management information systems (MMIS)
New maintenance policies	Techniques in isolation	Maintenance strategy in MRP system, Joint implementation of TQM, JIT and TPM, neural management maintenance, customized maintenance concept framework, object-oriented maintenance management model and its integration to ERP, knowledge of maintenance engineers utilization, correlation between changeover performance and maintenance tasks

Table III.
Emerging trends in maintenance management

strategy, the engineering management policies, the methods of failure detection, etc.

- Integration of quantitative optimization models with qualitative ones like RCM, TPM, etc.

(2) *Performance measurement oriented*:

- Examining case studies on MMT with a view to allow quick evaluation of maintenance performance during a fixed duration.
- Feasibility of applying BSC model for managing maintenance performance and applications of BSC in military applications.
- Designing of an effective data collection system for computing OEE in an organization and problems with its implementation.
- Use of CMMS by personnel outside maintenance function has the potential to improve maintenance responsiveness and equipment condition. More work needs to be done to link CMMS design and use with actual maintenance performance.
- Problems and factors associated with implementation of PMS using QFD technique require further research.

(3) *Information system oriented*:

- Evolution in middleware software, e.g. communications between corporate (i.e. ERP) and plant-floor information systems.
- Future scope includes BPR through workgroup computing technology, organizational transformations (e.g. decentralized MRO stores) and recasting of external relationships, e.g. outsourcing through inter-enterprise technology.
- Problems relating to application and development of an object oriented decision support system for maintenance management.

(4) *Maintenance management integration oriented*:

- Integration of maintenance management in to MRPII using appropriate system design that will improve logistics management and physical distribution functions of the organization.
- Problems related to implementation of object oriented maintenance management model and its integration to ERP.
- Integration of PMS with an effective MMIS.
- RCM has potential to be utilized in an automated environment i.e. more work on its integration with CMMS can be attempted.
- Integration of various scheduling models in to MMISs may be investigated to ensure effective planning and scheduling of maintenance jobs.

(5) *Maintenance concept oriented*:

- Future studies in the joint implementation of TQM, JIT and TPM to examine their close linkage and pinpointing exact nature of interactions.

- A new technique i.e. neural management maintenance is yet to be developed to reduce involvement of analysts/engineers in data processing and thus adding quality in decision-making process.
- Development of the customized maintenance concept framework to include more modules, e.g. material selection, data management, maintenance policy, standardization, etc. to allow selection of modules for which a decision support module is foreseen.
- The area of maintenance outsourcing has tremendous potential for investigation as more and more clients are becoming interested in contracting out maintenance.

(6) *Human behavior oriented*. Knowledge of maintenance engineers i.e. the expert judgment may be useful in the design of customized maintenance concept.

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