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ORIGINAL ARTICLE

A systems approach to integrated E-maintenance of large engineering plants

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Abstract Large engineering plants (LEP) such as power plants, process plants, ship-borne machinery and aircraft have certain unique features that a combination of both time and condition based maintenance of the plants is considered necessary. It has, however, been observed that applied research leading to a systematic development of such a maintenance strategy needs further study. Such a strategy should not only harness the advantages of both time and condition based maintenance but also adopt a wholesome 'Systems' approach so that the realisation of the overall objectives of maintenance is maximised. e-Maintenance has in the last decade emerged as a coherent and effective amalgamation of information and communication technologies in the arena of maintenance playing a crucial role in maintenance decision making. The focal area of application of e-maintenance has been that of condition based maintenance—e-monitoring, e-diagnosis and e-prognosis. It may be observed that as far as LEPs are concerned, the capability of e-maintenance can be enhanced to add value to the entire maintenance strategy for the plant. In this paper a maintenance strategy for LEPs involving an integration of both time and condition based maintenance which also harnesses e-maintenance features is suggested. Frameworks are presented for maintenance decision making, integrated TBPM and CBPM, e-maintenance of LEPs and a systems approach to maintenance of LEPs.

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1 Introduction

Maintenance has an essential role in ensuring that engineering systems perform at desired levels of reliability, availability and safety in a cost effective manner and in keeping with the corporate demands. Appropriate maintenance also contributes towards life extension of components and systems. Maintenance of large engineering plants (LEPs) such as, aircraft, shipboard machinery, power plants and nuclear installations, have certain unique set of requirements, which have to be addressed to genuinely realize the benefits of maintenance.

Over the last four decades, extensive research in the field of maintenance has been reported, which have very diligently presented different segments of research involving modeling, optimization, planning and organization of maintenance systems. The ever increasing drive for presenting realistic maintenance decision models and frameworks which are capable of providing decision support closer to practical maintenance scenarios is a noteworthy trend in maintenance research. Some of the detailed coverage of classical maintenance models and policies can be found in works of Jorgenson et.al. (1967), Dekker (1996), Bhadury and Basu (2003), Wu and Croome (2005) and Wang and Pham (2006). Classical maintenance models have been adopted or improved to accommodate imperfect maintenance, opportunistic maintenance and maintenance with economic dependence which were being recognized as contemporary maintenance challenges to be addressed. Maintenance frameworks and schemes were developed for the application of one or more maintenance models as suited to maintenance management requirements. Structured and systematic designing of maintenance management tools (Sherwin 2000; Kelly 2006a, b; Levitt 2009) enabled establishment of maintenance as an important element of asset management as well as development of a range of computerised maintenance management systems.

Most early maintenance models were aimed at single or fewer unit systems. However, with the realization of the importance of maintenance in LEP, newer models or adaptations of classical models and development of suitable frameworks were found necessary for company-wide strategic maintenance (Jonsson 1999). One of the requirements in the planning of maintenance of LEPs is to integrate time and condition based maintenance strategies for concurrent implementation so that objectives of maintenance can be effectively achieved. One of the early efforts in this direction was an optimal replacement strategy wherein a failed item is replaced instantaneously at failure by a new one. Items with age b or less at instants kT ($k = 1,2,\ldots$) are allowed to remain in service. This strategy is shown to be more efficient than the basic block replacement strategy aiming to maximize steady state availability (Jamali and Ait-Kadi 2005). Frangopol et.al. (2009) have presented global cost optimization by means of a cost-optimized condition-reliability profile (COCRP) approach for assessment of structures in a probabilistic framework. COCRP computations are carried out through advanced Monte Carlo Methods. Niu et al. (2010) have developed a condition based maintenance (CBM) system that integrates data fusion strategy (to improve maintenance accuracy) with traditional CBM (to enhance cost effectiveness of maintenance) within the architecture of RCM management.

While time based maintenance and 'run to failure' maintenance are being practiced in LEP, Condition Based Predictive Maintenance (CBPM) is gaining popularity due to its proactive approach. However, CBPM tools and techniques require elaborate instrumentation and modeling efforts. To be able to render them effective a requirement analysis is necessary (Kothamasu et al. 2006). Jardine et al. (2006) have reviewed recent research and development in machinery diagnostics and prognostics implementing CBPM. It is observed that future CBPM systems would focus on various aspects of continuous monitoring and automatic diagnostics and prognostics. To be able to achieve effective implementation of CBPM, there is a need to optimize the characteristics of both the condition monitoring system and the plant that is being maintained starting at a macro level. The condition monitoring system is required to be optimized with regard to its ability to detect the onset of an impending failure and predict the time of final failure. On the other hand, the plant that is being maintained will need to be optimized for its amenability for being effectively subjected to CBPM. This optimization will enable decisions regarding the area and extent of effective applicability of CBM for a large plant consisting of several sub-systems arranged in a complex way.

E-maintenance provides an excellent platform for the above mentioned integrated maintenance, particularly for LEPs operating over wide, geographically distributed areas. Simply put, e-maintenance can be considered as a maintenance management system where assets are monitored and proactive maintenance decisions arrived at over the internet and other remote communication tools. More specifically, one of the main objectives of e-maintenance is to enhance maintenance process based on information and communication technology (ICT) that provides the right information at the right time, of the right quality, to the right actor (Karim et al. 2009). There are several e-maintenance platform software and schemes available, some of them being commercially off the shelf (COTS) products. However, the focus of this paper is to highlight the need for a robust requirement analysis through models of relevant maintenance strategies. This paper discuses modeling of both time based maintenance and condition based maintenance for large engineering systems using discrete event model and a continuous state space Markov process, respectively. In order to be able to predict the effectiveness of e-maintenance platforms there is a need to quantify certain less tangible features of, say, the condition monitoring system such as detectability, predictability and diagnostic ability. Although such details are not quantifiable in crisp terms, considerable amount of information is available with experts in the field. The expertise will therefore need to be gathered and quantified using fuzzy inference tools and supply the details as inputs to maintenance models.

2 Large engineering plants and their time based preventive maintenance

LEPs are designed as 'first of its kind' systems without much statistical information to plan time based preventive maintenance. Therefore, there is a need to ab initio identify decision variables such as preventive maintenance interval, maintenance resources such as workforce and features of condition monitoring system.

LEPs have multiple parts in the form of systems, subsystems and components. On the basis of functionality and maintainability, the parts of a large engineering plant can be organized into modules. A set of modules can further be grouped into higher modular assemblies (HMA). The HMAs are organised as series constituents of the plant, that is, it is necessary to have all the HMAs operational so that the plant as a whole is operational. The HMAs may have redundant modules within them as shown in Fig. 1. It is assumed that it is imperative to have all the HMAs, including the redundant modules within each HMA, fully operational at the commencement of each mission (operational period). Operational periods will be interspersed with maintenance periods.

As far as shut down maintenance is concerned, it will be desirable to carry out maintenance of all the HMAs concurrently so as to minimize the overall plant down time for maintenance. However, practically, 'concurrence of maintenance periods' will be limited by the fact that the optimum maintenance interval and duration of maintenance for all HMAs will be different owing to the level of complexity, inherent reliability, maintenance cost and resources considerations. Further, recommendations regarding the preventive maintenance intervals are provided by the equipment manufacturers which are expected to be different for different equipment. Operation and maintenance periods for four HMAs and also the net availability of the complete plant are shown in Fig. 2. It can be seen that due to the differing operational and maintenance periods of the HMAs, the uptime of the plant as a whole is low. In order to increase the plant uptime it is necessary to conduct maintenance of all HMAs as concurrently as possible. The extent to which maintenance actions can be carried out concurrently would vary from time to time. Therefore, the concurrence of maintenance is also realtime variable to be factored into e-maintenance decisions.

											% Uptime
HMA1	U	U	U	U	D	D	U	U	U	U	80%
HMA2	U	U	U	D	D	U	U	U	D	D	60%
HMA3	U	U	U	U	D	U	U	U	U	D	80%
HMA4	U	U	D	U	U	D	U	U	D	U	70%
PLANT	U	U	D	D	D	D	U	U	D	D	**40%**

U = Up state (operational)
D = Down state (under maintenance)

Fig. 2 Operational-maintenance cycle of four HMAs of a plant and that of the complete plant (Verma and Ramesh 2007)

preventively at certain scheduled intervals, although sometimes not otherwise warranted is considered necessary.

These periods of maintenance are scheduled with adequate plan. However, failures could still occur despite scheduled preventive maintenance (Amari et al. 2006). Hence there is a need to closely monitor performance of plants and also sense telltale signs of onset of failure, if any, and undertake predictive maintenance before a catastrophic failure could occur. It may therefore be noticed that there is a need to augment time based preventive maintenance (TBPM) with and condition based predictive maintenance (CBPM) for LEPs to ensure desired levels of reliability and availability. Thus, while the machinery modules of a plant are subjected to TBPM, the performance parameters of the modules are also to be monitored, time for failure predicted, logistic preparations initiated and preventive repair actions undertaken if necessary just in time thereby precluding a catastrophic failure.

Integration of TBPM and CBPM for a LEP is shown schematically in Fig. 3. An optimal set of objective values of reliability, availability of the plant and cost of maintenance are obtained through CBPM and TBPM modeling. The maintenance decision maker will choose that set of

3 Integrated maintenance

Generally operation of LEPs is carried out in areas remote from where large scale or depot maintenance support is available. Further downtime for repair or maintenance is very expensive, primarily because of considerations of lost opportunities (Verma and Ramesh 2007). The time required for mobilization of maintenance resources could be very large. Therefore, undertaking maintenance

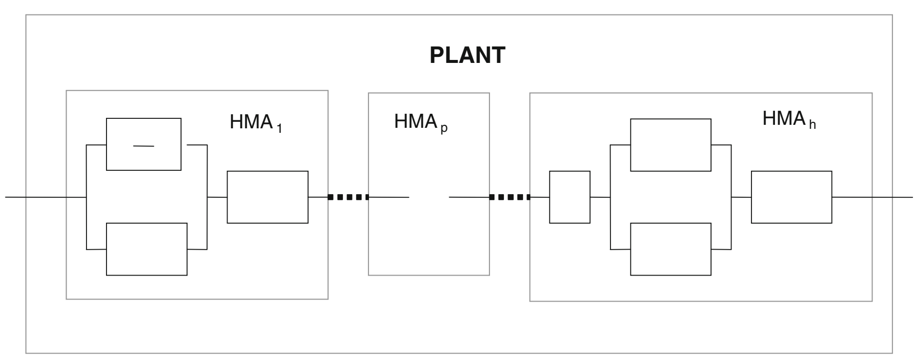


Fig. 1 Schematic representation of a plant consisting of HMAs which in turn consists of modules that may or may not have redundancies

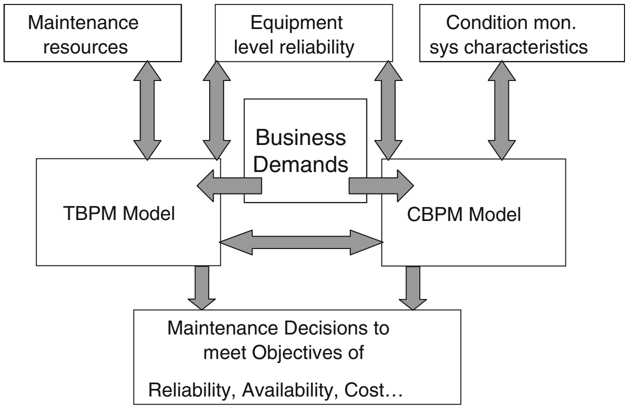


Fig. 3 Activities in the integrated maintenance of LEPs

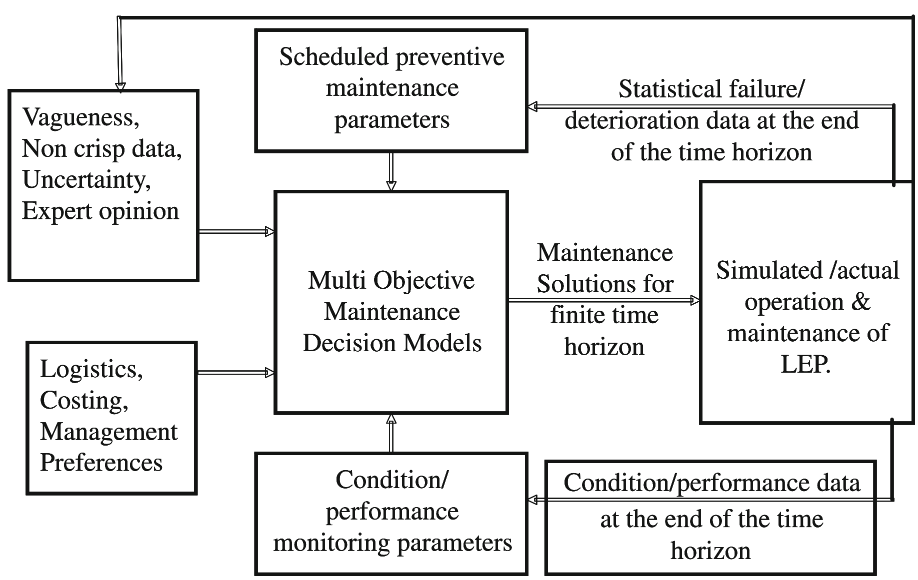
objective values in the light of business requirements. The flow of activities in an integrated TBPM and CBPM scenario is shown in Fig. 4. As it may be seen from the figure, an integrated maintenance problem for a LEP is a not only one with multiple and competing objectives but also a modeling problem that requires inputs from statistical data as well as fuzzy information and expert opinion.

4 E-Maintenance of LEPs

Recently e-maintenance has effectively harnessed ICT, the prowess of ICT such as wireless, telephony and internet in the arena of maintenance playing a crucial role in maintenance decision making. It can efficiently integrate geographically distributed sources of data, information and knowledge for optimal maintenance decisions and also enable use of technologically advanced sensors, signal processing tools and decision making techniques. e-maintenance has been defined as an asset information management network that integrates and synchronizes the various maintenance and reliability applications together and deliver asset information where it is needed and when it is needed (Moorer and Starr 2006). A comprehensive research by Karim (2008) has led to the characterisation of e-maintenance, development of e-maintenance solution for complex systems from a service oriented perspective and identification of related maintenance support information services. In the author's research e-Maintenance is defined as 'the part of maintenance support that ensures that the maintenance process is aligned with the operation and modification processes to obtain business objectives, through proper information logistics by information & communication technology (ICT) utilization and provision of information services'. Collaboration of local maintenance personnel at site with remotely located experts is the central theme of e-maintenance frameworks (Han and Yang 2006; Garcia et al. 2004). Real time diagnosis, prognosis and intelligent maintenance decision support systems are critical in the implantation of e-maintenance. Since e-maintenance platform is intended to support maintenance process, the components of the platform need to be considered from a service oriented perspective (Candell et al. 2009) so that information can be seamlessly shared between various elements of the e-maintenance platform, that is provide an effective ICT support to the maintenance process.

Apart from the design and reliability challenges of e-maintenance hardware and software, there are two additional challenges that need to be addressed. Firstly, time based maintenance will have to be integrated in the e-maintenance decision making framework into an integrated maintenance strategy for LEPs as discussed in the

Fig. 4 Integrated TBPM and CBPM for LEPs



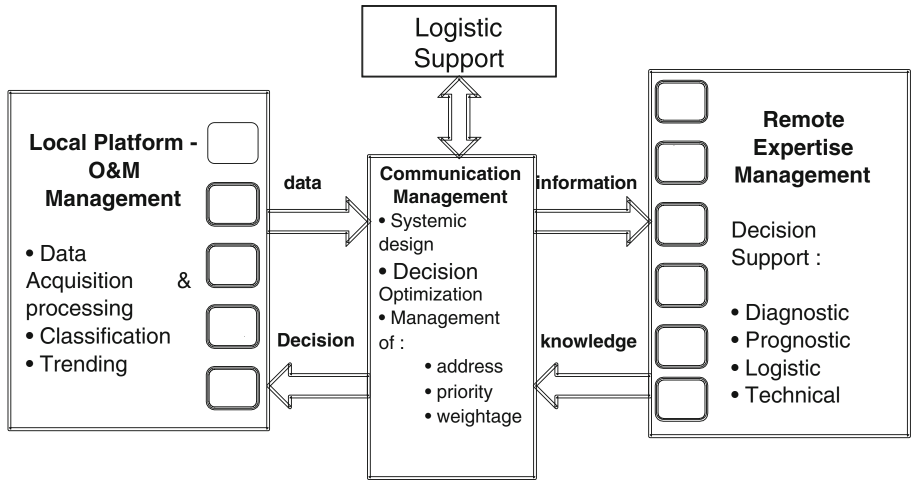


Fig. 5 Framework for e-maintenance

previous section. Secondly, the integrated maintenance strategy will need to be designed from a systems perspective which is essential for enhancement of effectiveness of maintenance.

A framework for e-maintenance proposed for maintenance management of LEPs is shown in Fig. 5. The local platform consists of the machinery and systems to be monitored and the condition monitoring system themselves. Data pertaining to the performance and health of machinery and systems are recorded by the condition monitoring system. The same are processed to the extent feasible within the local platform and classified into normal and abnormal values (fault detection) as well as analyzed for visible and significant causes and trends (diagnosis and prognosis). However, the capacity of the local platform to undertake fault detection, diagnosis and prognosis is limited. The remote centres of expertise are therefore to be configured into the system to extend the capacity of the local platforms. Data, partly or fully processed, are transmitted to the remote centres for creation of diagnostic, prognostic, logistic and technical knowledge support are transmitted back to the local platforms. An important module in the proposed e-maintenance framework is the communication management module. This module plays a central role in ensuring the overall success of the e-management effort. It has the decision optimisation models, prioritisation information, capacity and constraint data and inputs pertaining to corporate preferences. The framework also integrated e-logistics for maintenance and operations support.

One of the major factors that would determine the success of e-maintenance of LEPs is the result of requirement analysis: Provisioning of appropriate hardware, software and human expertise at appropriate locations. A systems approach to implementation of e-maintenance is a response to this requirement. Such an approach with integration of both time and condition based maintenance strategies is discussed in the next section.

5 A systems approach to macro level maintenance planning

It is a common observation at several large engineering plants that the condition monitoring tools and techniques have been applied to only a few of the equipments of the plant as standalone arrangements. Therefore, some of the equipment for which condition monitoring tools were easily applied benefitted from the CBPM strategy. However, failures of the plant continued to occur due to the failure of the balance subassemblies of the plant which were not covered adequately by CBPM. Further, all those equipment for which condition monitoring techniques were applied did not benefit to the same degree since the effectiveness of the monitoring system, the relevance of the monitored parameter and the frequency of monitoring were not entirely appropriate. Clearly, the solution to this problem is implementation of a comprehensive plant-wide CBPM coverage adopting a systems approach. As discussed in the earlier sections, in the case of LEPs, additionally TBPM is also required to be implemented through a systems approach.

A systems approach to e-maintenance of LEPs looks at the structure of the plant holistically. The approach recognises the interrelationships across the plant and scans the complete plant to identify failure causes. This approach enables maximisation of the objectives of maintenance. A systems approach for e-maintenance of LEPs is schematically shown in Fig. 6. In the systems approach shown in the figure, the plant is first divided into systems and subsystems and then into HMAs as discussed earlier. There are two parallel maintenance processes in the framework—one for CBPM and the other for TBPM.

In the TBPM strategy, as the next step necessary data is collected, processed and TBPM model inputs such reliability, cost of maintenance and other model parameters are estimated. A multi-objective TBPM optimization is

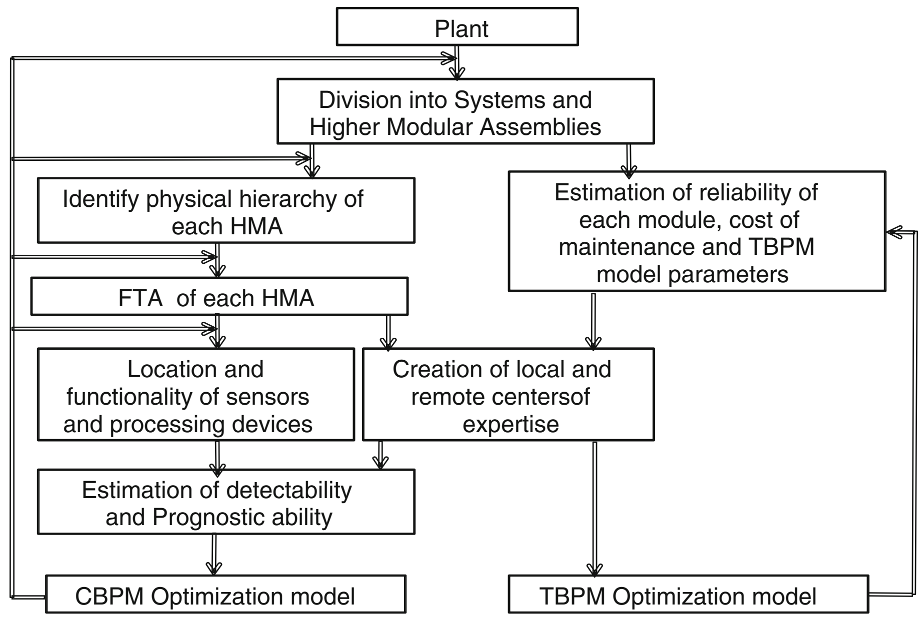


Fig. 6 Framework showing systemic approach to e-maintenance of LEPs

carried out which gives optimum sets of reliability of the plant and cost of maintenance and corresponding values of maintenance intervals.

In the CBPM strategy for the LEP, as the next step, the physical hierarchy of each of the HMAs is established. Also FTAs are generated for the HMAs. While the physical hierarchy indicates the required location of the sensors for condition monitoring, the FTA indicates the type of sensors and processing devices required to be provided. Having designed the condition monitoring system sensor network for the plant, it is necessary as the next step to estimate the ability of the condition monitoring system to detect the onset of failure (detectability) and predict the time of final failure (predictability). The estimated values of detectabilities and predictabilities of the condition monitoring systems in respect of all the HMAs are used in the CBPM (Markov) model as part of the state transition rates (Verma et al. 2008). The plant availabilities, cost of CBPM and other parameters are computed as a multi-objective optimization problem. The computed values of availability and cost are examined for their acceptability in the light of the organizational requirements and if the values are found unsatisfactory, the condition monitoring system sensor network is redesigned.

6 Conclusion

Comprehensive maintenance strategies are required to be planned, optimised and executed for LEP with both time and condition based maintenance arrangements integrated in order to maximize the achievement of the objectives of maintenance. However, for such integrated maintenance to be successful, it is necessary to undertake a requirements analysis from a systems approach. Optimal provisioning of hardware, software and support from remote expert centres as well as deployment of maintenance personnel play crucial parts.

E-maintenance with all the computational and information networking and transmission capabilities can emerge as a force multiplier for the maintenance of LEPs. An integrated e-maintenance will be able to acquire and harness information such as the rates and modes of failure of the equipment to be maintained, appropriateness of the condition monitoring arrangement, expert opinion, domain expertise, both local and remote, optimization and prioritization of maintenance objectives leading to optimal decisions. Frameworks in keeping with these requirements have been proposed in this paper.

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