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Condition-based Maintenance in Facilities Management

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A B S T R A C T

A facility management strategy requires that an organization's major operational concerns are dealt with, such as: avoiding the risk of catastrophic failures, planning for asset maintenance and reducing the quantity of spare parts and associated inventory costs. To bring this into further perspective, it is a well known fact that many systems suffer increasing wear with usage and age and are subject to random failures that are linked to the deterioration of these assets. Some examples of such affected items can be building components, hydraulic structures, turbine blades, and rotating equipment. In these cases, various physical deterioration processes can be observed, such as cumulative wear, crack growth, corrosion, fatigue, and so on.

The deterioration and failures of such systems might incur safety hazards, as well as high operational costs (due to work stoppage, delays, unplanned intervention, etc.). To cope with this, preventive maintenance strategies are often adapted thereby replacing the deteriorated system before it even fails. If the deterioration of the system, or a parameter strongly correlated with the state of that system can be directly measured (via corrosion assessment, wear monitoring, etc.), and if the system stops functioning when it deteriorates beyond a given threshold, then it is appropriate to base any maintenance decisions on the actual deterioration of the system rather than on its age. And this leads to the choice of a condition-based maintenance (CBM) policy. CBM techniques provide an assessment of the system's condition, based on data collected from the system through continuous monitoring and/or via inspections. The main intent is to determine the required maintenance plan prior to any predicted failure. Such a strategy will contribute by minimizing maintenance costs, improving operational safety and reducing the number of in-service system failures. This paper will address the merits of adapting CBM strategies in Facilities Management.

THE ROLE OF MAINTENANCE IN FACILITY MANAGEMENT

Modern maintenance management strategies have evolved over time; organizations are now trying to ensure high asset reliability and availability while trying to adhere to a limited maintenance investment. Arriving at a maintenance strategy for individual assets, to satisfy corporate objectives and with minimum investment remains a challenge. A number of maintenance strategies are being practiced today:

Corrective Maintenance or 'Run-to-failure': For a long time, organizations have practiced a “run to failure” maintenance strategy, which means an asset is operated until it fails. Maintenance action, which typically involves repair or replacement, is taken with the intention of correcting the fault. For non-critical assets, this is still considered a good operating strategy. But failures of many assets (such as critical) have far-reaching consequences. These failures can shut down entire production lines, make buildings unusable, or can even cause accidents. It is imperative that these types of failures are prevented.

Preventive Maintenance: A different type of maintenance strategy widely known as preventive maintenance has evolved to address some of the above problems. It involves looking at the asset failure history, and initiating maintenance to “fix” the asset before there is a high probability of its failing. The preventive strategy advises that maintenance be performed more often than is absolutely necessary. And since maintenance incurs costs in both labour and parts, this strategy can result in “over-maintenance”. Preventive maintenance often requires that assets be taken off-line for servicing, which in turn can incur costs due to down time and lost production.

Predictive vs. Condition-based Maintenance (CBM): Since preventive maintenance has become expensive, organizations have developed a different approach to maintenance, one that involves continuously (or frequently) monitoring an asset's condition until it begins to show evidence of deteriorating performance or failure. Maintenance is then performed in-time to prevent total failure. Compared to what preventive maintenance can offer, the new strategy (often known as predictive or condition-based) results in overall cost reductions, while providing better asset availability and performance. This strategy uses real-time information on the asset's condition to identify when maintenance will become necessary, which may also allow it be deferred until it is actually needed. The terms “predictive” and “condition-based” are sometimes used interchangeably, yet there is a distinct difference between the two. Predictive maintenance is activated by the analysis of equipment condition data that is gathered periodically, often manually. This contrasts with the CBM approach in which equipment condition data is collected in a continuous manner and analyzed in real-time. The evolution of maintenance may be depicted in the form of a picture as shown in Figure 1.

Figure 1: Evolution of Maintenance

Condition-based maintenance can be initiated according to the state of a degrading system that is monitored through various measures that typically describe the state of the system. Once the degradation characteristic crosses a specified threshold, action to perform the maintenance is triggered. This means that degradation measures must be identified that effectively relate the state of the system (or asset) to its remaining useful life, along with a decision on a failure threshold, with the feasibility of implementing a condition monitoring technology. Rausch (2008) has listed the most common monitoring methods being practiced today, like *Process monitoring*, *Vibration monitoring*, *Thermography*, *Tribology*, *Visual inspection* etc.

DEGRADATION MODELS FOR CONDITION-BASED MAINTENANCE

Selecting a suitable model to be used in a CBM scheme is not a trivial task. It should be based on the ability of the model to accurately describe the degradation process and make effective extrapolations of the component state into smart decisions related to the maintenance. The model must ensure that the degradation phenomenon is captured by the most realistic and practical method available for implementation. Degradation measurements traverse downward (or upward) toward a threshold, and the system is said to have failed at the instance when the measured value crossed a predetermined failure threshold. There are continuous time, discrete time, continuous state, and discrete state degradation representations. Many of the discrete state/time methods involve Markov methods, while some of the continuous degradation models include polynomials, cumulative damage, Brownian motion and gamma processes.

Scarf (2007) suggested a structured approach to choose an appropriate model for condition-based maintenance with the aid of a number of models. It is logical to place condition-based maintenance in the context of a general maintenance framework for a large complex system, one that considers all elements of the system (machines, units, components) that have failure characteristics. But, if it is not possible to define a failure threshold, and no condition indicator data are available at failure, and further that a warning threshold cannot be defined, then condition-based maintenance for the item is not feasible. In such cases, other maintenance policies should be explored – age- based, routine inspection, operate to failure, etc.

Grall et al. (2002) have described a system that undergoes random deterioration, while being monitored through “perfect” inspections. When the system condition exceeds its failure level, it enters into a failed state and a corrective replacement is carried out. When the system state is found to be greater than a critical threshold level, the still-functioning system is considered as ‘worn-out’ and a preventive replacement is performed. A low critical threshold leads to frequent preventive maintenance operations, and prevents the full exploitation of the residual life of the deteriorated (still functioning) system. But, a high critical threshold tends to keep the device working even in an advanced deterioration state, with increased risk of failure.

Goto et al. (2008) have proposed an on-line deterioration and residual life prediction method for the rotating equipment. The equipment is inspected for vibration measures and a mathematical model is created in order to predict the future condition of the equipment. Prior to building the deterioration model, the 'noise' in the vibration data caused by measurement errors is eliminated, which will also improve the accuracy of the model. An on-line deterioration data management scheme is included.

In most CBM modeling approaches, the deterioration measures are inspected and compared with a predefined threshold for maintenance decisions. Departing from this approach, Lu et al. (2007) describe what is called a predictive CBM (PCBM) to foretell the deterioration condition in the future. In the PCBM model the degradation states are modeled as continuous states using a state-space model in which the state vector includes both the degradation level and the degrading rate, both of which influence maintenance decisions.

Many researchers have provided multiple approaches to optimize maintenance decisions by taking into account the various characteristics of the complete system. For example, environmental conditions can affect the deterioration rate of a system; an excessive humidity level favours corrosion. Conversely, excessive deterioration of the operating system can make changes in the environment. One way of capturing the effect of the environment on an item's life span is to randomize its failure rate function and treat it as a stochastic process. In this context, a well known approach is the proportional hazard rate approach which consists of modeling the effect of the environment with the introduction of covariates in the hazard function.

Deloux et al. (2008) have described a condition-based maintenance decision framework to tackle the potential variations in system deterioration, especially in the rate of deterioration. In this work, the system condition at a specific time can be summarized by a scalar variable which varies increasingly as the system deteriorates, which can be the measure of a physical parameter linked to the resistance of a structure, (example: length of a crack).

The CBM modeling of deteriorating systems with multiple different units has not been a focus item. Wang et al. (2009) present a novel CBM approach for multi-unit systems in which the deterioration processes of multi units are modeled using continuous-time Markov chains. Segmenting the system deterioration into several discrete states is more practical than describing the deterioration condition by a single scalar continuous variable.

Rao and Naikan (2009) propose a condition-based preventive maintenance (CBPM) scheme for deteriorating systems; the associated model considers deterioration and random failures with minimal and major maintenance strategies. Minimal repairs are carried out after every random failure, whereas the device is replaced after the occurrence of the deterioration failure. The system undergoes random inspections to assess the condition; based on the condition of the device, a signal is prompted to do 'nothing', do minimal maintenance, or do major maintenance.

An important assumption that is implicit in many of the research works is that after each maintenance action, the state of the system returns to its initial state. Shahanaghi et al. (2008)] extend this assumption. In a nutshell it means that after each maintenance action, the system state is not fully improved and the amount of improvement made on the system state depends on the current state of the system.

INTELLIGENT CBM AND 'P-F' INTERVAL

According to Yam et al. (2001), intelligent systems that are used for condition-based fault diagnosis fall into three categories - rule-based diagnostic systems, model-based diagnostic systems and case-based diagnostic systems. Rule-based systems detect and identify equipment faults in accordance with the rules representing the relation of each possible fault with the corresponding condition. A model-based system uses various mathematical, neural network and logical methods and compares the real time monitored condition with the model of the object in order to predict the fault behavior. Case-based systems use historical records of maintenance cases to provide an interpretation for the actual monitored conditions of the item. A record of all previous incidents and system malfunctions along with their maintenance solutions are stored in a computer. If a fault similar to a stored case occurs, the case-based diagnostic system will pick up a suitable maintenance solution from the case library.

Figure 2: P-F interval

In a CBM scenario, the maintenance frequency is determined based on the hypothesis that most failures do not occur instantaneously. If sufficient evidence can be gathered that something is in the final stages of a failure, then it is also possible to take action to prevent it from failing completely and/or at least avoiding the consequences. According to Sethiya (2008), and as illustrated in Figure 2, maintenance task intervals should be determined based on the expected P-F interval. The P-F interval curve shows how a failure starts and deteriorates to the point at which it can be detected (point of potential failure "P"). Thereafter, if not detected and no action taken, it continues to deteriorate - usually at an accelerating rate - until it reaches the point of functional failure (Point "F"). The amount of time which elapses between the points of potential and functional failures is known as the P-F interval. To detect the

potential failure, an inspection scheme must be instituted, the interval of which must be significantly less than the P-F interval in order to avoid reaching the threshold of functional failure. The P-F interval can be measured in units relating to exposure to fatigue cycles (running time, units of output, stop-start cycles, etc).

APPLICATION TO BRIDGES AND BUILDING FACILITIES

The CBM approaches to maintenance found early acceptance in hardware equipment. Yet the techniques are equally applicable to assets that are in the form of buildings and structures, provided one can construct “P-F” curves for these assets. However, one should take note that geographical location plays an important role in the actual deterioration rate of buildings, since facilities are affected by environmental factors like exposure to sunlight, humidity, rain, snowfall, etc. This means that the same building can exhibit different degradation phenomena depending upon the location.

Markovian approaches are finding broad applications in the field of building component maintenance. Many systems employing this approach have been typically adapted to the bridge structure domain; but a few applications are in the works in the domain of building maintenance. As detailed in Lacasse et al. (2008) and Talon et al. (2008), the building façade maintenance management model developed at The National Research Council of Canada adapts the principles of bridge structures maintenance to the maintenance of building facades. It permits the optimization of maintenance planning, and introduces a system that permits a user to initiate building maintenance actions. The maintenance of many components is considered in the context of long term maintenance planning. The significance of various components with respect to others in the façade system is determined first by conducting a Failure Mode Effect and Criticality Analysis on all façade components. This approach permits the development of a component criticality index from which their relative importance is assigned amongst the different façade components. Optimization of various maintenance actions is considered with respect to the cost of such actions. This includes the replacement of components based on a multi-objective index, where the index provides a means of relating competing maintenance objectives.

Lounis and Vanier (1998) have presented a systematic approach for bridge maintenance management that combines a stochastic Markovian performance prediction model with a multi-objective optimization procedure. The main purpose was to determine the optimal allocation of funds and prioritization of bridges for maintenance, repair and replacement. The performance of bridges is dependent on many factors, like the materials involved, age, environmental conditions, traffic loading, past maintenance, etc. The Markov chain model is utilized in this system, as it can forecast the future condition of the bridge network, thus rationalizing the need for allocating required funds for maintenance. The stochastic modeling of the bridge performance via a discrete Markov chain model captures the time-dependence, uncertainty and variability associated with condition ratings, resulting from deterioration and maintenance, and the Markovian transition probability matrix is estimated from the condition ratings data collected during bridge inspections.

Lounis and Vanier (2000) developed a multi-objective and stochastic optimization system for the maintenance management of roofing systems that integrates stochastic condition-assessment and performance-prediction models with a multi-objective optimization approach. Its embedded model was based on in-field performance data collected during roofing inspections, considering the system and material types, environmental conditions, age, workmanship, and maintenance level. The system's main features are: i) Condition assessment of roofing components using infield visual inspection and non-destructive testing, ii) Prediction of future performance and remaining service life of building elements using stochastic Markovian models and iii) Multi-objective maintenance optimization of roofing maintenance by considering multiple conflicting objectives, namely, (a) minimization of maintenance costs, (b) maximization of network performance, and (c) minimization of risk of failure.

CONCLUSION

The condition-based maintenance (CBM) approach ensures a reduction in maintenance uncertainty, based on the needs indicated by the asset's condition. The monitoring process involves the collection and interpretation of the relevant asset (or component) parameters for identifying the state of deviations and changes from their normal conditions. The parameters in this context represent a set of characteristics that indicate the actual asset's condition. Any abnormality in these characteristics indicates the occurrence of some sort of functional failure. A built-in fault diagnosis scheme can be activated by the detection of such an abnormal condition; this would recognize and analyze the symptomatic information, identify the root causes of the failure and infer the fault development trend, as well as predict the remaining life of the asset. By monitoring the operating conditions of the defective item, future key symptoms associated with the deterioration of the component can be predicted. Equipped with this kind of monitoring system, an advanced alarm can be activated when the predicted value falls within an alarm band. This will help the system operators to take adequate actions to check the condition of the item and repair the defects prior to a total failure.

REFERENCES

- Deloux, E., Castanier, B. and Bérenguer, C. (2008). "Maintenance policy for a deteriorating system evolving in a stressful environment", Proc. IMechE Vol. 222 Part O: J. Risk and Reliability.
- Goto, S., Adachi, Y., Katafuchi, S., Furue, T., Uchida, Y., Sueyoshi, M., Hatazaki H., and Nakamura, M. (2008). "On Line Deterioration Prediction and Residual Life Evaluation of Rotating Equipment based on Vibration Measurement", SICE Annual Conference, Japan.
- Grall, A., Bérenguer C. and Dieulle, L. (2002). "A condition-based maintenance policy for stochastically deteriorating systems", Reliability Engineering & System Safety Volume 76, Issue 2, pp. 167-180.

- Lacasse, M.A.; Kyle, B.R.; Talon, A.; Boissier, D.; Hilly, T.; Abdulghani, K. (2008) "Optimization of the building maintenance management process using a Markovian model", NRC Canada Report NRCC-51170
- Lounis, Z and Vanier, D. J., (2000) "A Multi-objective and Stochastic System for Building Maintenance Management", Computer-Aided Civil and Infrastructure Engineering 15 Pp 320–329
- Lounis, Z and Vanier, D. J., (1998) "Optimization of Bridge Maintenance Management Using Markovian Models", International Conference on Short and Medium Span Bridges, Calgary, Alberta, Pp.1045-1053, V.2
- Lu, S., Tu, Y. C and Lu, H. (2007). "Predictive Condition-based Maintenance for Continuously Deteriorating System" Qual. Reliab. Engng. Int. 23. pp 71–81.
- Rao, P. N. S., and Naikan, V.N. A. (2006). "An Optimization Methodology for Condition Based Minimal and Major Preventive Maintenance", Economic Quality Control, Vol 21, No. 1, pp 127 – 141.
- Rausch, M. T. (2008). "Condition based Maintenance of a single system under Spare Part Inventory Constraints", M.Sc. Thesis, Wichita State University.
- Scarf, P. A. (2007). "A Framework for Condition Monitoring and Condition Based Maintenance" Quality Technology & Quantitative Management, Vol. 4, No. 2, pp. 301-312.
- Sethiya, S.K. "Condition Based Maintenance (CBM)", Secy. to CME/WCR/JBP
- Shahanaghi, K., Babaei, H., Bakhsha, A., and Fard, N. S. (2008) "A new condition based maintenance model with random improvements on the system after maintenance actions: Optimizing by Monte Carlo simulation", World Journal of Modelling and Simulation, Vol. 4 No. 3, pp. 230-236.
- Talon, A., Boissier, D., Hans, J., Lacasse, M.A., Chorier, J, (2008) "FMECA and Management of Building Components". National Research Council Canada Report NRCC-51168.
- Wang, L., Zheng, E., Li, Y., Wang, B., and Wu, J. (2009). "Maintenance Optimization of Generating Equipment based on a Condition-based Maintenance Policy for Multi-unit Systems", CCDC – IEEE 2009.
- Yam, R. C. M., Tse, P. W., Li L., and Tu, P. (2001) "Intelligent Predictive Decision Support System for Condition-Based Maintenance", Int. Journal of Advanced Manufacturing Technology 17. Pp 383–391