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Adaptive Control Approach in Modeling Life-cycle Maintenance Policy Selection and Optimisation During Infrastructure Systems Conceptual Design & Operation.

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Abstract

The availability of infrastructure systems are increasingly becoming of utmost importance due to their heavily bonded external interactions compared to other engineered systems. However, during the conceptual design and operational stage of these infrastructure systems, not enough parameter information (e.g. from historical database etc) may be available for a realistic availability and cost estimation. To circumvent this, we propose in this paper, an adaptive control approach.

Keywords Adaptive Control, Maintenance policy, Infrasystems, Conceptual design.

1. Introduction

Infrastructure systems - natural gas, electricity water and wastewater as well as process systems availability is greatly influenced by a number of key decisions

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and parameters (such as the inherent reliability and the maintenance policy etc) taken at various levels of the life-span of such infrastructure system. From the process systems domain (which we believe is to a larger extent also true in the infrastructure systems domain), the traditional common practice in ensuring system availability through adequate maintenance policy selection is usually relegated to the detailed engineering and operational phase. In some strict cases, assumptions based on experience are made about the maintenance policy and the system availability. The reason behind this practice is that at the conceptual stage, not much information may be available for quantitatively determining the exact maintenance policy. A paradigm shift from these traditional experienced based and late consideration of the maintenance aspect of the system to a new knowledge(model)-based and early consideration of not only maintenance aspects but also other Reliability, Availability and Maintainability (RAM) aspects have been emphasised by many researchers [1,2]. In this new paradigm, quantitative models are used at different phases of the system life cycle(starting from the conceptual design phase when the designer have the greatest degree of freedom to incorporate these performance criteria in the most cost effective manner) to set RAM targets. As identified in [1] these targets which may not be at the optimal desired levels, perhaps due to the unavailability of detailed historical data and information, could later be controlled throughout the asset life cycle. Based on this philosophy, we propose an adaptive control strategy for modelling the life-cycle maintenance policy selection and optimisation of Infrastructure Systems. The adaptive control formulation is conceptualised as having two parts; first is the posterior estimation of the uncertain parameters, based on prior estimates, historical observation and/or envision of the past states of the system using any known parameter estimation method and on the basis of the refined parameter estimates, an update of the maintenance strategy is carried out.

2. Model Development

The incorporation of infrastructure systems maintenance early in the design and operational process involves three core areas: 1) performance modelling, 2) data collection and updating and 3) design decision making on maintenance policy selection.

2.1. State-based Maintenance Performance Model:

In this section, the performance model in the form of optimisation model which minimizes the overall maintenance cost taking into account, the various states the infrastructure system may reside along its life cycle is formulated.

Assuming that the probability of the components of the infrastructure system changing from state i to state j as a result of maintenance activity m could be captured as:

$$\pi_{ij}(m) = \Pr\left(S^{t+1} = j \middle| S^{t} = i\right) \quad 1 \le i, j \le I, t = 0,1,...T-1, m \in M \tag{1}$$

The maintenance transition matrix given that maintenance policy or activity *m* is performed on the system as:

$$\Pi(m) = \begin{bmatrix} \pi_{11}(m) & \pi_{11}(m) & \dots & \pi_{1I}(m) \\ \pi_{21}(m) & \pi_{22}(m) & \dots & \pi_{2I}(m) \\ \vdots & \vdots & \vdots & \vdots \\ \pi_{I1}(m) & \pi_{I2}(m) & \dots & \pi_{II}(m) \end{bmatrix} \tag{2}$$

The **state-based maintenance performance model** can be formulated as shown:

$$Min \sum_{i=1}^{I} \sum_{m \in M} f^{t}(i,m).\left(C^{t}(i,m)\right) \tag{3}$$

$$s.t \;\; \varepsilon_{it}(x_{it}, z_{it}, \theta_{it}..) = 0 \tag{4}$$

$$g_{it} \;\; (.x_{it}, z_{it}, \theta_{it}..) \ge 0 \tag{5}$$

$$f^{t}(i,m) \ge 0 \quad \forall i, m, t = 1,2,...T \tag{6}$$

$$\sum_{i=1}^{I} \sum_{m \in M} f^{t}(i,m) = 1 \quad \forall t = 1,2,...T \tag{7}$$

$$\sum_{m \in M} f^{t+1}(j,m) = \sum_{i=1}^{I} \sum_{m \in M} f^{t}(i,m).\pi_{ij}(m) \quad \forall j, t = 1,2,...T \tag{8}$$

$$B^{t}_{\min} \le \sum_{i=1}^{I} \sum_{m \in M} f^{t}(i,m).(C^{t}(i,m)) \le B^{t}_{\max} \quad \forall t = 1,2,...T \tag{9}$$

$$Q^{t}_{\min} \le \sum_{m \in M} f^{t}(i,m) \le Q^{t}_{\max} \quad \forall i, t = 1,2,...T \tag{10}$$

Where: $f^t_{(i,m)}$ is the fraction of the components of the infrastructure network that may be in state *i* and may be acted upon by a maintenance activity m in time *t*. $C^t(i,m)$ is the total cost associated with carrying out maintenance activity *m* on a component in state *i*. $\Pi(m)$ is the maintenance transition matrix given that maintenance policy or activity *m* is performed on the system. *I* is the total number of discrete states the infrastructure components can reside. π_{ij} is the probability of the components of the infrastructure system changing from state *i* to state *j* as a result of maintenance activity *m*. S^t is the state or condition of the infrastructure component at time *t*. *i,j* are the indices indicating the states of the components. *m* is the maintenance activity or policy in the set of activities or policies. *M* is the set of maintenance activities or policies. *T* is the total time in horizon. The objective function, Eq. (3), aims at minimizing the total maintenance cost given the deteriorating states at which the components of the infrastructure system might reside during its life cycle. Eq. (4-10) are the constraints necessary for the minimization of the maintenance cost to hold. Eqs. (4 & 5) are the system related equality and inequality constraints accounting for the infrastructure resource constraints and the associated design decision variables. Eqs. (6 & 7) are indicative of the fact that at each point in time, the fraction of the components in the infrastructure network should be non-negative and the sum of the all the fractions should be equal to unity. Eq. (8) conserves the components changing their states from state i to state j under maintenance activity *m*. The budget constraint, Eq.(9) allows for minimum and maximum values of maintenance budget while Eq. (10), imposes a minimum quality on the states of the components of the infrastructure system.

2.2. Observability of System States and Updating Procedure

During the conceptual design process, since the information and data regarding the systems internal or intermediate states are usually sketchy, the systems internal states are generally viewed as black box with only the binary (working and failed) states often captured. To capture the reality, both the internal and the external states of the systems should be equally modeled using the most available information at hand and some engineering judgment, which may later be corrected or updated once the uncertainty enveloping such information becomes clear during design and operation.

The updating procedure adopted here is the principles of maximum likelihood estimation and/or the bayes updating procedure [3]. In the realm of observability, using field or historical data, at time t+1, the number of components which might change from state i to state j in time t+1, under maintenance activity *m* could be obtained. Denoting this as $x^t_{ij}(m)$:

$$X_i^t(m) = \sum_{i=1}^{I} x_{ij}^t(m) \quad \forall i, m, t \tag{11}$$

$$n_{ij}^t(m) = \sum_{h=0}^{t} x_{ij}^h(m) \quad \forall i, j, m, t \tag{12}$$

$$N_i^t(m) = \sum_{h=0}^{t} X_i^h(m) \quad \forall i, m, t \tag{13}$$

Using the principles of MLE and/or bayes updating [3] the transition probability at time $t+1$ could be estimated:

$$\pi_{ij}^{t}(m) = \frac{\sum_{h=0}^{t} x_{ij}^{h}(m)}{\sum_{h=0}^{t} X_{i}^{h}(m)} = \frac{n_{ij}^{t}(m)}{N_{i}^{t}(m)} \qquad \forall i, j, m, t \tag{14}$$

And the updated transition matrix given that maintenance activity *m* is performed becomes:

$$\Pi^{t}(m) = \begin{bmatrix} \pi_{11}^{t}(m) & \pi_{12}^{t}(m) & \dots & \pi_{1I}^{t}(m) \\ \pi_{21}^{t}(m) & \pi_{22}(m) & \dots & \pi_{2I}^{t}(m) \\ \vdots & \vdots & \vdots & \vdots \\ \pi_{I1}^{t}(m) & \pi_{I2}^{t}(m) & \dots & \pi_{II}^{t}(m) \end{bmatrix} \tag{15}$$

Where $\pi_{ij}^{t}(m)$ is the updated transition probability of the component changing from state *i* to state j given that a maintenance activity m is performed on it at time *t*. $\Pi^{t}(m)$ is the updated transition probability matrix for maintenance activity m in time *t*. Based on the new updated matrix, the maintenance performance model is also updated and a suitable policy selected in line with the updated matrix.

3. Case Study and Results

A gas pipeline network (a typical energy infrastructure) which transports natural gas from a supply point (source) to several demand points (physical sinks,) through the arcs (pipes and compressor stations) is used as a case study. Based on a criticality rating, the compressor station and the pipeline segment have been singled out for further analysis. The failure mechanism of the system components is modelled in five multi-states. For the pipeline segment, let states *U, D1, D2*, and *C2* represent the fully operational state, minor pipeline cracks, major pipeline cracks and pipeline rupture states respectively. At the design and operational stage, information concerning the occupancy of these states may not be clear. At any time interval, given the update on failure rate and repair rates, etc, the probability of the system components to be in a particular state and the associated maintenance cost at that state, the system designer or managers will be better placed in selecting an optimal maintenance strategy at the most effective cost. Table 1 shows the prior and the estimated posterior probabilities for the pipeline and compressor components. The updating technique reveals better, the true state occupancy of the system. The impact of this on the system design is that the use of the base case where a constant availability is assumed without updating, as is in the current practice, produces either an extremely optimistic or pessimistic design. This will also affect the maintenance policy selection as well as the cost of maintenance. With the analysis and update, it becomes easy to trade-off the envisioned reliability & availability of a given component or sub-system with the perceived cost of maintenance at any given point in time during the life cycle of the system.

Table 1: Estimated prior & posterior state probabilities at different time intervals

Time	**Case**	Component	State U	State D_1	State D_2	State C_1	State C_2	Cost (€)
t_0	**Base case**	Pipeline	0.9997	0.00059	0.00012	0.00005	0.000	10,000
		Compressor	0.9679	0.00930	0.01520	0.00760	0.000	
t_1	**Update 1**	**Prior**						
		Pipeline	0.9997	0.00059	0.00012	0.00005	0.000	10,000
		Compressor	0.9679	0.00930	0.01520	0.00760	0.000	
		Posterior						
		Pipeline	0.9797	0.00069	0.00022	0.00005	0.000	17,000
		Compressor	0.9479	0.01030	0.02520	0.00760	0.000	
t_n	**Update n**	**Prior**						
		Pipeline	0.9320	0.0645	0.00825	0.0005	0.000	35,000
		Compressor	0.5652	0.01035	0.0155	0.01850	0.3530	
		Posterior						
		Pipeline	0.9420	0.0545	0.00825	0.0005	0.000	32,000
		Compressor	0.6052	0.00835	0.0155	0.01850	0.3530	

4. Conclusions and Remarks

One of the issues hindering the effective integration of design and maintainability is the unavailability of complete data at this stage of the design process and somewhat early in the operational stage. We propose a Bayesian updating solution to this problem. The adaptive control approach provides an excellent way of combining and updating engineering knowledge with any available historical data in a robust manner. The applicability of the framework as a decision support for explicitly determining the maintenance strategies most suitable for the component and/or subsystem of a given infrastructure system is demonstrated in a simple gas transmission network (GTN) system. Though the case study is simple, its applicability in real complex cases is very possible.

References

1. H.D. Goel, PhD Thesis, Technical University of Delft, DUP Science (2004).
2. J. Grivink, K. Smit, R.Dekker, C.H.F Van Rijn, Foundation of Computer Aided Process Operation FOCAP-O, (1993).
3. M. H. de Groot, Optimal statistical decisions. New York: McGraw-Hill, Inc. (1970).