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Stopping time optimisation in condition monitoring

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Abstract

Automated condition monitoring of active components of a system can improve the cost-efficiency of preventive and corrective maintenance and the availability of the production system. The validity, reliability and correct interpretation of the signals obtained from the condition monitoring instrumentation is important for the realisation of the potential benefits. The utilisation of experts in the interpretation of the condition monitoring signals is therefore crucial.

In the paper, a stopping time model is formulated, where experts' judgements on the remaining operating time of a component, given an indication of incipient failure, are utilised to arrive at optimal operational maintenance decisions. Optimality is defined in the sense of maximising expected utility. An expert model is also formulated, which utilises percentile information elicited from the experts. The modelling framework allows for the testing of different modelling assumptions which affect the decision outcomes.

Keywords: Condition monitoring; Stopping time optimisation model; Expert judgement; Predictive maintenance

1. Introduction

Short-term operational maintenance decision-making based on condition monitoring has to take into consideration the predictive power of the observations made. Basically, observations can be made through process and condition monitoring. Especially, automated physical measurement of the condition of equipment has lately been increasingly implemented for predictive maintenance. In this case, the validity, reliability and the correct interpretation of the readings of the sensors are essential for the benefits of condition monitoring to realise. The signal validation project [1] in the Halden Reactor Project, develops on-line methods to verify the correctness of the signal received from the sensors. Wrong judgements from inspections and tests, or wrong interpretation of measurements due to faulted or miscalibrated instrumentation might lead to operative decisions, which are non-optimal in terms of costs due to excessive production losses or repair. Operational maintenance decisions also have safety implications in many cases, stressing the importance of proper decision-making.

In the case of automated condition monitoring, we are confronted with the operational maintenance decision problem of continuing operation with a degradation in the active equipment or component, given that an indication of an incipient failure has been received from the sensors. We can distinguish between outcomes of a certain operational maintenance decision as shown in Table 1. The basic temporal realisations of the functional breakdown of a component, denoted by t_1 and t_2, are shown in Fig. 1 together with the time points related to the decision options.

The earlier described short-term evaluation of the decision outcomes does not take into account the long-term 'costs' of the different outcomes on safety and work culture such as compliance with safety rules and adherence to the quality of maintenance work. These long-term aspects have to be considered in the decision-making also and are usually expressed as design and operative constraints of systems [2].

Ideally, we can argue that from the point of view of the owners of a production system, the optimal design of a system or a component is such that its lifetime coincides with the scheduled time for replacement or overhaul. Roughly speaking, a system or a component should be good enough to perform as planned (planned output/input and lifetime), but not better (waste of resources). By introducing proper condition monitoring, the production personnel/manager can obtain information about unexpected discrepancies in the condition of the components of a system and make risk-informed maintenance decisions given this information. The rationale is that the cost induced

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Nomenclature

s	operating time
s_0	time of incipient failure indication
τ	stopping time, control variable
τ^*	optimal stopping time
L	time of scheduled shutdown
$J(\tau)$	profit function
C	cost, random variable
c	a realisation of C
c^{u}	upper bound of C
c^{l}	lower bound of C
r	constant income rate
T	failure time, unknown but observable random variable
$\mathbf{X}$	$(n \times 1)$ random vector of expert judgements on T
$\mathbf{x}$	$(n \times 1)$ vector $\mathbf{x} = (x_1, \ldots, x_n)$ as elicited from the experts, a realisation of $\mathbf{X}$
$\mathbf{y}$	$(n \times 1)$ vector $\mathbf{y} = (y_1, \ldots, y_n)$ of measures of uncertainty as elicited from the experts
$\mathbf{z}$	$(n \times 2)$ vector of expert judgements; $\mathbf{z} = (\mathbf{x}, \mathbf{y})'$, $z_i = (x_i, y_i)$ is the ith element
$\mathrm{v}(\tau\|\mathbf{z})$	value of τ given information $\mathbf{z}$
$u(J)$	utility of receiving J
α, β, γ	positive constants specifying the utility function $u(\cdot)$
$f_{T\|\mathbf{z}}(t\|\mathbf{z})$	probability density of T conditional on $\mathbf{z}$
$F_{t\|\mathbf{z}}(t\|\mathbf{z})$	cumulative probability function of T conditional on $\mathbf{z}$
$F_C(c)$	cumulative probability function of C
n	denotes the number of experts
X_i	random variable representing experts i judgement on the median of T
x_i	a realisation of X_i
η_i	a random variable representing the bias and spread of expert i's judgements
σ_i	standard error of the logarithm of expert i's judgements
$\boldsymbol{\Sigma}_{\mathbf{z}}$	the co-variance matrix of experts' judgements on T
a_{ij}	elements of the inverse matrix $\boldsymbol{\Sigma}_{\mathbf{z}}^{-1}$
ρ	correlation coefficient of experts' judgements $(n = 2)$
$T^{.50}$	the prior estimate of the median of the failure time
$T^{.95}$	the prior estimate of the 95%-percentile of the probability distribution of T

by implementing condition monitoring is out-weighted by the benefits of the information that it produces. The assessment of the validity of this rationale is a task related to long-term maintenance planning [3].

In the following, we will utilise expected utility (EU) theory in the formulation of a stochastic stopping time model [4]. The stopping time model is utilised for operative maintenance decision-making when an incipient failure has been detected. This entails the modelling of the decision-makers subjective risk-attitude, on one hand, and the modelling of experts' judgements on the failure time, given the incipient failure indication, on the other hand.

Expert judgement will be used in a direct way: experts are asked to provide percentile information on residual lifetime of the component given the indication of incipient failure. Thus, the modelling will focus on the use of expert judgement rather than on physical degradation processes [5].

The optimal maintenance decision in terms of the optional basic (generic) operational maintenance decisions in Table 1, will be concluded on the basis of the optimal stopping times derived from the stopping time model. Optimality is defined in the sense of maximising EU [6].

In Section 2, the operational maintenance decision problem is formulated as a stopping time optimisation problem. Section 3 describes a probabilistic expert judgement model. An emphasis is put to modelling dependence between these judgements by specifying a probabilistic model based on the multivariate normal data model. Section 4 demonstrates the stopping time model through an example and interprets the results in terms of the basic operational maintenance decision options.

2. Stopping time model

2.1. Stopping time

Basically, we will ask how should the stopping time τ be determined given an incipient failure indication at operating time $s = s_0$. The theoretical domain of τ is the positive real line $[0,\infty)$, where the starting point coincides with the operating time s_0. If, an optimal stopping time τ^* is found, then the following *decision rule* is applicable

$$\begin{aligned} &\text{if } \tau^* \geq L - s_0 \text{ continue operation until } s = L \\ &\text{else continue operation until } s = s_0 + \tau^* \end{aligned} \tag{1}$$

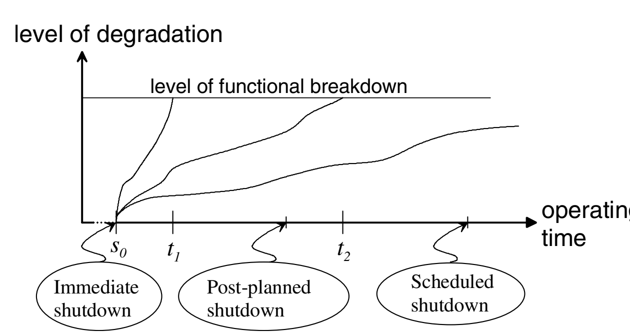

Fig. 1. Possible failure times t_1 and t_2 together with time points related to maintenance decision options. The detection time of an incipient failure is denoted by s_0.