Reliability Engineering and System Safety 130 (2014) 33–41

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

# Cost modelling in maintenance strategy optimisation for infrastructure assets with limited data

Wenjuan Zhang [a], Wenbin Wang [b,c,*]

[a] ORMS Group, Warwick Business School, University of Warwick, Coventry CV4 7AL, UK
[b] Dongling School of Economics and Management, University of Science and Technology Beijing, Beijing 100083, China
[c] Faculty of Business and Law, Manchester Metropolitan University, Manchester M15 6BH, UK

ARTICLE INFO

*Article history:*
Received 17 October 2012
Received in revised form
28 March 2014
Accepted 27 April 2014
Available online 14 May 2014

*Keywords:*
Maintenance
Infrastructure asset
Cost modelling
Bayes linear estimator
Elicitation
Metal girder

ABSTRACT

Our paper reports on the use of cost modelling in maintenance strategy optimisation for infrastructure assets. We present an original approach: the possibility of modelling even when the data and information usually required are not sufficient in quantity and quality. Our method makes use of subjective expert knowledge, and requires information gathered for only a small sample of assets to start with. Bayes linear methods are adopted to combine the subjective expert knowledge with the sample data to estimate the unknown model parameters of the cost model. When new information becomes available, Bayes linear methods also prove useful in updating these estimates. We use a case study from the rail industry to demonstrate our methods. The optimal maintenance strategy is obtained via simulation based on the estimated model parameters and the strategy with the least unit time cost is identified. When the optimal strategy is not followed due to insufficient funding, the future costs of recovering the degraded asset condition are estimated.



## 1. Introduction

Infrastructure assets require huge investment to ensure that they meet functional requirements, and infrastructure companies must select appropriate maintenance strategies for their assets. The rail company that we consider in this paper estimates that five billion pounds are required to maintain its bridges and civil structures over the next 50 years. To protect the investment and sustainability of the rail infrastructure, it is vital to maintain these long-life assets as economically and efficiently as possible. Cost models can help to identify the optimal maintenance strategy with the least cost while maintaining safety, and have attracted a great deal of attention from infrastructure industries [1] in areas such as rail [2], water and environment [3], bridges [4], building [5] and civil infrastructure [6].

Despite this, the development and application of such optimal maintenance strategies have not advanced much over the years. There are still many challenges to overcome, as demonstrated in Skinner et al. [2]. Key challenges in the rail industry include:

- Defining the size and configuration of the asset. The asset should be analysed, and any sub-asset hierarchy down to a maintainable item (MI) should be specified because the faults and failures occur at the MI level. Such MIs are the base unit for planning and executing the required maintenance. For example, a single-span bridge constructed of a concrete deck with masonry jack arches on metal girders with masonry end supports is defined with four MIs, each with its own degradation rate, cost and intervention cycle.
- Lack of historical data in defining asset relationships. The timings of different interventions are required for optimising the maintenance strategy, together with the capital and operational expenditure costs for the range of interventions. Ideally, this information should be based on an asset's historical failure and maintenance data. Failure data is rarely available, but maintenance data should normally be available from asset management information systems. However for organisations in a low maturity level of asset management, e.g. in our case study, although there are sufficient historical maintenance records available, these records are not stored electronically and it would take many man-hours to obtain the required information from paper records.
- Dealing with uncertainty. Even if the current conditions of all assets were known, it would not be possible to predict future investment costs with certainty.

Therefore, it is acknowledged that a statistical estimation of costs is needed. Detailed information would be gathered by investigating only a small sample of assets. In addition, a large amount of general and

* Corresponding author at: Dongling School of Economics and Management, University of Science and Technology Beijing, Beijing 100083, China.
Tel.: +86 10 62332744.
*E-mail addresses:* wenjuan.zhang@wbs.ac.uk (W. Zhang), wangwb@ustb.edu.cn (W. Wang).

http://dx.doi.org/10.1016/j.ress.2014.04.025

local knowledge and expertise is inevitably acquired during routine data collection practices. This expert knowledge is useful in asset management when sufficient historical data is not available. Wang and Zhang [7] utilised expert knowledge to predict an asset's residual life when the historical data is lacking in both quantity and quality. Because of the subjective element of experts' beliefs, the elicitation and use of expert knowledge should be handled carefully. O'Hagan [8] considered the practical elicitation of experts' beliefs through two contrasting examples. The first example concerns elicitation of engineers' beliefs in the forms of prior means, variances and covariance about various quantities relating to the future capital investment need of a water company. A computerized procedure was required that could be routinely used by engineers (after training), unsupervised. The second example is a single, application-specific elicitation of the beliefs of hydrogeologists about properties of certain rocks. A full probability specification was ideally to be obtained from an intensive, supervised elicitation with several experts together. Garthwaite and O'Hagan [9] reported an experimental study for quantifying expert opinion in the UK water industry, and Wang [10] commented on expert elicitation for reliability system design.

When making asset management plans, O'Hagan et al. [11] adopted the background knowledge of experts. Some sample data are collected, and Bayes linear methods are used to combine the sample data with the expert knowledge to estimate the costs of the interventions for each asset and also the timings of the various interventions. However, these two kinds of uncertain quantities were dealt with separately, and there was no attempt made to combine the uncertainties of costs and timings to predict capital investment.

This paper addresses the problematic issues associated with data and uncertainty when carrying out the cost model. Our contributions are:

- First, we deal with the lack of available historical data by investigating only a small sample of assets with detailed information, and then using structured elicitation techniques to extract experts' knowledge (both general and local) and expertise based on the experiences they have gained from routine data collection practices.
- Second, unlike previous applications, we treat both intervention timing and costs as uncertainties. We then adopt Bayes linear methods to combine the sample data with the experts' knowledge, to make estimates that use all available information.
- Third, we build an asset cost model based on these estimates, identify the optimal maintenance strategy and estimate the penalty for delaying maintenance when funding is not sufficient.

The remainder of the paper is organised as follows: Section 2 introduces the methodology; Section 3 gives a brief description of the case problem; Section 4 explains the intervention cost and sojourn estimations; Section 5 shows the results of the cost model for various maintenance strategies through simulation, and the estimated penalty for delaying maintenance; Section 6 presents the modelling validation; and Section 7 presents a conclusion based on the analysis with the recommended optimal maintenance strategy.

## 2. Methodology

### 2.1. Problem formulation

Infrastructure assets are classified down to MIs because the faults and failures occur at the MI level. For each MI, there are generally two types of interventions, custom intervention (CI) and standard intervention (SI). CIs are designed to address specific concerns that are currently known to apply to an MI, or that are expected to develop over time due to the postponement of work. CIs are one-off actions that are not planned to be repeated for that MI, e.g. metal structure strengthening. In practice SIs are usually repeated at regular intervals to maintain safety, e.g. painting a girder on a bridge. The condition of an MI is classified from 1 to 5, which is from good to bad. Condition 5 is normally a safety critical state; one should never see this on file as an MI should have already received intervention before it reaches this critical condition. In this paper, we focus on the planning of the SIs and investigate the optimal maintenance strategy. There are different maintenance policies for each standard intervention of an MI. One policy could be to maintain when an MI is in condition 2 or above and bring it back to the start of condition 1 if found in condition 2; bring it back to the start of condition 2 when found in condition 3; and bring it back to the start of condition 3 when found in condition 4. And another policy could be to maintain when an MI is in condition 2 or above and bring it back to the start of condition 1 regardless of which specific condition it is found in. We only consider the renewing strategies in this paper, which always bring the MI back to the start of the $i$th condition and the same maintenance action is repeated when the MI is found in a condition larger than $i$. This definition of a renewing strategy is a broad one which does not mean to always bring the MI back to an as new condition. Rather the strategy calls to always bring the MI to a condition it started before except at the very beginning when the MI is new. The cycle between two consecutive maintenance actions is identical and independent so it is a renewal process when the MI is far from the origin. We define $T$ as the inspection interval, and use $G_{ij}$, $1 \le i < j \le 4$, to denote the various renewing strategies. The engineers inspect the MIs at regular interval $T$ and maintain when the condition is equal to or above $j$, and to bring the MI back to the start of condition $i$. Table 1 demonstrates the six renewing strategies.

Due to the availability of funding for asset maintenance, any of these strategies could be adopted. But the key questions are what is the optimal maintenance strategy and how often should the MI be inspected? We use cost modelling as a means of answering these questions.

We define the sojourn in condition state $j$ as $x_j$ with pdf $f_{X_j}(x)$. $f_{X_{ij}}(x)$ is the convolution of $f_{X_i}(x) \otimes \cdots \otimes f_{X_j}(x)$ for $j > i$. For $i{=}j$, we have $f_{X_j}(x)$. $C_{ij}$ is the cost of intervention for bringing the item back to the start of condition $i$ when it is in condition $j$ for $j > i$. We define $C_s$ as the cost of inspection, and $C_f$ as the cost of the item in condition 5, which can be a high penalty cost.

We let $W_n$ denote the condition at inspection time $nT$. For strategy $G_{ij}$, the probability that an MI deteriorates from condition

**Table 1**
Renewing strategies.

| *Strategy* | *Notes* |
|---|---|
| $G_{12}$ | Strategy 1: Maintain when the condition is equal to or above 2, and bring the item back to the start of condition 1 |
| $G_{13}$ | Strategy 2: Maintain when the condition is equal to or above 3, and bring the item back to the start of condition 1 |
| $G_{23}$ | Strategy 3: Maintain when the condition is equal to or above 3, and bring the item back to the start of condition 2 |
| $G_{14}$ | Strategy 4: Maintain when the condition is equal to or above 4, and bring the item back to the start of condition 1 |
| $G_{24}$ | Strategy 5: Maintain when the condition is equal to or above 4, and bring the item back to the start of condition 2 |
| $G_{34}$ | Strategy 6: Maintain when the condition is equal to or above 4, and bring the item back to the start of condition 3 |