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Condition-based maintenance of multi-component systems with degradation state-rate interactions

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ABSTRACT

This paper presents an approach to optimise condition-based maintenance (CBM) of multi-component systems where the state of certain components could affect the rate of degradation of other components, i.e., state-rate degradation interactions. We present a real example of an industrial cold box in a petrochemical plant, where data collected on fouling of its tubes show that the extent of fouling of one tube affects the rate of fouling of other tubes due to overloading. A regression model is used to characterise the state-rate degradation interactions for this example. Further, we optimise the condition-based maintenance policy for this system using simulated annealing. The outcomes of the case study demonstrate that modelling degradation interactions between components in the system can have significant positive impact on CBM policy of the system. The paper therefore tackles a problem that has not been addressed in the literature, paving way for further developments in this important area of research with practical applications.

1. Introduction

This paper presents an approach to model the degradation interactions that exist between states and rates of degradation of different components in a multi-component system and to optimise the condition-based maintenance policy, i.e., their inspection timings and maintenance/replacement thresholds. The term "multi-component system" is most widely used in academic literature to refer to both a complex system consisting of more than one asset (i.e. multi-asset system) or an engineering asset consisting of more than one component (multi-component asset). Traditional research on maintenance optimisation considered a complex engineering system as a collection of individual (and independent) components, and maintenance models for such systems were devised with this independence in mind [4]. Research development in this area is often based on an extension of a single component [1] into a maintenance model for independent multi-component systems [2]. However, considering the complexities involved in complex engineering systems and the need to extract more value from maintenance activities, it is no longer sensible to treat each component in such systems as an independent individual component.

There are usually dependencies between the components in a complex system and these dependencies lead to further complications in understanding the behaviour of the system. Of particular interest is a class of dependency that is commonly known as 'stochastic dependence', where failure or degradation of some components in the system could affect the failure or degradation of other components in the system [8]. This type of dependency is evident in different industries, especially in mechanical systems [11]. Literature in this area predominantly focus on the interactions which are triggered by failure of a component (failure interactions). Examples of such studies can be found in [7] and [14].

While failure interactions exhibit stochastic dependencies upon a complete failure of a component in the system, there is another type of stochastic dependence which is not necessarily triggered by a component failure. Such dependencies are also sometimes triggered by degradation of a component. Degradation processes of components in the system could actually be influenced by degradation of a component in a degraded state without having to completely fail. Such incidents are defined here as degradation interactions. There are few papers that study degradation interactions. [10] have applied Dynamic Bayesian Networks to characterise degradation interactions. The complexity of the algorithm would however make it computationally difficult for modelling the development of multi-component system degradation over time due to the size of the networks required. Meanwhile, [3] also did not account for the continuous degradation of the performance (states) of the system.

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Extensive review of the literature has revealed that research on degradation interactions has so far mainly been limited to reliability modelling of multi-component systems where the states of the components in a system are dependent. The degradation states of dependent components are characterised by a joint probability distribution, enabling the estimation of the reliability of the system. Multivariate normal distribution [12], Bayesian Networks [6] or copula functions [13] have been used to represent such probability distributions. However, the interaction between states of degradation does not wholly represent the definition of the term 'degradation interactions'. This is because degradation process of a component is not only represented by its states of degradation but also its rate of degradation. It is evident from the review that there is a gap in the literature where degradation interactions involving degradation rates of the components are not addressed.

In this paper, we use a real industrial example to motivate the need for further research in this area and addresses this challenge by developing an approach to improve predictability of the condition of the system through explicit consideration (and modelling) of interactions between states and rates of degradation between components in the system, thereby improving the maintenance policy for each component in the system. The optimal maintenance policy strikes the balance between maintenance investments and the benefits of improved operating conditions of the system.

The structure of this paper is as follows. To start with, a description of the system is given in Section 2. A short summary of the modelling approach is outlined in Section 3. Sections 4 and 5 describe the degradation models and the maintenance optimisation model respectively and discusses the results of the solution. Finally, suggested future work and a summary are then concluded in Section 6.

2. System description

The system under consideration is part of an industrial cold box unit in a petrochemical plant. We consider two components which are gas tubes, feeding excess-heated gas into the cold box unit. The excess heat would then be used by the cold box unit to heat up other 'cold' gas to be ready for further processes in the plant. The performance of the system depends on the amount of excess heat in which the cold box can obtain from the two gas tubes. More excess-heated gas delivered into the cold box unit via the gas tubes would lead to more energy savings.

As the tubes are feeding the excess-heated gas into the cold box unit, fouling would occur within the tubes and consequently reducing the amount of heat which can be delivered into the cold box. Pressures in the tube are measured to act as surrogates to the degradation states of a component at a certain time. Lower pressure would indicate less amount of fouling and more effective heat transfer into the cold box. As fouling occur during operation, the pressure would be increased on the tube and hence result in decreasing performance of the system.

Degradation interactions between the two components can occur as when one tube is already subject to a high fouling state, the excess-heated gas would then be forced to go through the other tube and hence overloading that other tube which then leads to accelerated fouling as a result. This scenario calls for the use of the degradation model for the components with degradation interactions as described earlier.

Current maintenance policies of the system include a daily condition monitoring and the system is allowed to operate until the pressure of a gas tube exceeds the safety threshold level. The failed tube is then maintained, allowing the pressure level to reduce and increase the performance of the system. However, this may not be the optimal maintenance policy for the tubes because of the loss due to performance degradation of the system. By moving the maintenance threshold earlier than the safety threshold, the system would be reducing the loss due to performance degradation albeit with increased maintenance costs. This suggests that investments in more maintenance of the tubes may allow the system to reduce its average cost in the long term.

It should be noted here that, due to confidentiality issues, the numerical figures used in this paper is masked (e.g., currency has been changed to GBP) and scaled to protect the identity of the source and to help visualise the results. The next section presents an approach to model the interaction between the state of one tube and the rate of degradation of the second tube. Following this, in Section 5 we use simulated annealing to optimise the condition-based maintenance policy. In both sections, we first provide a general model followed by its application to the cold box example.

3. Modelling approach

Fig. 1 demonstrates the structure of the modelling approach used in this paper, along with the techniques used for each phase of the approach. This approach consists of three main parts, namely, Independent Degradation Model, Interactive Degradation Rate Generic Path (IDRGP) Model and CBM Optimisation Model.

The Independent Degradation Model is developed using a General Degradation Path (GDP) model and is used to understand the underlying independent degradation of components in the system. This would form a basis for improved degradation predictions in the IDRGP Model where degradation interactions are included. CBM Optimisation Model is then used to optimise a maintenance policy based on the degradation model.

4. Degradation model

First, we consider a generic system consisting of N components. Each component is periodically inspected to reveal the degradation state of the component. The following assumptions are made in the development of this model:

- The components are subject only to gradual degradation and not to sudden failures.
- Only one condition or performance indicator is used to represent the degradation states of each component.
- All components are non-repairable components whose degradation states monotonically increase with its age until its replacement.
- Replacement will bring the component back to its brand new state.

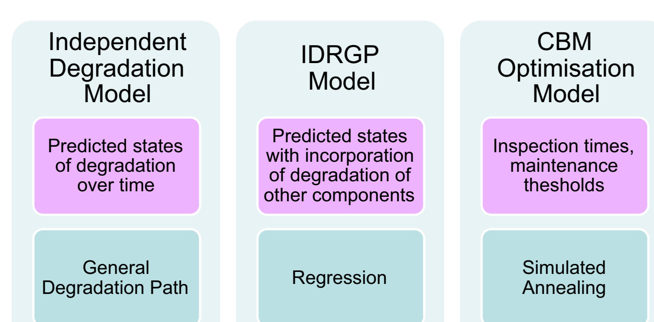

Fig. 1. Modelling approach.