Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Optimising Maintenance of Multi-Component Systems with Degradation Interactions

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Abstract: This paper presents a generic approach to optimising maintenance of multi-component systems with degradation interactions. A degradation model for *M*-component systems where *N* (*N*<*M*) components are subject to degradation interactions is developed using General Path Degradation Modelling and regression techniques to characterise the degradation interactions. An industrial case study is also presented in a petrochemical plant where the scope of the study is on an industrial cold box system. The outcomes of the case study demonstrate that a simulation model built with the proposed degradation interactions modelling can have significant impact on maintenance planning of the system.

Keywords: Maintenance, Degradation, Interactions, Multi-Component Systems, Regression

1. INTRODUCTION

Over the years, engineering assets have grown more complex due to the increasing need for higher efficiencies and applications of manufacturing technologies. Maintenance of complex engineering assets has received more attention from academic researchers in the past decade. Systems or assets with multiple components are starting to be treated differently from single-component systems. In doing so, a good understanding of interactions between components within the system needs to be developed.

In the most recent complete review of maintenance of multi-component systems, Nicolai and Dekker (2000) classified dependencies between the components in a multi-component system into three types. These are economic dependence, structural dependence and stochastic dependence. Economic dependencies have been thoroughly studied with topics including group maintenance and opportunistic maintenance which influence maintenance costs. Dekker et al. (1997) provided an extensive review focusing on studies of multi-component systems with economic dependence. Structural dependence refers to when the components within the system are structurally or functionally bonded, and maintenance of a component requires at least dismantling or maintenance other units. An example of a multi-component system with structural dependence can be found in (Barros et al., 2006).

Stochastic dependence exists when failure or degradation of a component can influence failure or degradation of others. This type of dependence has received less attention in the academic literature. Literature in this area are predominantly on the interactions which are triggered by failure of a component (failure interactions). Examples of such studies can be found in (Lai, 2007) and (Zhang et al., 2011).

There are few papers that study the phenomenon where gradual changes in condition of one component can affect the rate of degradation of other components (degradation interactions). Straub (2009) 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, Bian and Gebraeel (2013) also have yet to account for the continuous degradation of the performance (states) of the system. Yang and Xue (1996) argued that by using just time to failure measure, the relationship among failure mechanisms and physical parameters is cut out. The purpose of this study is to contribute to the maintenance literature of multi-component systems with degradation interactions by proposing a generic approach to optimise maintenance of such complex systems.

The structure of this paper is as follows. To start with, the modelling problem is formally outlined in Section 2. Then, a case study considering two components in an industrial cold box system is presented in Section 3 to demonstrate the application of this model in an industrial setting. Section 4 discusses the impact of this proposed method on maintenance of multi-component systems. Finally, future work and a summary are then concluded in Section 5.

2. PROBLEM FORMULATION

Consider a system consisting of *M* degrading components where *N* (*N*<*M*) components are subject to degradation interactions. Each component is periodically inspected to reveal the degradation state of the component. A maintenance action is compulsory once the degradation level is found to exceed a safety threshold. The safety threshold is determined by the manufacturer and acts as an upper-bound of the degradation level for which the component can still operate. Upon inspection, a preventive maintenance action can also be performed on a component in case the degradation state of the component is found to exceed a pre-determined maintenance threshold. Fig. 1 provides an operation and maintenance flow chart of a component in the system.

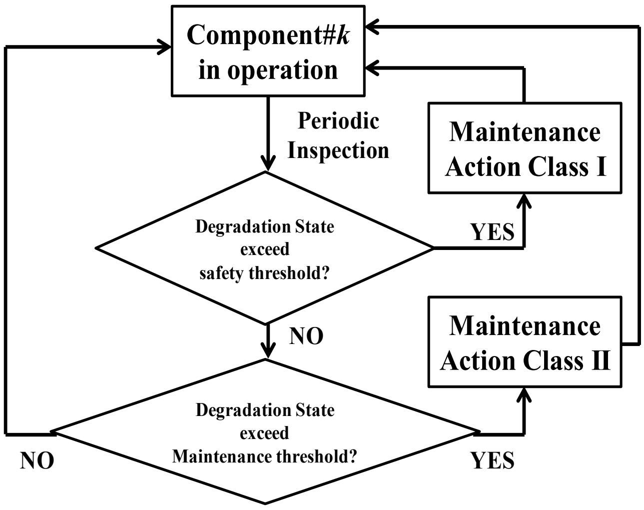

Fig. 1. Operation and Maintenance Flow Chart of Component#*k* in the system

Performance of the system at a certain time is a function of the condition of the components. The goal of this problem is to maximise the average benefit of the system over time, which accounts for the performance of the system and maintenance costs, by finding an optimal maintenance threshold for each component. The following subsections provide the steps to achieving this goal in detail.

2.1 Assumptions

The assumptions made for this model are:

- The whole system is inspected simultaneously at a fixed interval.
- All inspection and maintenance actions are perfect and instantaneous.
- Inspection costs are negligible.
- The components are subject only to gradual degradation over time and not sudden failures.
- Historical inspection and maintenance data is provided.

2.2 List of Notation

The following notations are used throughout this paper;

$S_k(T)$ = the degradation of Component#*k* at inspection time T where $k = 1,\ldots,M$

$ƛS_k$ = the change in the degradation of Component#*k* between two adjacent inspections

W_k = the safety degradation threshold for Component#*k*

D_k = the maintenance degradation threshold for Component#*k*

C_k = Cost of maintaining Component#*k* when its degradation has not yet exceeded its safety threshold

C'_k = Cost of maintaining Component#*k* when its degradation has exceeded its safety threshold

2.3 Individual Degradation Model

Provided the historical condition monitoring data, the probability distribution of the change in the degradation state of a component between two adjacent inspections can be determined using the general degradation path model described in (Yang and Xue, 1996).

The individual independent degradation of Component#*k* can then be developed as a discrete-time accumulated damage model, a sum of $ƛS_k$, as;

$$S_k(T) = S_k(T_0) + ƛS_k \quad (1)$$

where $S_k(T_0)$ denotes the state of Component#*k* at time T_0 which is the latest inspection time prior to T and $ƛS_k$ is characterised by a probability distribution constructed with the historical data.

2.4 Component Interaction Model

A technique based on regression is introduced in this section to identify the relationship between the parameters of individual degradation models. The purpose of this step is to characterise the interactions between degradations of the components.

Since there are two parameters involved in an individual degradation model, possible ways in which a regression function g can influence the relationship between the parameters can be listed, as an example, for a two-component system. Equations (2) to (5) list the modified degradation model with degradation interactions are characterised by the regression function g.

In cases where the degradation states of Component#1 affect the degradation states of Component#2

$$S_2(T) = S_2(T_0) + ƛS_2 + g(S_1(T)) \quad (2)$$

In cases where the changes in degradation states of Component#1 affect the degradation states of Component#2

$$S_2(T) = S_2(T_0) + ƛS_2 + g(ƛS_1) \quad (3)$$

In cases where the degradation states of Component#1 affect the changes in degradation states of Component#2

$$S_2(T) = S_2(T_0) + ƛS_2 \quad (4)$$

where the probability distribution of $ƛS_2$ is modified by a function g of $S_1(T)$

In cases where the changes in degradation states of Component#1 affect the changes in degradation states of Component#2

$$S_2(T) = S_2(T_0) + ƛS_2 \quad (5)$$

where the probability distribution of $ƛS_2$ is modified by a function g of $ƛS_1$

These equations can be expanded in a similar manner to characterise degradation interactions for N components, and will be presented in the full journal version of this paper.

2.5 Maintenance Model

In this study, the performance of the system at a certain time is assumed to be a function of the states of the components at that time. As the components degrade according to the model developed in Subsection 2.4, maintenance costs are incurred when the components are found to have degraded beyond the safety or maintenance threshold. The aim of this maintenance model is to maximise the average benefit from the system over time.

The benefit which the system is generating at time T ($B(T)$) is given by

$$B(T,\boldsymbol{D}) = P(T) - M(T,\boldsymbol{D}) \tag{6}$$

where

$P(T)$ is the performance function of the system at time T, which reflects the revenue generated from the system, depending on the state of each component at time T

$$P(T) = P(S_1(T),S_2(T),\ldots, S_M(T)) \tag{7}$$

$M(T,\boldsymbol{D})$ is the total maintenance cost incurred at time T provided the maintenance threshold $\boldsymbol{D} = (D_1,\ldots,D_M)$ of the components.

$$M(T,\boldsymbol{D}) = \sum_{D_k<S_k(T)<W_k} C_k + \sum_{S_k(T)>W_k} C'_k \tag{8}$$

Optimal value of $\boldsymbol{D}$ ($\boldsymbol{D}^*$) can then be found through a simulation method to maximise the average benefit of the system over a period of time (τ) i.e.

$$\boldsymbol{D}^* = \boldsymbol{D}, \max \left(\frac{\sum_{\gamma=1}^{\tau} B(\gamma,\boldsymbol{D})}{\tau}\right) \tag{9}$$

The proposed process of optimising maintenance of a multi-component system with degradation interactions is summarised in Fig. 2.

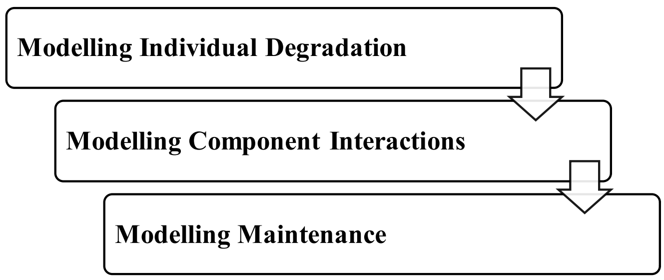

Fig. 2 Overall process of optimising maintenance of a multi-component system with degradation interactions

3. CASE EXAMPLE

To demonstrate the use of this model in an industrial application, a case study is conducted in a petrochemical plant setting. The scope of the system under consideration is part of an industrial cold box unit in a petrochemical plant.

3.1 Cold Box Unit Tubes

The system consists of 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 (4) as the degradation model for the components with degradation interactions.

The existing maintenance policy for the system can be listed as follows:

- Pressures on the two tubes are manually recorded at an equal regular interval (ƛT) on both tubes.
- Maintenance actions are performed independently on the two tubes to reduce the fouling level only when the pressure of the tube exceeds its safety threshold W_1=140 or W_2=110.
- Effects of maintenance actions on a component include lower pressure and higher performance.
- Historical condition monitoring and maintenance data are in provided (See Fig 3).
- Performance function of the system at time T is given by $P(T) = P(S_1(T),S_2(T))$ as shown in Fig 4, when $S_1(T)$ and $S_2(T)$ is the pressure at time T of Tube#1 and #2 respectively.

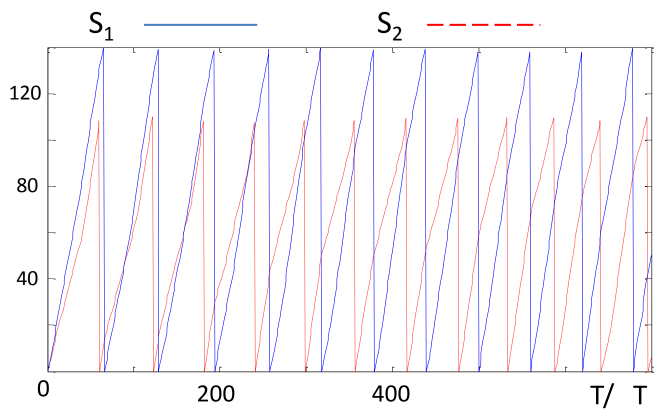

Fig. 3 Historical condition monitoring and maintenance data of the system showing states of Tube#1 and #2 over time

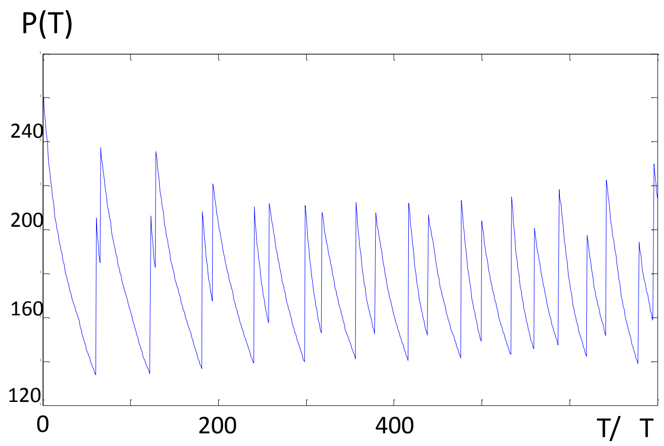

Fig. 4 Historical performance of the system based on the states of the components in Fig 3

It should be noted here that, due to confidentiality issues, the numerical figures used in this paper is masked and scaled to protect the identity of the source and to help visualise the results. The following subsections demonstrate the process shown in Fig 2.

3.2 Modelling Individual Tube Degradation

First, independent individual degradation models of the components are developed based on the data provided in Fig 3 and 4.

Degradation states of Tube#1 is independently modelled as

$$S_1(T) = \sum_{i=0}^{T} \alpha_i \quad (10)$$

where α ~ Normal distribution with mean 2.3 and s.d. 0.5

Degradation states of Tube#2 is independently modelled as

$$S_2(T) = \sum_{i=0}^{T} \beta_i \quad (11)$$

where β ~ Normal distribution with mean 1.9 and s.d. 0.6

α and β denote a change in the pressure of Tube#1 and #2 between two adjacent inspections respectively.

3.3 Modelling Interactions Between the Tubes

As discussed in Subsection 3.1, the degradation interactions in this case study can be characterised by a scenario described in (4). The modified individual degradation models for the components once degradation interactions are introduced can be shown as:

$$S_1(T) = \sum_{i=0}^{T} \alpha_i \quad (12)$$

where the probability distribution of α is modified by a function $g(S_2(T))$, and

$$S_2(T) = \sum_{i=0}^{T} \beta_i \quad (13)$$

where the probability distribution of β is modified by a function $h(S_1(T))$

In order to find a suitable function g and h, Fig. 5 and 6 provides a plot of α at different values of S_2 and β at different values of S_1 respectively. A regression technique called Gaussian Process Regression (GPR) is used to build the functions g as shown in Fig. 7 and h in Fig. 8. GPR is used in this case study because of its ability to allow the observed data to influence the shape of the regression function. This feature is particularly helpful in this case since the types of relationships between the parameters were not explicit. For further details on GPR techniques, please refer to (Ebden, 2008).

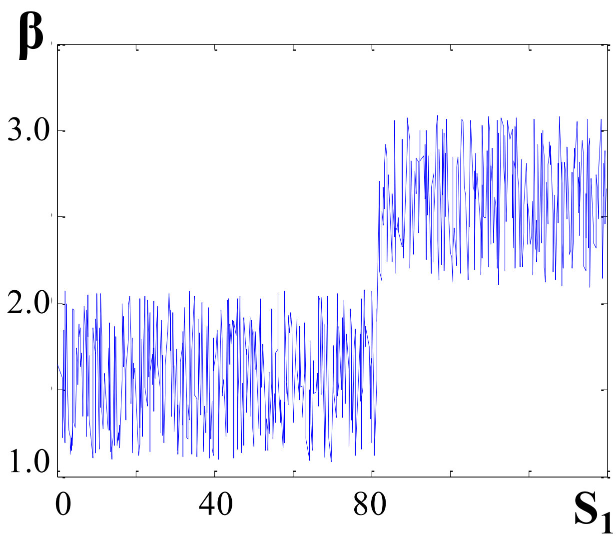

Fig. 5 Changes in the pressure level of Tube#2 between two adjacent inspections (β) at different values of S_1

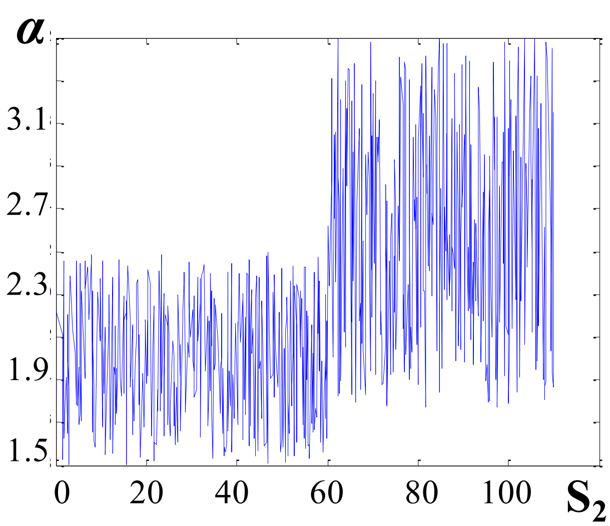

Fig. 6 Changes in the pressure level of Tube#1 between two adjacent inspections (α) at different values of S_2

Once the degradation model with degradations interactions is integrated, the optimal maintenance plan can be generated – this is presented in the next section.

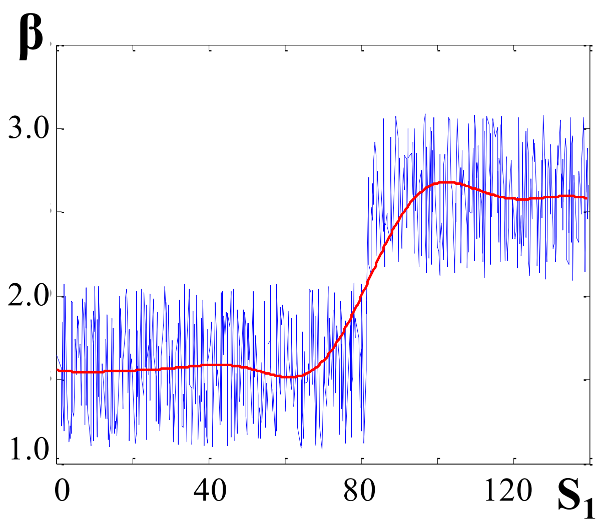

Fig. 7 Fitted regression function $g(S_1)$

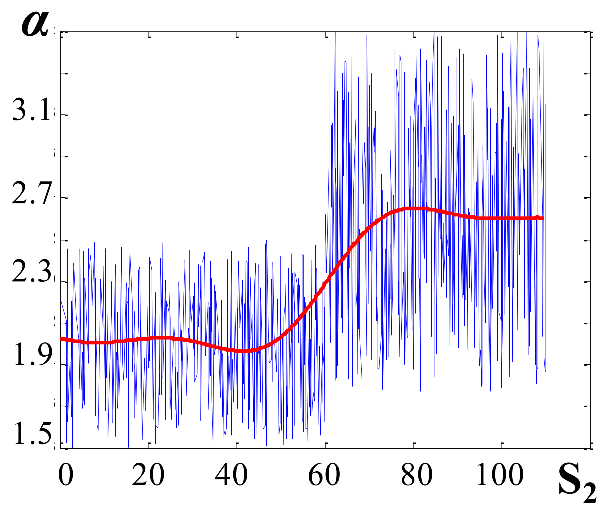

Fig. 8 Fitted regression function $h(S_2)$

3.4 Optimising Maintenance

With the degradation model provided by (12) and (13), the average benefit over time of the system at different maintenance thresholds D_1 and D_2 is calculated based on a simulated degradation and the given performance function in Subsection 3.1. The optimal thresholds D_1* and D_2* are then determined through resulting average benefit plot shown in Fig. 9 as

$D_1* = 127$

$D_2* = 105$

By introducing these maintenance thresholds, an improvement of (124-99)/99 = 25% (as shown in Fig. 9) is realised compared to the original maintenance policy of maintaining the tubes when the pressure of the tube exceeds 140 and 110 for Tube#1 and #2 respectively.

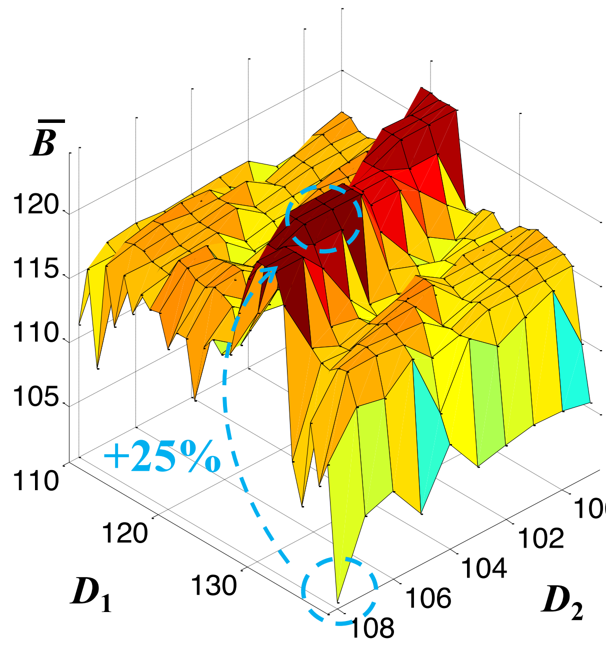

Fig. 9 Average benefit ($\underline{B}$) of the system simulated from the degradation interaction model at different values of D_1 and D_2

4. DISCUSSION

The purpose of this section is to demonstrate the impact of introducing degradation interactions into the system's degradation model.

In order to see the impact of modelling degradations interactions on maintenance of multi-component systems, independent degradation models for the two gas tubes (as provided in Subsection 3.2) are used to optimise the maintenance thresholds of the system (instead of Subsection 3.3). The average benefit of the system over time at different thresholds simulated through this model is shown in Fig. 10. This would yield different 'optimal' thresholds as $\boldsymbol{D}^{**}$ = (120,100).

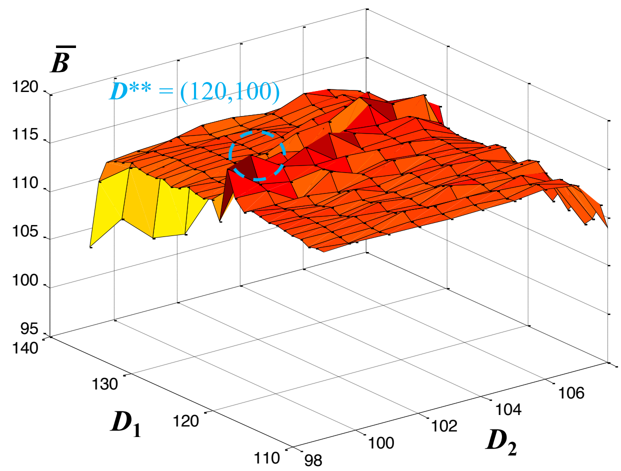

Fig. 10 Average benefit ($\underline{B}$) of the system simulated from the independent degradation model at different values of D_1 and D_2

An implication of this is that without the degradation interactions model, the maintenance thresholds of (120,100) would have been implemented instead of (127,105). This would mean that the average benefit of the system over time would not be fully realised. As shown in Fig 11, improvement of the average benefit from the existing maintenance policy (140,110) through degradation interactions model is (25-19)/19 = 32% higher than through independent degradation model.

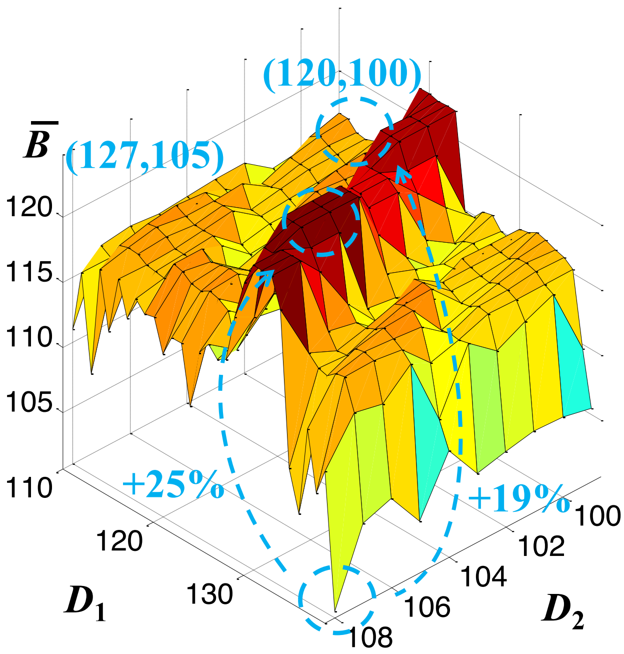

Fig. 11 Impact of modelling degradation interactions on improvement of average benefits of the system

5. CONCLUSIONS

This paper has proposed a generic approach to modelling degradation interactions and maintenance planning for multi-component systems. This approach is capable of characterising different types of degradation interactions found in practice as described in Subsection 2.4. An industrial case study is also provided to support that degradation interactions can affect maintenance of the systems. Further extension of this work is under way by relaxing the assumption of simultaneous inspections and implementing other techniques than regression to characterise the relationships between degradation parameters. The results of this work will be presented in the extended version of this paper. Additional suggested lines of work can be done on addressing other assumptions such as imperfect or non-instantaneous inspection and maintenance actions.

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