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# On fault propagation in deterioration of multi-component systems

Zhenglin Liang*, Ajith Kumar Parlikad, Rengarajan Srinivasan, Nipat Rasmekomen

*Institute for Manufacturing, 17 Charles Babbage Road, Cambridge CB3 0FS, United Kingdom*

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ABSTRACT

In extant literature, deterioration dependence among components can be modelled as inherent dependence and induced dependence. We find that the two types of dependence may co-exist and interact with each other in one multi-component system. We refer to this phenomenon as fault propagation. In practice, a fault induced by the malfunction of a non-critical component may further propagate through the dependence amongst critical components. Such fault propagation scenario happens in industrial assets or systems (bridge deck, and heat exchanging system). In this paper, a multi-layered vector-valued continuous-time Markov chain is developed to capture the characteristics of fault propagation. To obtain the mathematical tractability, we derive a partitioning rule to aggregate states with the same characteristics while keeping the overall aging behaviour of the multi-component system. Although the detailed information of components is masked by aggregated states, lumpability is attainable with the partitioning rule. It means that the aggregated process is stochastically equivalent to the original one and retains the Markov property. We apply this model on a heat exchanging system in oil refinery company. The results show that fault propagation has a more significant impact on the system's lifetime comparing with inherent dependence and induced dependence.

## 1. Introduction

Advances made by the reliability engineering community in modelling the deterioration of multi-component systems have significantly improved the ability to manage and maintain the multi-component systems. Such models consider the deterioration processes of individual components as well as the dependence among them. Three types of dependencies have been identified: economic dependence, structural dependence, and stochastic dependence [1]. Economic dependence and structural dependence express the opportunities and constraints in managing and maintaining the multi-component system. Stochastic dependence is defined by Dekker [1] as where "... the state of a component influences the lifetime distribution of other components". It is a critical factor that needs to be considered when modelling the deterioration of multi-component systems. In [2], stochastic dependence is further classified into failure dependence and degradation dependence, the last of which is the focus of this paper. In extant literature, two different types of approaches are used to describe the degradation dependence, namely induced dependence and inherent dependence.

(1) *Induced dependence* indicates damage to other components caused by the malfunction of one component. It highlights the directional causality between malfunctioned component and influenced components. The typical model to express the induced dependence is shock damage model. The literature within this category are [3–7].
(2) *Inherent dependence* is an underlying interactive deterioration mechanism among aging components because their operational and functional interactions, such as load sharing. Unlike the induced dependence, inherent dependence focuses the deterioration dependence in a way of co-degradation. Multivariate distribution and copulas are two prevalent approaches to model the inherent dependence. References for inherent dependence are [8–12].

For multi-component systems composed of critical components and non-critical components, in normal situations, the deteriorations of critical components may correlate with each other in the manner of inherent dependence. When non-critical components are damaged by an exogenous event and becomes malfunctioned, it may change the operating environment of critical components so that they are no longer deteriorating under their rated condition. Therefore, a malfunctioned non-critical component could result in the accelerated deterioration of one or more of the critical components and may subsequently damage their interconnected critical components, thus causing the system to deteriorate faster than normal pace. In this paper, this scenario is referred as fault propagation, which represents the inter-

* Corresponding author.
*E-mail address:* zl284@cam.ac.uk (Z. Liang).

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**Notation**

| | |
|---|---|
| $\nu$ | The number of critical components. |
| $X_0(t)$ | The of vector of the system condition in normal system deterioration process at time. |
| $X_{l,0}(t)$ | The deterioration state $l^{th}$critical component in normal system deterioration process at time $t$. |
| $w_{l,0}(t)$ | Deterioration rate of $l^{th}$ critical component in normal system deterioration process at time $t$. |
| $r_{l,0}$ | The intrinsic deterioration rate of critical component in the normal system deterioration process. |
| $\lambda_{ni,0}$ | Normal deterioration rate between the $i^{th}$systemic state and the $(i+1)^{th}$ systemic state. |
| $X_h(t)$ | The of vector of the system condition component in the fault propagation caused by the $h^{th}$ type of malfunction on non-critical components. |
| $X_{l,h}(t)$ | The deterioration state $l^{th}$critical component in the fault propagation caused by the $h^{th}$ type of malfunction on non-critical components. |
| $w_{l,h}(t)$ | Deterioration rate of $l^{th}$ critical component in the fault propagation caused by the $h^{th}$ type of malfunction on non-critical components. |
| $r_{l,h}$ | The intrinsic deterioration rate of critical component in the $h^{th}$ fault propagation. |
| $\mathcal{L}$ | Partitioning rule for Markov aggregation. |
| $\lambda_{di,h}$ | The deterioration rate of $h^{th}$ fault propagation between the $i^{th}$ state and the $(i+1)^{th}$state, where $\lambda_{di,h} > \lambda_{ni,0}$. |
| $\lambda_{fi,h}$ | Rate of $h^{th}$ type of malfunction on non-critical components at systemic state $i$. |
| $Y_{i,0}(t)$: $i^{th}$ | $i^{th}$Aggregated state in the fault propagation caused by the $h^{th}$ type of malfunction on non-critical components. |
| $Y_{i,h}(t)$ | $i^{th}$Aggregated state in the fault propagation caused by the $h^{th}$ type of malfunction on non-critical components. |
| $f_f(t)$ | Failure time distribution of a multi-component system with fault propagation. |
| $f_h(t)$ | Failure time distribution of a multi-component system with inherent dependence. |
| $\Delta_f$ | Lifetime reduction caused by fault propagation. |
| $\Delta_d$ | Lifetime reduction caused by induced dependence. |
| $\Delta_h$ | Lifetime reduction caused by inherent dependence. |

dependence of inherent dependence and induced dependence. It is an interdependence between inherent dependence and induced dependence – a "*meta-dependence*". Fault propagation with the meta dependence characteristic is not sufficiently explored in the literature. However, some industrial systems are experiencing the fault propagation. A typical example can be found in concrete bridge decks. The concrete bridge deck is a primary element that needs to be considered for bridge maintenance. It may be subject to the attack of chloride ion, which is regarded as one of the most significant factors in progressive deck deterioration. The chloride ion may penetrate through the crack and accelerate the deterioration of the reinforcing bars which matches with the characteristic of induced dependence. Because reinforcing bars share the load, the damage on one steel reinforcing bar will increase the load on others and accelerate their deterioration. This scenario fits in the scenario of inherent dependence. The induced chloride ion can further propagate through inherent dependence and accelerate the deterioration of concrete deck. This indicates the practical existence of fault propagation scenario. Based on the observation of field experts, fault propagation can have a significant influence on the lifetime.

Because of the significant impact of fault propagation in multi-component systems, it starts to gain more attention in the field of reliability engineering. The dominant threat of transient fault propagation in networked control systems is also analysed by an ontology-based fault propagation analysis [13]. The balance between redundancy and working sharing is optimized by genetic algorithm. Huang et al. have proposed a hierarchical scheme for analysing the transient fault propagation in brake-by-wire systems [14]. The scheme can detect and mitigate the transient fault propagation on both node level with a signature based detection and system level with an anomaly based method. Xing and Levitin have developed a combinatorial method for evaluating the exact reliability of binary-state systems subject to competing propagated failure and failure isolation [15]. They have also developed an approach by universal generating function and reliability block diagram for assessing the performance of the series-parallel multi-state system with propagated failures having selective effect [16]. In [17], the approach has been improved by considering the randomness of failure propagation time. Peng et al. have considered both redundancy and working sharing in a series-parallel multi-state system with multi-fault coverage [18]. In [19], an integrated safety prognosis model has been developed based on the dynamic Bayesian network to model the complex system with fault propagation. The risk of the fault propagation is estimated by an ant colony algorithm. Yang and Aldemir have proposed a computationally efficient approach based on Markov/cell-to-cell mapping technique for tracing the fault propagation throughout the system [20]. A pruning algorithm is developed to control the complexity reduction rate. Verlinden et al. have designed a hybrid approach by combining static reliability block diagram with continuous-time Markov chain (CTMC) for a dynamic system with redundancy and online repair [21]. The approach can overcome the state space explosion problem caused by CTMC. As a synthesis of the recent literature, most of the studies have demonstrated the dynamic state-space model is a powerful technique for modelling multi-component systems with fault propagation. However, such type of model may encounter the state space explosion problem. The existing approaches for the state space and complexity reduction normally induces errors to the system.

This paper differentiates itself by exploring the meta-dependent features of fault propagation in multi-component systems. In addition, we have derived a partitioning rule to attain the ideal, albeit theoretical, lumpability for the deterioration model. It can effectively reduce the size of state space without inducing error while keeping the Markov property on the aggregated process. The rest of paper is structured as follow: we model the deterioration of multi-component systems as a multi-layered vector-valued CTMC in Section 2. Then, a theorem is provided to aggregate the state space of the model and achieve a more compact model for further study. Section 3 discusses and analyses the impact of fault propagation on the lifetime with an illustrative example. The exact lifetime distribution is expressed analytically. The result is verified by an extreme case scenario. Section 4 applies the deterioration model to a heat exchanging system. The impact of fault propagation on the system's lifetime is calculated and compared with the inherent dependence and induced dependence. The sensitivity of the parameters of the fault propagation is analysed. Section 5 summarizes the concluding remarks of this paper.

## 2. Modelling fault propagation

### 2.1. System description

We study the multi-component system consisting of critical components and non-critical components. The multi-component system may subject to fault propagation during their lifetime. The critical component is essential to system's operation and directly related to the system's condition. The condition of critical components is deteriorating over time. The deteriorating rate of the critical component is related

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