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by

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Degradation Modeling and Reliability Assessment for A Multi-Component System with Structural Dependence

Abstract: Structural dependence between components within industrial architecture implies that components structurally form a connected set (a block), and the maintenance of a component requires disassembly of some other components in order to reach it. In that way, the disassembly operations for maintenance may have a significant impact on the degradation processes of the disassembled components. The potential failure risk of these components will be underestimated if this impact is ignored. Therefore, the aim of this paper is to investigate the impact of disassembly operations on the degradation processes and reliability of the components/system. The disassembly operations and their impact on the components' degradation processes are firstly analyzed. Next, a model based on connections matrix is proposed to quantify the impact of disassembly operations on the degradation processes of the components. The proposed model allows considering different influencing factors such as the property of the component, the strength of the connection between the components as well as the degree of expertise of the technician and tool used to perform the disassembly operations. Then, the impact of disassembly operations on the system reliability is analyzed and formulated for a multi-component. Finally, a numerical example of a gearbox system is introduced to illustrate the use and the advantages of the proposed models in reliability assessment and maintenance optimization framework.

Keywords: Reliability; selective maintenance; degradation modeling; multi-component system; structural dependence; disassembly operations.

1. Introduction

Modern machinery and shop-floor level of manufacturing system consist of several interdependent components or sub-systems. The maintenance of these systems plays an important role in their efficient usage in term of cost, reliability and availability. The key in maintenance action is predicting the failure or the lifetime of the components. This becomes more complicated when the components in the system are interdependent. There are different forms of dependency between components: economic, stochastic, and structural dependencies (Thomas, 1986; Nicolai & Dekker, 2008). The economic dependency implies that joint maintenance of a group of components is either cheaper (positive economic dependence) or more expensive (negative economic dependence) than when these components are individually maintained.

There are several studies focusing on taking advantages of positive economic dependence by grouping maintenance (Hameed and Jørn, 2012; Vu et al., 2014; Chalabi et al., 2016). Stochastic dependency occurs when the state of a component influences lifetime distribution of other components (Do et al., 2019; Shi & Zeng, 2016, Li et al., 2017). Finally, structural dependence applies in situation where components structurally form a connected set, and the repair or replacement of a component requires some other components to be dismantled. It means that to reach the component for maintenance, other obstructing components, which block the disassembly path of the components to be maintained, must be disassembled. As a result, these components may be damaged (Keizer et al., 2017).

The dependences between components in multi-component system cause challenges not only in maintenance optimization process but also in degradation modeling of the systems' components. Actually, most of the existing studies assumed that the components in the system are independent, and hence, the degradation process of each component is individually modeled (Nicolai & Dekker, 2008). Recently, some studies consider external impact on degradation modeling for multi-component system (Song et al., 2014; Shen et al., 2018; Rafiee et al., 2014). In these works, the impact of external shocks on the degradation process of components is modeled. However, the interaction between components is not yet considered. In that way, several degradation models with degradation rate interaction have been recently proposed to take account the stochastic dependence between components (Bian & Gebraeel, 2014; Assaf et al., 2018; Rasmekomen & Parlikad, 2016). Nevertheless, the interaction between components may occurs not only during operations but also during maintenance. For example, disassembly operations for maintenance of the components in a multi-component system with structural dependence may affect the degradation process of the disassembled components. Even thought, from a practical point of view, structural dependence exists widely, the impact of structural dependence has not been however considered in degradation modeling of the components.

In the literature, disassembly operations are categorized into three types: non-destructive, semi-destructive and destructive disassembly (Vongbunyong & Chen, 2015). Destructive disassembly deals with the partial or complete destruction of the obstructing components. The semi-destructive approach aims to destroy only connective components leaving the main components with little or no damage. For non-destructive disassembly method, the components are claimed for remaining undamaged, this is desirable for maintenance. This technique requires that all fasteners between the components of the system must be reversible or semi-reversible. However, few systems nowadays are actually designed according to design for disassembly guidelines (Vongbunyong & Chen, 2015). Even though the fasteners are reversible or semi-reversible, the disassembly process also can cause some undesired damages. In this case, the interaction between the faying surfaces of the components or between the components and the devices used to perform the disassembly operations may cause some damage such as scratches, dents, blows, wearing down, deformation, etc. These damages increase the likelihood of failure, which in effect, reduce the reliability and operating performance of the components (Santochi et al., 2002). For example, in the case of journal bearings, a scratches can lead to the prevention of the development of hydrodynamic pressures over the scratch, degrading the load capacity of the bearings, by serving as a leakage path away from a potential load region of the bearing (Dobrica & Fillon, 2012). The damage during disassembly operations may be caused due to the poor skill of maintenance technician, lack of design for serviceability and maintenance, or certain parts of the components cannot be easily removed without being broken (Pyy, 2001; Raouf et al., 2006; Scarf & Cavalcante, 2012, Do et al. 2015).

From the above analysis, regardless to whether non-destructive, semi-destructive or destructive disassembly methods are applied, the disassembly operations may impact on the degradation process of the surviving components. An example of the impact of disassembly operations for maintenance on component's degradation process could be the disassembly of the bearings of the gearbox system. The gearbox system consists of several bearings and gears, which are tightly mounted on the shafts. To disassemble the bearings, force is applied to pull the bearings out of the shaft and these operations could cause scratches, wear, or dent, etc. on the shaft and the bearings as shown in Fig.1 (AG, F. K, 2003). Detail of bearing mounting and dismounting process is discussed in (Schaeffler Technologies AG & Co. KG, 2013).

Fig. 1. Damages of bearings due to mounting/dismounting operations: (a)-Brinell marks appear as indentations in the raceways, increasing bearing vibration, (b)-supporting lip is partly or completely broken off or crack and (c)-metal cage with dents (AG, F. K, 2003)

The failure risk of the components and the system will be underestimated if the impact of the disassembly operations on the components' degradation processes is ignored. This could lead to inaccuracy reliability assessment and suboptimal maintenance plan. However, most of the existing studies on the maintenance for multi-component system with structural dependence only considered the impact of disassembly operations on maintenance duration and omitted its impact on the degradation process of the components (Geng et al., 2015; Zhou et al., 2015; Iung et al., 2016). To the best of our knowledge, the impact of disassembly operations on the degradation processes of components, hereinafter is called as disassembly operations impact, has not been studied yet. Face to this issue, the objective of this paper is to investigate the impact of disassembly operations on the degradation processes and reliability assessment of the components. In that way, the main scientific contributions of this paper are:

- Modeling and formulation of the impact of disassembly operations on the degradation processes of components using the connections matrix and directed graph.
- Development of a degradation model integrating the impact of disassembly operations.
- Integrating the impact of disassembly operations on the reliability assessment and maintenance model.
- Application of the proposed model for evaluating the reliability of a multi-component system with structural dependence.

So, the rest of this paper is organized as follow. Section 2 presents the modeling of disassembly operations impact on the degradation processes of components and proposes a degradation model integrating the impact of disassembly operations. Next, a reliability analysis considering the impact of disassembly operations for system subject to a selective maintenance strategy is carried out in section 3. A numerical example is then given in section 4 to illustrate the impact of structural dependence as well as the disassembly operations impact on the system reliability and the maintenance optimization. Finally, the conclusions and potential future works are summarized in section 5.

2. Degradation modeling with the impact of disassembly operations

2.1. System description and general assumptions

Consider a multi-component system subjected to structural dependence. In the reliability and maintenance framework, several main components of the system are usually considered. In that way, it is assumed that the system consists of n, $n \geq 1$, components connected in series. A stoppage of each component for whatever reason, e.g., failure or preventive maintenance, leads to a shutdown of the whole system.

It is also assumed that each component i (i=1, 2,…n) subject to an accumulative continuous degradation (intrinsic degradation process) in time and can be described by a scalar random variable $X_i(t)$. Inspection is periodically carried out to reveal the degradation level of the components. Inspection is assumed to be perfect, means that degradation level of a component can be observed without error. Furthermore, inspection does not impact on the components' degradation processes. Component i is considered as failed when its degradation level exceeds its critical threshold (or failure threshold), L_i. Failure of a component is soft failure and not self-announcement, can only be revealed by inspection.

To avoid the components/system failure, both preventive and corrective maintenance are considered. The preventive maintenance is defined as the maintenance actions performed on a surviving component, i.e., the degradation level of the component is lower than its failure threshold. The corrective maintenance is applied when a component is failed, i.e., its degradation level is higher than its failure threshold. Whether preventive or corrective maintenance is applied, the maintenance action is assumed to be perfect. It means that the maintenance action brings the maintained component to "as good as new".

2.2. Disassembly operations and their impact on the degradation processes

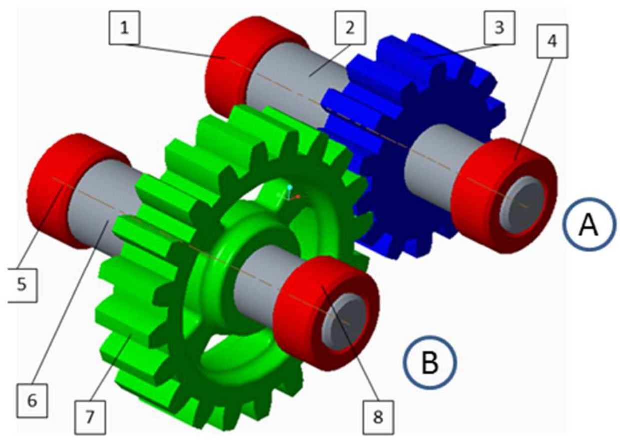
2.2.1. Disassembly operations for maintenance

Disassembly operation for maintenance is defined as a process to separate the maintained components from the system (Zhong et al., 2011). For the system with structural dependence, this process includes partially or completely disassembly of the obstructing components. The precedence relations govern the order of disassembling components, which is represented by directed graph (Zhou et al., 2015). In the system, components are interconnected with each other via connections. The connection between the components is the physical connecting relationship between components. Therefore, we further define the disassembly operations for maintenance in detail. Disassembly operation for maintenance is a process to disconnect the related connections in order to remove the components to be maintained from the system and reassembly the components to re-build the system after maintenance. The reassembly process is the inverse of the disassembly process and has the same impact. Therefore, we combine these processes as disassembly process in short. In that way, the disassembly operations of a component for maintenance include the disassembly of the connections on its disassembly path and these operations may impact on the degradation process of the components. Therefore, to represent the connecting relationships between the system's components, we used the connection matrix to represent the system structure. The connections matrix of the system, $G_c = [r_{ij}]_{n\times n}$, is a $n \times n$ connectivity matrix, each element r_{ij} of the matrix represents the existence of the connection between the two corresponding components i *and* j. The value of element r_{ij} is "1" if a connection exists, and "0" if no connection (Ziqiang et al., 2015).

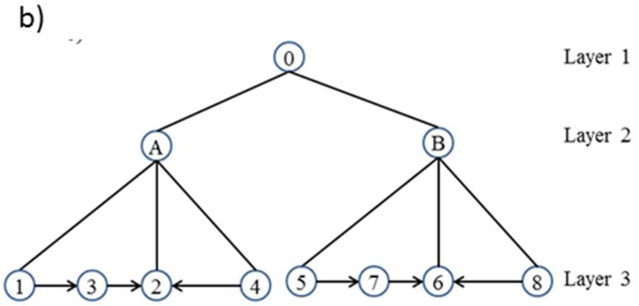
In that way, the directed graph describes the sequences of components to be disassembled to maintain a given component. Therefore, it allows defining which connections need to be disconnected to reach a target component. While the connection matrix helps to quantify the impacts of disassembly operations on the associated components.

Figure 2 shows a gearbox system with its connection matrix and directed graph. Regarding to the directed graph, node 0 represents the whole system, nodes with letter (A, B) represent the subsystem and the numbered nodes (1, 2…) represent the components. The line connecting the node in upper layers and the node in lower layer indicates that disassembly of the lower layer node requires disassembly of the upper node. The arrow between the nodes in the same layer represents the disassembly sequence between the nodes. For example, to remove the gears 3, regarding to the directed graph, the bearing 1 also needs to be disassembled. Therefore, based on the connection matrix, the connections between the bearing 1 and shaft 2 (1,2), and connection between gear 3 and shaft 2 (2,3) need to be disassembled. The disassembly of these connections may impact on the degradation process of the bearing 1 and shaft 2.

a)



b)



c)

$$G_c = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

Fig. 2. (a)-a gearbox system (b)- its directed graph, and (c)-the corresponding connection matrix

2.2.2. *Impact of disassembly operations of a connection*

To model the impact of disassembly operations of connection (i, j) between the two connecting components i and j, it is assumed that disassembly the connection between the two components results in an impact on degradation level of each component. The impact on the degradation level of component i due to disassembly of the connection (i, j) can be described by an amount of damage δ_{ij} (δ_{ji} denotes the damage on component j), knowing that δ_{ij} may be zero. It is clearly that δ_{ij} depends on the strength of the connection between the two components, the property of the component i, and maintenance methods/ tools and degree of expertise of the technicians used to perform the disassembly operation.

The amount of damage δ_{ij} depends on the strength of the connection between the two components, i.e., the more difficult to break the connection, the higher degree of impact on the component's degradation level. For example, in the case of disassembly the connection between bearings and shaft, the smaller clearance between bearings and shaft results in the higher friction force between gear and bearing and the higher force needed to apply for disassembly the bearing. This leads to the higher degree of damage on the bearings and shaft. Note that the connection strength between the two components may be changed when one or both components are failed due to the failure effects. However, in this study, we assumed that the strength of the connection does not depend on the state of the components. In that way, the meaning of the connection matrix needs to be extent. It is used for representing not only the existence but also the strength of the connection, $G_c^{extent} = [S_{ij}]$, $S_{ij} \geq 0$ is the strength of the connection (i,j) between the two components (i and j). The strength of a connection depends on the property of that connection, for example, it can be the friction force in the case of the connection between bearings and shaft or connection between the screws and thread holes. This parameter is deterministic and can be acquired during the designing stage. For example, based on the clearance between the bearing and shaft, the friction force between bearing and shaft can be calculated. The example of the extent connection matrix, G_c^{extent}, for the gearbox system shown in Fig. 2 is given in Eq. (1), whereas each element of the connection matrix represents the friction force between the two corresponding components.

$$G_c^{extent} = \begin{pmatrix} 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 3 & 6 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4 & 0 & 3 & 4 \\ 0 & 0 & 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 \end{pmatrix} \quad (1)$$

The property of the component i also influences the amount of damage δ_{ij}. Components made of high strength materials will be suffered less damage than the components made of low strength materials. For example, the shaft made of high strength steel alloy will suffered less damage than the journal bearing made of copper alloys. This is common in machinery design, when a component is designed to be a sacrificed component, so that in the interaction between the two components, the sacrificed component will receive more damage, while the main component will receive little or no damage. This is due to the cost of maintenance of the sacrificed component is much cheaper than maintenance cost of the main component.

The amount of damage, δ_{ij}, also depends on the methods/tools used for conducting the disassembly operations. For disassembly a connection, several methods/tools can be applied, and the impact of each method/tool is different from each other. For example, using mechanical method, such as using hammer for dismounting the bearings causes higher impact than hydraulic method (Schaeffler Technologies AG & Co. KG, 2013). The degree of expertise of technicians also influences the disassembly operations impact, δ_{ij}. The maintenance induced damage due to the skill of maintenance technicians was reported in (Pyy, 2001; Raouf et al., 2006; Zhao et al., 2019). Some technicians have very good skill and experience, while some are poor skill. The maintenance technicians with good skill know the ways to minimize the impact of disassembly operations, while the poor skill technician can cause higher impact on the degradation of the component. In that way, the adjustment factor θ_{ij} is used to reflect the degree of expertise of technician and the methods/tools used to perform the disassembly operation of the connection (i, j). It should be noted that the methods/tools for disassembly a connection may be different from each other.

From above analysis, the impact of disassembly operations, δ_{ij}, can be expressed in a form of linear function of the connection strength, component's property and the adjustment factor taking account the impact of disassembly tools and technicians. It should be noted that the linear form is inspired by the linear model for calculating the volume of wear out due to friction (Thompson & Thompson, 2006) since they have similar physical meaning. However, other forms may be possible. As an example, a quadratic model for the impact of disassembly operations is discussed in Appendix A.

In that way, the impact of disassembly operations can be written as follows:

$$\delta_{ij} = k_i . S_{ij} . \theta_{ij} \tag{2}$$

Where:

- $k_i \geq 0$ is called as the component property coefficient of component i, which represents the property of component i. The higher strength material, the lower value of component property coefficient is. The coefficient k_i can be estimated from previous data, life testing, engineering judgment, etc.
- S_{ij} is the strength of connection between component i and component j, (i, j). In that way, $k_i . S_{ij}$ is the impact of disassembly operations when the disassembly operations are conducted with perfect maintenance tools and by a perfect technician.
- θ_{ij} is the adjustment factor taking account the impact of degree of expertise of maintenance technician and methods/tools used to perform the disassembly operations of the connection (i, j). It is clearly that $1 \leq \theta_{ij}$, when $\theta_{ij} = 1$, the disassembly operations are carried out with a perfect maintenance tool and by a technician with perfect skill.

The adjustment factor, θ_{ij}, can be seen as the quality of the disassembly operations. It is very difficult to evaluate precisely the quality of a disassembly operation. It is therefore more realistic to assume that the quality of the disassembly operations is stochastic and therefore could be modeled as a random variable governed by an appreciate distribution function. The expected value and standard deviation of θ_{ij} are denoted by $\mu_{\theta_{ij}}$ and $\sigma_{\theta_{ij}}$, respectively. The expected value $\mu_{\theta_{ij}}$ of the adjustment factor θ_{ij} reflects the impact of method/tools used to perform the disassembly of the connection (i, j). The uncertainty endowed with maintenance technician quality is characterized by the corresponding standard deviation, $\sigma_{\theta_{ij}}$, which reflects the expertise degree of the maintenance technician to correctly perform a disassembly operation. From above analysis, the half-normal distribution is herein used to model the adjustment factor. This distribution is flexible with two dimensions which can be used to present the impact of the disassembly method and the quality of maintenance technician. By this assumption, if $\mu_{\theta_{ij}} = 1$, the disassembly method is perfect and does not have any influence in disassembly impact. On the other hand, if $\sigma_{\theta_{ij}} = 0$, the technician skill is perfect and has no influence in disassembly impact. The probability density function of the half-normal distribution (Cooray & Ananda, 2008) is:

$$f_{\sigma_\theta,\mu_\theta}(x) = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_\theta} e^{-\frac{1}{2}\left(\frac{x-\mu_\theta}{\sigma_\theta}\right)^2} . I(x) \tag{3}$$

Where, $I(x) = 1$ if $x \geq \mu_\theta$ and $I(x) = 0$ otherwise.

Therefore, the disassembly operations impact on component i, δ_{ij}, also follows a half normal distribution with mean $\mu_{\delta_{ij}} = k_i . S_{ij} . \mu_{\theta_{ij}}$ and variance $\sigma^2_{\delta_{ij}} = \left(k_i . S_{ij}\right)^2 . \sigma^2_{\theta_{ij}}$, respectively.

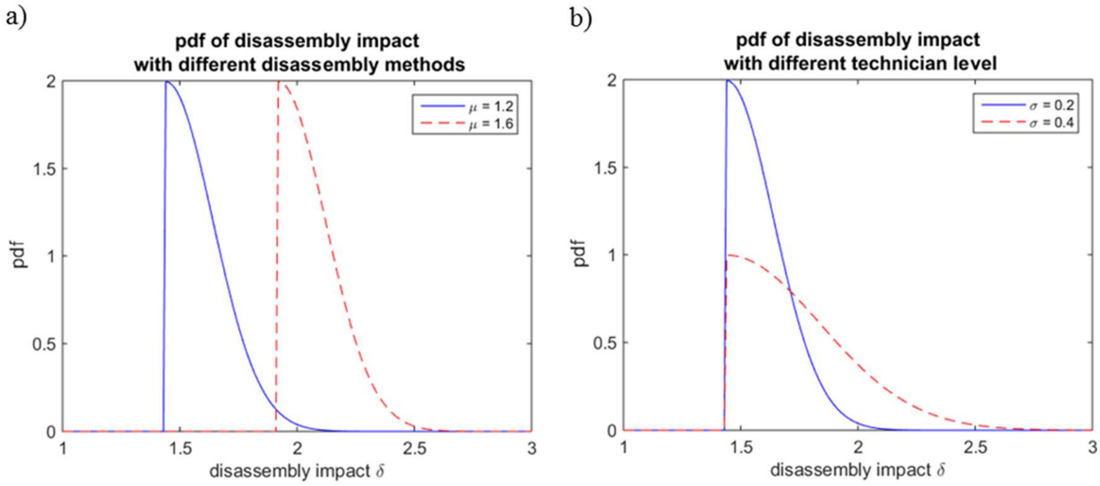


Fig. 3. Disassembly impact when the disassembly operations are conducted by (a)-different methods and (b)-different technician levels.

Fig. 3(a) shows disassembly operations impact when the disassembly operations are conducted by different methods ($\mu_{\theta_{ij}} = 1.2$ and $\mu_{\theta_{ij}} = 1.6$) with the same technician level ($\sigma_{\theta_{ij}} = 0.2$). While the disassembly operations impact shown in Fig. 3(b) is for the case where disassembly operations is conducted by the same method ($\mu_{\theta_{ij}} = 1.2$) and different technician level ($\sigma_{\theta_{ij}} = 0.2$ and $\sigma_{\theta_{ij}} = 0.4$). The components' property coefficient and the strength of connection are $k_i = 0.3$, $S_{ij} = 4$, respectively. It shows that the lower value of $\mu_{\theta_{ij}}$ and $\sigma_{\theta_{ij}}$, the better disassembly method and maintenance technician skill are, respectively.

2.2.3. Impact of disassembly operations of a component/group of components

In section 2.2.2, the impact of disassembly of a connection on the degradation of the corresponding components is considered. In the system, a component may be connected to several components, i.e., this component has several connections. For the system with structural dependence, in order to reach the component for maintenance, the obstructing components need to be partially or completely disassembled. A component is completely disassembled when all connections between this component and the related components are disconnected. Therefore, it is now necessary to investigate on the impact of disassembly operations of a component/group of components for maintenance on the degradation level of other related components.

Components are disassembled in sequence. In that way, we define the disassembly path of a component is the sequence of connections need to be disconnected in order to completely disassemble that component. There are several methods for finding optimal disassembly path (Gungor & Gupta, 1997; Lambert, 2003; Dao & Zuo, 2017; Kheder et al., 2017). However, finding the optimal disassembly path is out of scope of this study, the disassembly path for each component is assumed to be predefined due to the technical constraints. The disassembly path of component h is represented by its disassembly matrix:

$$I^h = \left[I_{ij}^h\right]_{n\times n} \tag{4}$$

Where, $I_{ij}^h = 1$ if connection between the two component i and j is on the disassembly path of component h. It means that for disassembly of component h, the connection between the two components i and j needs to be disconnected. $I_{ij}^h = 0$ in the other cases. For example, reconsider the system shown in Fig. 2, for maintenance of the gear 3, the connection between bearing 1 and shaft 2, and connection between gear 3 and shaft 2, are disassembled. Therefore, the disassembly matrix of component 3 is:

$$I^3 = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{5}$$

In that way, the impact of disassembly of component h for maintenance on the degradation level of component i can be expressed as:

$$H_{ih} = \sum_{j=1}^{n} \delta_{ij}.I_{ij}^h \tag{6}$$

With δ_{ij} represents the impact of disassembly the connection between component i and component j on the degradation level of component i; I_{ij}^h is the element (i,j) of the disassembly matrix of component h, I^h, which indicates whether or not this connection is on the disassembly path of component h.

When conducting maintenance on a group G^k of several components, it can exist intersections among the disassembly paths of different components. This implies that a component i may exist in the disassembly path of several components. In such instance, the disassembly path of the group G^k should be defined as:

$$I^{G^k} = I^j \cup I^l \cup \ldots \cup I^v, j, l, \ldots, v \in G^k \tag{7}$$

For example, suppose that the group G^k consisting of gear 3 and bearing 1 of the gearbox system shown in Fig.2. The disassembly path of the bearing 1 includes disassembly the connection between bearing 1 and shaft 2, while the disassembly path of gear 3 also includes the disassembly of the connection between bearing 1 and shaft 2. Therefore, the disassembly path of group G^k is the same as the disassembly path of the gear 3 as shown in Eq. (5).

In that way, the impact of disassembly operations for maintenance of the group G^k on the degradation of component *i*, $(i \notin G^k)$ can be expressed as:

$$H_{iG^k} = \sum_{j=1}^{n} \delta_{ij} . I_{ij}^{G^k} \tag{8}$$

2.2.4. Degradation modeling with disassembly operations impact

From the above analysis, each component is subjected to both continuous degradation (intrinsic degradation process) in time and the damage caused by disassembly operations. In that sense, the degradation process of component *i* can be expressed as:

$$X_{Hi}(t) = X_i(t) + \sum_{k=0}^{N(t)} H_{iG^k} \tag{9}$$

In which:

- $X_i(t)$ is the continuous accumulative degradation in time of component i, which is, in this work, described by a linear degradation path model, i.e.,

  $$X_i(t) = \alpha_i + \mu_i t + \sigma_i . B(t) \tag{10}$$

  Where, α_i is the initial degradation and μ_i is the degradation rate, σ_i is the degradation volatility, and $B(t)$ is standard Brownian motion. This model has been extensively studied and successfully applied in the literature (Wang, 2010; Ye & Xie, 2015; Nguyen et al., 2018; Wen et al., 2018).
- H_{iG^k} is the impact of disassembly operation of group G^k on the degradation of component i at the maintenance time k^{th}, which is calculated by E.q (8).
- $N(t)$ is the number of maintenance operations of a group of components until t, $t \geq 0$.

Note that, when component *i* is correctively/preventively maintained, the impact of disassembly operations is reset to zero.

Figure 4(b) illustrates the impact of the disassembly operations on component's degradation process in the case of system composed of three components, knowing that the directed graph of the system is shown in Fig. 4 (a). The directed graph underlines that component 1 and component 2 are restricted mutually and the disassembly of one component always means the disassembly of the other, while component 3 is structurally independent with the other components. The system starts working at time $t = 0$ with the initial degradation of the components equal to zero. At time t_1^1, preventive maintenance (PM) is performed on component 1. Due to the impact of disassembly operations, the degradation of component 2 jumps by an amount of δ_{21}. Similarly, at time t_2^1, component 2 has failed and a corrective maintenance (CM) is applied. The disassembly operations impact causes the degradation level of component 1 jump by an amount of δ_{12}. Since components 3 is structurally independent with component 1 and component 2, the disassembly operations of these two components does not affect the degradation process of component 3 and vice versa.

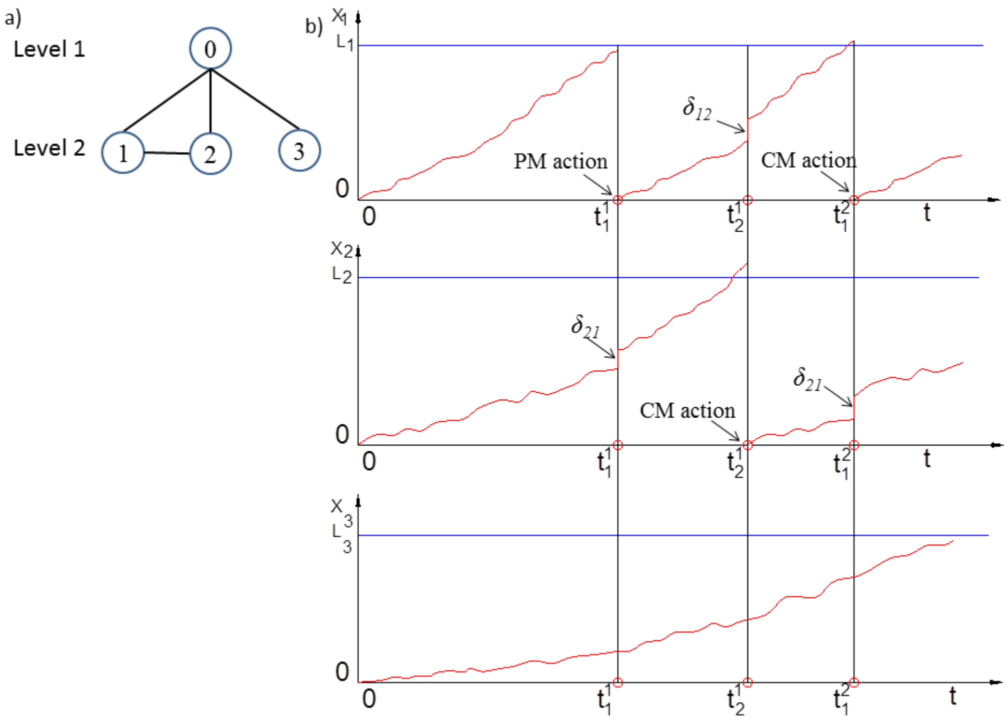


Fig. 4 (a) - Directed graph of a system composed of three components and (b) - the illustration of the impact of disassembly operations on components degradation process.

3. Reliability assessment with consideration of disassembly operations impact

As pointed out in the previous sections, the disassembly operations for maintenance of a component influence the degradation process, i.e., influence the failure probability of related components. It is now necessary to analyze the impact of the disassembly operations on the reliability of these components and hence the whole system. Note that the disassembly operations impact only occurs at each maintenance time. In that way, the maintenance policy may significantly influence the disassembly operations impact. Thus, we analyze the system reliability in the case of system subject to a selective maintenance policy considering the impact of disassembly operations for maintenance.

3.1. Description of the selective maintenance policy

The selected maintenance policy was firstly introduced by (Rice et al., 1998). It then has been extensively studied in the literature (Cassady et al., 2001a; Cassady et al., 2001b; Dao & Zuo, 2017; Khatab et al., 2018a). This maintenance policy implies that the system is operated according to a sequence of missions and scheduled breaks. At each break, some components may be selected for maintenance in order to ensure that the system operates at a desirable level of reliability/availability and avoid the system failure with the lowest maintenance cost. A maintenance action (corrective or preventive maintenance) brings the maintained component to be "as good as new" state.

To illustrate the impact of disassembly operations on the system reliability, the maintenance policy introduced in (Khatab et al., 2018b) is extended by considering the impact of disassembly operations.

The detail of the maintenance policy is described as follows:

- The system serves a sequence of missions, mission z^{th} (z = 1, 2, …) starts from T_z and ends at $T_{z+1} = T_z + \Delta T_z$, ΔT_z is called as the duration of the mission z^{th};
- At the end of each mission, inspections are carried out to reveal the state and the degradation level of the components. Based on the inspection results, all the failed components are firstly correctively maintained. For the surviving components, based on the degradation of the components, reliability of the components and then the entire system for the next mission, $R_s(T_{z+1})$, are evaluated. The decision for selecting components to be preventively maintained as the following:
    - If the predicted reliability of the system at the end of the z^{th} mission, $R_s(T_{z+1})$, is not lower than a reliability threshold, $R^z_{threshold}$, any maintenance action is needed;
    - If the predicted reliability of the system at the end of the z^{th} mission, $R_s(T_{z+1})$, is lower than the reliability threshold, $R^z_{threshold}$, one or several components are selected for preventive maintenance. The selection is based on the fact that after maintenance the system's reliability for the z^{th} mission is not lower than the reliability threshold, $R^z_{threshold}$. If several groups of components are possible, the group with lowest maintenance cost is then chosen.
- It is also assumed that the maintenance resource is always available at the breaks.

Figure 5 illustrates the evolution of the system reliability under selective maintenance policy.

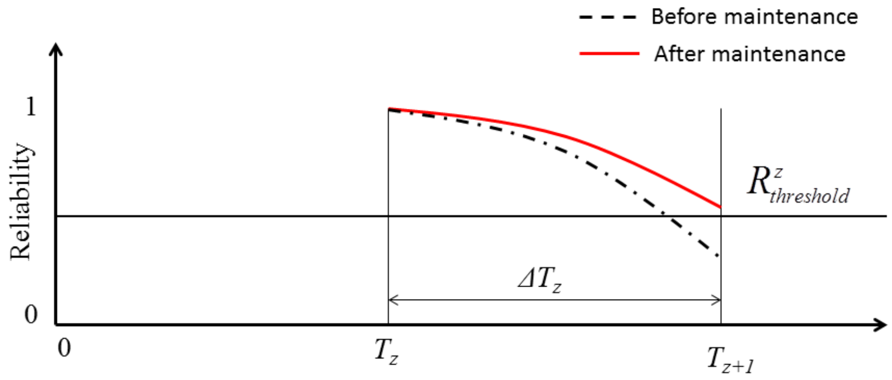


Fig. 5. Illustration of the evolution of the system reliability under the selective maintenance strategy

3.2. Reliability evaluation

The reliability $R_i(t)$ of component i at time t is defined as the probability that component i is in functioning state between time 0 and t (Rausand & Høyland, 2003). For a gradually degrading component, reliability is the probability that its degradation signal $X_i(t)$ is still below a given failure threshold (Lu et al., 2001), and can be expressed as:

$$R_i(t) = P[X_i(t) \le L_i] \tag{11}$$

At the end of the current mission, inspection is carried out to reveal the degradation level of the components. Assuming that at time T_z, degradation level of component i is x_i^z, then the probability that the component i will survive for the z^{th} mission of duration ΔT_z is computed by the conditional reliability $R_i(T_{z+1}|x_i^z < L_i)$ as follow:

$$R_i(T_{z+1}|x_i^z \le L_i) = P[X_i(T_{z+1}) \le L_i|x_i^z \le L_i] \tag{12}$$

For a series system, the reliability of the system at the end of the z^{th} mission is calculated by:

$$R_s(T_{z+1}) = \prod_{i=1}^{n} R_i(T_{z+1}|x_i^z \le L_i) \tag{13}$$

If the reliability of the system for the z^{th} mission is less than its reliability threshold, $R^z_{threshold}$, some components are selected for maintenance. Suppose that a group of components, G^z, are selected for maintenance. The reliability of component i ($i \notin G^z$) considering the impact of disassembly operations on group G^z is:

$$R_i(T_{z+1}|x_i^z, G^z) = P\,[X_i(T_{z+1}) + H_{iG^z} \le L_i|x_i^z \le L_i, G^z] \tag{14}$$

Where, H_{iG^z} is the damage on component *i* due to the disassembly operations of group G^z for maintenance at the end of mission *(z-1)*th, and is calculated by Eq. (8). H_{iG^z} follows a half-normal distribution with mean μ_{H_i} and variance $\sigma^2_{H_i}$ are shown in Eq. (15) and Eq. (16), respectively.

$$\mu_{H_i} = \sum_{j=1}^{n} k_i.S_{ij}.I_{ij}^{G^z}.\mu_{\theta_{ij}} \tag{15}$$

$$\sigma^2_{H_i} = \sum_{j=1}^{n}\left(k_i.S_{ij}.I_{ij}^{G^z}\right)^2.\sigma^2_{\theta_{ij}} \tag{16}$$

Therefore, Eq. (14) becomes:

$$\begin{aligned} R_i(T_{z+1}|x_i^z \leq L_i, G^z) &= \int_{H_{iG^z}} F_{X_i}(L_i - H_{iG^z}).f_{H_{iG^z}}(H_{iG^z}).dH_{iG^z} \\ &= \int_0^{\infty} \Phi\left(\frac{L_i - H_{iG^z} - x_i^z - \mu_i \Delta T_z}{\sigma_i \Delta T_z}\right).f_{H_{iG^z}}(H_{iG^z}).dH_{iG^z} \end{aligned} \tag{17}$$

Where:

- $\Phi(.)$ is the cumulative distribution function of the standard normal distribution;
- $f_{H_{iG^z}}$ is the probability density function of the damage on component *i* caused by disassembly operations of group G^z for maintenance, H_{iG^z}.

The system reliability for the next mission under consideration of the disassembly operations impact is then rewritten as:

$$R_s(T_{z+1}|G^z) = \prod_{i=1}^{n} R_i(T_{z+1}|x_i^z \leq L_i, G^z) \tag{18}$$

The reliability analysis of a multi-component system with structural dependence is numerically discussed though a gearbox system in the next section.

The procedure for modeling the reliability of the system considering the impact of disassembly operations is shown in Appendix B.

4. Numerical example

The purpose of this section is to illustrate (i) the impact of disassembly operations on the degradation process of the components and (ii) how the disassembly operations impact on the reliability of the system and maintenance selection.

Reconsider the gearbox system shown in Fig. 2 with its extent connection matrix given in Eq. (1). For maintenance of the system, the selective maintenance policy presented in section 3.1 is applied. Suppose that the next mission starts at T_z=*60* (time unit) and will last for the duration of ΔT_z = 60 (time unit). The reliability threshold of the next mission is at a fix level of $R_{threshold}$ = 0.7. At the end of the current mission (T_z=60), inspection is carried out to reveal the state and degradation level of the components. The value of the component's parameters are given in **Table 1**.

Table. 1. The components parameters

Parameters \ Component	1	2	3	4	5	6	7	8
L_i (Failure threshold)	50	50	50	50	50	50	50	50
x_i^z (Current degradation)	20	15	25	20	15	15	25	20
μ_i (Degradation rate)	0.3	0.2	0.45	0.42	0.28	0.19	0.42	0.28
σ_i (Degradation volatility)	1.2	0.8	0.5	1.2	1.1	0.9	0.55	1.3
k_i (component's property coefficient)	1.2	0.3	0.8	0.9	0.6	0.24	0.8	0.9

The directed graph, connection matrix, and extent connection matrix (strength of the connections) are established based on the system structure as shown in Fig.2 (b-c) and Eq. (1), respectively. Then, the disassembly sequence of each component is established based on the directed graph. From the disassembly sequence and connection matrix, the disassembly matrix for each component is established. For example, from the directed graph, the disassembly sequence of the gear 3 consists of disassembly of the bearing 1 and gear 3. The disassembly of the bearing 1 and gear 3 requires disconnecting the connection (1,2), (2,1), (2,3) and (3,2) between bearing 1 and gear 3 with shaft 2. Therefore, the disassembly matrix of the gear 3 is established as shown in Fig. 6 (b). Similarly, the disassembly matrix of other components is shown in Fig. 6.

a)
$$\begin{pmatrix} 0&1&0&0&0&0&0&0\\ 1&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0 \end{pmatrix}$$

b)
$$\begin{pmatrix} 0&1&0&0&0&0&0&0\\ 1&0&1&1&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0 \end{pmatrix}$$

c)
$$\begin{pmatrix} 0&1&0&0&0&0&0&0\\ 1&0&1&0&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0 \end{pmatrix}$$

d)
$$\begin{pmatrix} 0&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0 \end{pmatrix}$$

e)
$$\begin{pmatrix} 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0 \end{pmatrix}$$

f)
$$\begin{pmatrix} 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&1&0&1&1\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&0&1&0&0 \end{pmatrix}$$

g)
$$\begin{pmatrix} 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&1&0&1&0\\ 0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0 \end{pmatrix}$$

h)
$$\begin{pmatrix} 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&1\\ 0&0&0&0&0&0&0&0\\ 0&0&0&0&0&1&0&0 \end{pmatrix}$$

Fig. 6 Disassembly matrix of component (a)-1, (b)-2, (c)-3, (d)-4, (e)-5, (f)-6, (g)-7 and (h)-8.

The elements $\mu_{\theta_{ij}}$and $\sigma_{\theta_{ij}}$ of the matrices μ_θ and σ_θ given in Fig. 7 represent the mean and standard deviation of the adjustment factor θ_{ij}, which reflects the impact of disassembly method/tools and maintenance technician used to perform the disassembly of the connection (i,j).

$$\mu_\theta = \begin{pmatrix} 0 & 1.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.2 & 0 & 1.1 & 1.2 & 0 & 0 & 0 & 0 \\ 0 & 1.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.2 & 0 & 1.1 & 1.2 \\ 0 & 0 & 0 & 0 & 0 & 1.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.2 & 0 & 0 \end{pmatrix} \qquad \sigma_\theta = \begin{pmatrix} 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.2 & 0 & 0.1 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.2 & 0 & 0.1 & 0.2 \\ 0 & 0 & 0 & 0 & 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.2 & 0 & 0 \end{pmatrix}$$

Fig. 7. Mean and standard deviation of adjustment factor engaging with the applied method and technician for disassembly of each connection

4.1. Reliability assessment & maintenance grouping

Based on the current degradation level, the reliability of the components and the entire system for the next mission is evaluated. As shown in Fig. 8, the reliability of the system at the end of the next mission (T_{z+1}= 120) in the scenario of no selective maintenance (dotted blue line) is 0.126, which is less than the reliability threshold (0.7). Therefore, one or several components need to be selected for maintenance in order to ensure that the reliability of the system at the end of the next mission will not be lower than the reliability threshold (0.7). For the purpose of illustration of the impact of disassembly operations on the reliability of the system, the maintenance optimization is not presented in this paper. Suppose that component 3 and component 7 are selected for maintenance at T_z = 60. In the scenario of ignoring the impact of disassembly operations (continuous blue line), the reliability of the system at the end of the next mission is 0.7309, this value meets the reliability requirement.

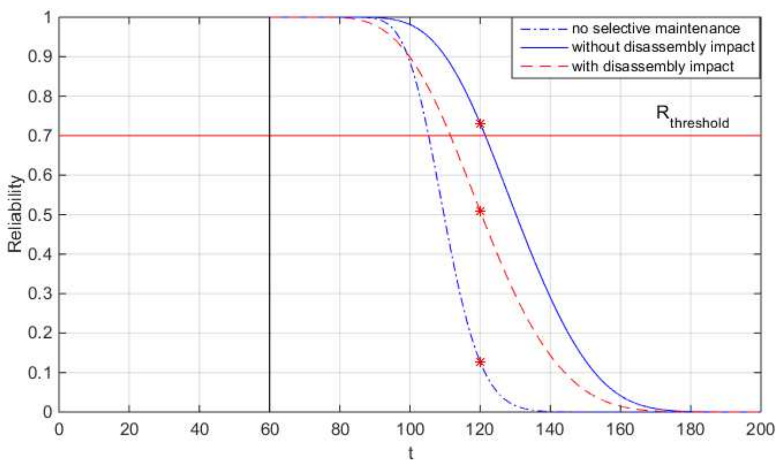


Fig. 8. The system reliability for the next mission in the scenarios of no selective maintenance, selective maintenance with and without considering the impact of disassembly operations

However, the disassembly of component 3 and component 7 requires disassembly of connections (1,2), (3,2), (5,6), (7,6), and hence impact on the degradation of the related components. Therefore, the reliability of these components and the system considering the impact of disassembly operations is calculated by Eq. (17) and Eq. (18), respectively. It shows in Fig. 8 that the impact of disassembly operations results in decrease of system reliability. In this scenario, the reliability of the system at the end of the next mission (dashed red line) is 0.5087, which is still less than the reliability threshold (0.7).

Due to the impact of disassembly operations, the reliability of the system at the end of the next mission may not meet the reliability threshold. Therefore, to ensure that the system reliability meets the reliability requirement for the next mission, it is necessary to consider more components for maintenance. Suppose that to ensure that the system reliability meets the reliability requirement for the next mission, component 1 is chosen for maintenance together with component 3 and component 7. Fig. 9 shows the system reliability for the next mission considering the impact of disassembly operations when three components, 1, 3, 7 are preventively maintained at the end of the current mission (T_z=60).

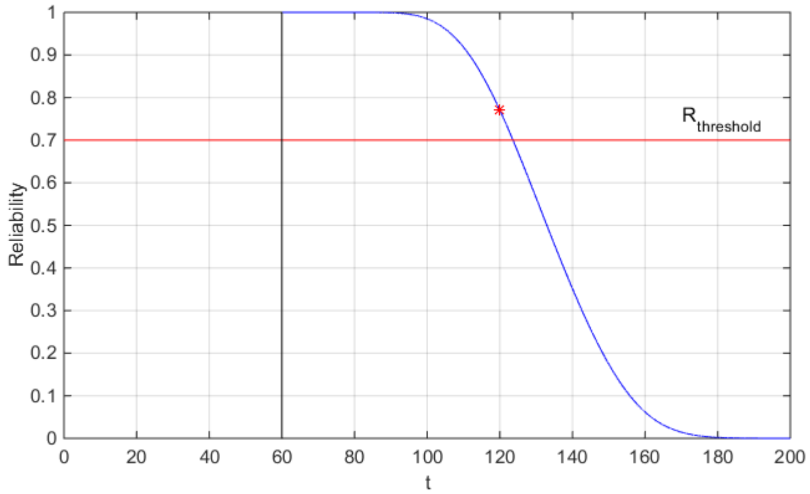


Fig. 9. System reliability for the next mission considering the impact of the disassembly operations impact when component 1 is selected for maintenance together with component 3 and component 7

4.2. Impact on the components ranking for individual maintenance

This section was conducted to analyze the impact of maintenance of each component individually on the improvement of the system reliability in two scenarios: with and without considering the impact of disassembly operations. Needed, the improvement of the system's reliability when component i is maintained at time T_z is defined as:

$$\Delta R = R_s(T_{z+1}|i) - R_s(T_{z+1}) \quad (19)$$

Where, $R_s(T_{z+1}|i)$ is the system's reliability when only component i is replaced; $R_s(T_{z+1})$ is the system reliability when no component is selected for maintenance.
The results on the system's reliability improvement at $T_{z+1}=120$, when a given component is replaced at $Tz=60$, is reported in Table 2.

Table 2 shows that without considering the impact of disassembly operations, component 3 is the most important component with the highest improvement in the system's reliability is 0.2292. However, when considering the impact of disassembly operations, the most important component is component 7, with the improvement in the system's reliability is 0.1304, compared to 0.1297 when component 3 is selected for maintenance. This is due to the impact of disassembly operations of component 3 is stronger than component 7. It also shows that, when considering the impact of disassembly operations, the improvement of the system's reliability when component 2 or component 6 individually maintained is negative. In this case, these components should not be individually selected for maintenance.

Table. 2. System's reliability improvement at $T_{z+1}=120$ when each component is individually replaced at $T_z=60$

Selected component for maintenance	System's reliability improvement (ΔR)	
	Without considering disassembly operation impact	Considering disassembly operation impact
1	0.0118	0.0117
2	0.001	**-0.0894**
3	**0.2292**	**0.1297**
4	0.0223	0.0222
5	0.0026	0.0025
6	0.0224	**-0.0548**
7	**0.1792**	**0.1304**
8	0.012	0.0119

4.3. Sensitive analyses

In this section, sensitive studies were conducted to analyze the effect of several parameters related to disassembly operations on the system reliability. In that way, the parameters of interest include the components' property coefficient k_i, and the strength of connections between components S_{ij}.

4.3.1. Sensitive analysis to the components' property

In this study, the component's property is changed by increasing the property coefficient from k_i to $k_i' = 1.5k_i$, which means that the components became more sensitive to the disassembly operations impact. The sensitivity result by changing the components' property is shown in Fig.10. It is noted that the reliability is evaluated given that both component 3 and components 7 are replaced at the end of the current mission (T_z=60). The obtained results show that the higher the components' property, the less the system reliability is given.

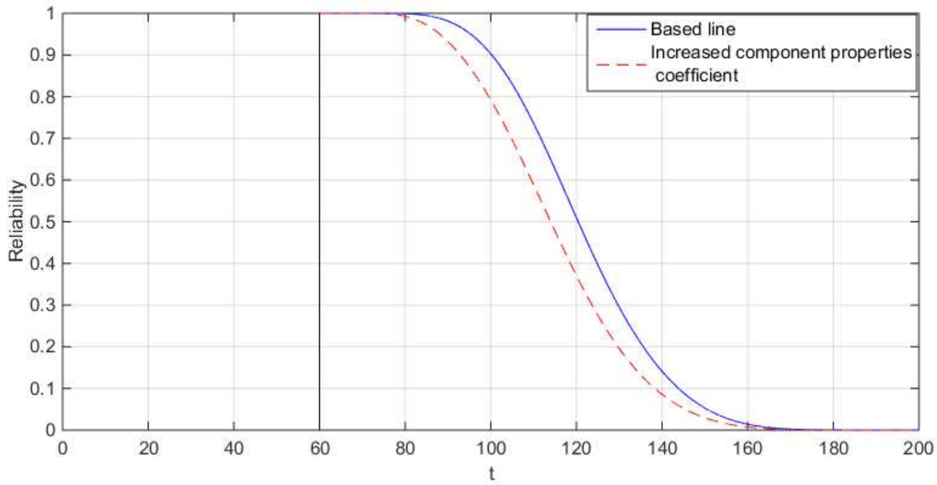


Fig. 10. Sensitivity analysis of components property's coefficient on the system reliability

4.3.2. Sensitive analysis to the strength of connections between components

Figure 11 depicts a sensitive analysis performed by increasing the strength of connections, from S_{ij} to $S_{ij}^{'} = 2S_{ij}$ for $i, j = 1,2 \dots ,8$. The increase of the strength of connection S_{ij} results in more difficult to disassembly the connection between two component i and j. Therefore, it needs to apply higher force. This leads to higher disassembly operations impact and may decrease the system reliability. It should be noted that, with this sensitivity study, only the connections related to the disassembly operations of components 3 and 7 (see the disassembly path for components 3 and 7) are concerned. The obtained results show again that the higher the connection strength, the more impact on the system reliability is provided.

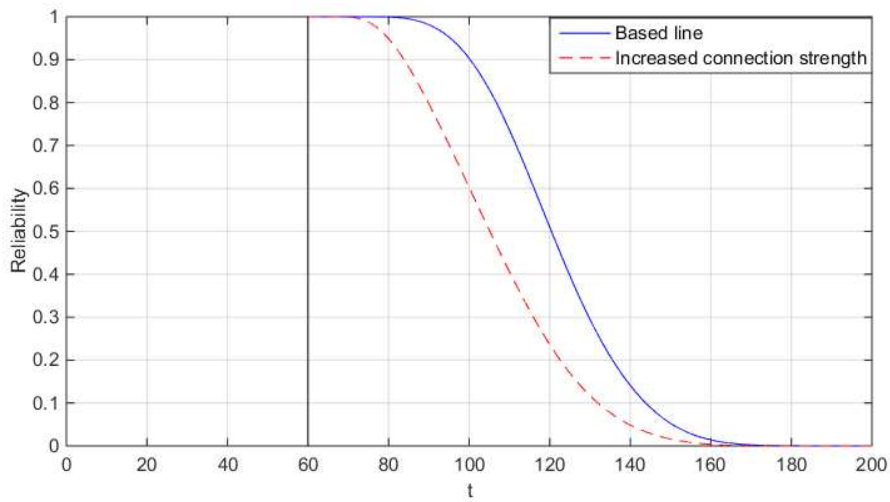


Fig. 11. Sensitivity analysis of connection strength on the system reliability

5. Conclusions

In this paper, we investigated the impact of structural dependence (disassembly operations for maintenance) on the degradation process and reliability of the components. For this purpose, the connection matrix and directed graph are employed to model the structural dependence between components. A model-based connection matrix is then proposed to quantify the impact of disassembly operations on the degradation of the components in multi-component system. The proposed model allows considering several influenced factors such as property of the component, system's structure, the strength of the connection between the components and the degree of expertise of the technician and tool used to perform the disassembly operations. This study also proposed a degradation model to integrate the intrinsic degradation process of the component and the damage caused by the disassembly operations. The impact of disassembly operations is then integrated into the reliability assessment model for a multi-component system subject to selected maintenance policy. The proposed model is finally applied for reliability assessment and maintenance of a gearbox system. The numerical results show that the failure risk of the components and the system will be underestimated if this impact is ignored. In addition, the results also show that the disassembly operations have a significant impact on the important ranking of the components and the selection of a component/group of components for preventive maintenance.

In terms of perspectives, the impact of disassembly operations should be studied not only on the degradation level of the components but also on the degradation speed of these components.

Moreover, Eq. (6), Eq. (7) and Eq. (8) imply that combining maintenance on a group of components can decrease the impact of disassembly operations on the degradation of other components. Therefore, working on the maintenance optimization to minimize the disassembly operations and the overall maintenance cost is a relevant orientation to be achieved.

APPENDIX A. Impact of disassembly operations: a non-linear model

A quadratic model of the impact of disassembly operation can be expressed as follows:

$$\delta_{ij} = \omega_0 + \omega_1 . k_i . S_{ij} + \omega_2 . \theta_{ij} + \omega_3 . \theta_{ij}^2$$

Where,

– the second term $\omega_1 . k_i . S_{ij}$ allows considering the impact of internal factors (components' properties, k_i, and strength of connections, S_{ij});

- $\omega_2.\theta_{ij}$ and $\omega_2.\theta_{ij}^2$ take into account the impact of external factors (i.e. degree of expertise of technician and tools);
- $\omega_0, \omega_1, \omega_2, \omega_3$ are the model's coefficients, which can be estimated from historical data;
- The adjustment factor θ_{ij} follows a haft normal distribution with mean and standard deviation $\mu_{\theta_{ij}}$ and $\sigma_{\theta_{ij}}$, respectively.

As an example, we suppose that the model's parameters are: $\omega_0 = 0, \omega_1 = 1, \omega_2 = 0.5, \omega_3 = 0.1, k_i = 0.3, S_{ij} = 4$, $\mu_{\theta_{ij}} = 1.2$ and $\sigma_{\theta_{ij}} = 0.2$. Figure 13 shows the histogram of the adjustment factor, θ_{ij} and the disassembly impact δ_{ij} using a numerical method.

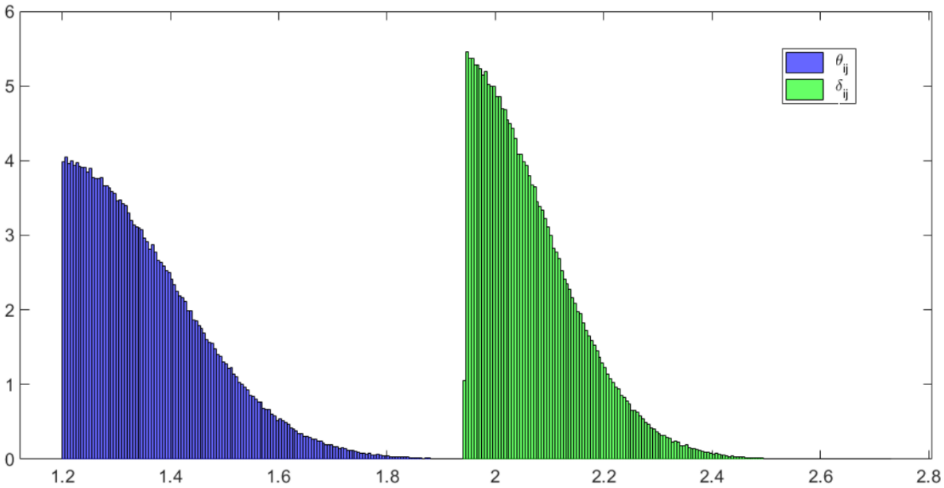
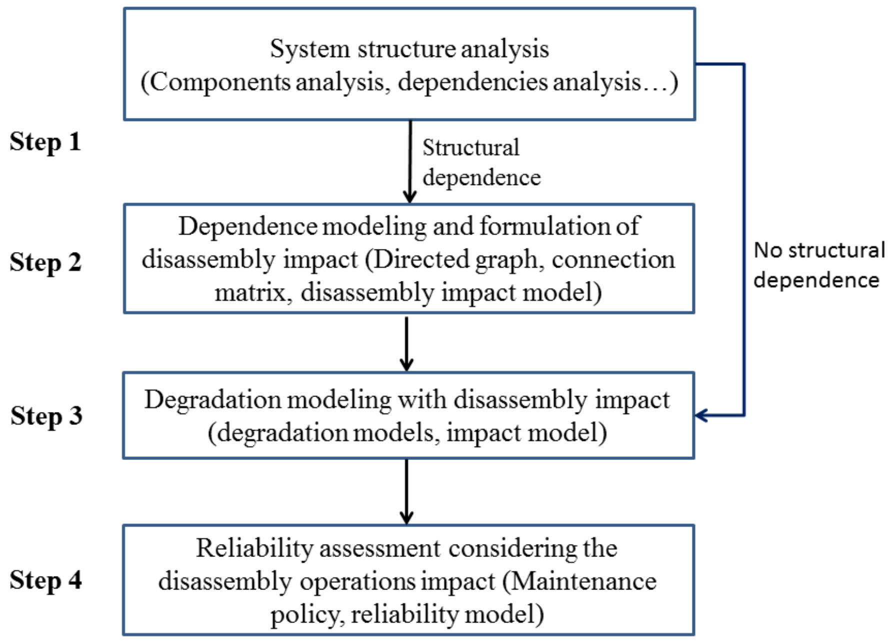


Fig. 12. Histogram of disassembly operations impact with regards to θ_{ij}

APENDIX B. Implementation procedure for reliability assessment with disassembly impact



Step 1: System structure analysis (component analysis, dependencies analysis...)

This step is conducted to analyze and identify the features of the system's components and the dependencies between components. If components in the system are structurally dependence, the process continues to step 2, otherwise, the process continues to step 3.

Step 2: Dependence modeling and formulation of disassembly impact (Directed graph, connection matrix, disassembly impact model)

In this step, the structural dependence between components is modeled through directed graph and connection matrix. Based on the directed graph and connection matrix, the disassembly matrix is achieved, and the impact of disassembly operations is formulated.

Step 3: Degradation modeling with disassembly impact (degradation models, impacts model)

The degradation process of the components is modeled. The impact of disassembly operations calculated in step 2 is then integrated in the degradation model.

Step 4: Reliability assessment considering the disassembly operations impacts (maintenance policy, reliability model)

Based on the proposed maintenance policy, the reliability assessment model is established. The degradation process considering the impact of disassembly operations formulated in step 3 is used to predict the reliability and the components.

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