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Maintenance policy optimisation for multi-component systems considering degradation of components and imperfect maintenance actions

Ronald M. Martinod[a], Olivier Bistorin[b,*], Leonel F. Castañeda[a], Nidhal Rezg[c]

[a] Universidad EAFIT, Department of Mechanical Engineering, Engineering School, Carrera 49 Nr. 7 Sur-50, Medellín, Colombia
[b] ICN Business School Nancy Metz, Dpt. Management de la Supply Chain et des Systèmes d'information, 3, place Edouard Branly, 57070 Metz Technopôle, Metz, France
[c] Université de Lorraine, Laboratoire de Génie Industriel de Production et de Maintenance (LGIPM), College of Mathematics, Information, Mechanics and Automatics, Ile du Saulcy, 57045 Metz Cedex, Metz, France

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ABSTRACT

This article proposes a stochastic optimisation model in order to reduce the long-term total maintenance cost of complex systems. The proposed work is based on the following approaches: (i) optimisation of a cost model for complex multi-component systems consisting of preventive and corrective maintenance using reliability analysis, which faces two different maintenance policies (periodic block-type and age-based) and (ii) a clustering method for maintenance actions to decrease the total maintenance cost of the complex system. This work evaluates each maintenance policy and measures the effects on imperfect maintenance actions. Finally, the proposed optimisation model is applied to a numerical example which focuses on passenger urban aerial ropeway transport systems, in which the current maintenance policy has been evaluated, considering the established by the international regulation of passenger aerial cable cars.

1. Introduction

Traditional optimisation models based on maintenance of complex systems have been considered as a collection of independent components (Chelbi & Aït-Kadi, 2001; Cho & Parlar, 1991; Yang, Ma, Peng, Zhai, & Zhao, 2017); nevertheless, taking account the complexities involved in engineering systems and the need to improve the maintenance activities, it is no longer sensible to treat each component in such systems as an individual component (Cheng, Zhou, & Li, 2017). The maintenance resources of an engineering system –production and service as well– can be reduced if a set of components are repaired using only one type of maintenance action (Peng & Zhu, 2017).

There are models (Briš & Byczanski, 2013; Gustavsson, Patriksson, Strömberg, Wojciechowski, & Önnheim, 2014) based on dependencies between the components in a complex system; these dependencies lead to further problems to understand the behaviour of the system (Briš, Byczanski, Goňo, & Rusek, 2017). The dependence-based models have assumed that all components in the system belong to a certain group according to an *a-priori* classification based on a deterministic criterion –e.g. the components are grouped by similarities of the shape, functionality, assembly or location within the system–. Some studies of dependence-based models have been focused on the optimal maintenance policies for a multi-component system (Ahmad & Kamaruddin, 2012; Nicolai & Dekker, 2008; Van Horenbeek & Pintelon, 2013; Yang, Zhao, Peng, & Ma, 2018), the set of the main dependencies are the following: (i) stochastic dependency, which considers the effect of the component deterioration regarding the lifetime distribution of others components, the studies in this area (Liu, Xu, Xie, & Kuo, 2014; Yang et al., 2017) focus on the trigger effect by failure of a component –i.e. failure interactions–; (ii) structural dependency (Iung, Do, Levrat, & Voisin, 2016; Peng & Zhu, 2017), which focuses on the assembly relationship condition of a component in a subsystem; and (iii) economic dependency (Do, Vu, Barros, & Bérenguer, 2015; Qiu, Cui, Shen, & Yang, 2017; Van Horenbeek and Pintelon, 2013; Zhou, Huang, Xi, & Lee, 2015), which assumes that a maintenance action cost of a grouped component does not equal to the sum of the maintenance cost of all individual components.

The effect of the clustering techniques on maintenance costs have been considered for a reduced set of systems with specific configurations (Wang, Tsai & Li, 2011). Yang, Djurdjanovic and Ni (2008) used a dependence-based model to develop a maintenance schedule based on the expected degradation of the machine by taking into account the complex interaction between the components, the production process, and the maintenance operations. Later, Tian and Liao (2011) proposed

* Corresponding author.
E-mail addresses: rmartino@eafit.edu.co (R.M. Martinod), olivier.bistorin@icn-groupe.fr (O. Bistorin), lcasta@eafit.edu.co (L.F. Castañeda), nidhal.rezg@univ-lorraine.fr (N. Rezg).

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Table 1
Indices and parameters used throughout the paper.

i	Intant of lifetime
$j = \{1, 2, ..., J\}$	Indices of the components on the system
$k = \{1, 2, ..., K\}$	Indices of clustered preventive maintenance actions
η	Horizon of time, long-term window of lifetime
B_k	Bernstein polynomial
$\mathscr{F}_h$	Parametric curve proposed by De Casterljeau
g	Piecewise-defined parametric curve
u	Parameter of the parametric curve $\mathscr{F}_h$
$P(\cdot)$	Probability function
Maintenance policy parameters:	
$\alpha_{j,\eta}$	Age reduction coefficient after a maintenance action of the jth component, over the η period of lifetime, $\alpha_{j,\eta} = \{\alpha_{p1}, \alpha_{p2}\}$
α_{p1}, α_{p2}	Age reduction after a major and minor preventive maintenance action, respectively
$\beta_{j,\eta}$	Stochastic hazard rate of the jth component and over the η period of lifetime, related to a human and technical uncertainty of a maintenance action
p	Relationship between the quantity of minor maintenance actions per each major maintenance action
f_j, F_j	Probability and cumulative fault distribution of the jth component [cycles], respectively
R_j, $\Delta R_{j,\eta}$	Reliability probability function and reliability gain of the jth component [cycles], respectively
R_{inf}	Lower threshold of the reliability function [cycles]
ω_j, ω_o, ω_A	Current working cycles, working cycles of the last maintenance action and working cycles of the next maintenance action of the jth component [cycles], respectively
$\varphi_{j,\eta}$	Failure probability average of the j th component over the finite period of time τ
τ	Period of time between preventive maintenance actions [year/maint.]
Optimisation parameters:	
Cp_j	Cost of a perfect maintenance action (AGAN) to the jth component, which is quantified on monetary unit (mu) per maintenance action [mu/maint.]
Cc_j	Cost of a corrective maintenance action to the jth component, which is related to the cost of the time-dead of the system, the cost of logistic actions, labour cost, cost of devices and equipment [mu/maint.]
C_1, C_2	Cost of the major and minor preventive maintenance action [mu/maint.], respectively
$C_{j,\eta}$	Optimisation function of maintenance cost to the jth component [mu/year]
$C^*_{j,\eta}$	Optimal maintenance cost value of $C_{j,\eta}$ [mu/year]
C^{**}_k	Opportunistic cost of the optimal period $C^*_{j,\eta}$ by clustering [mu/year]
e_k	kth cluster centre of a set of maintenance actions
E	Objective function by k-means algorithm
$\Gamma c_{j,\eta}$, $\Gamma p_{j,\eta}$	Cost of a corrective and a preventive maintenance of the jth component [mu/year], respectively
Decision variables:	
A_j	Range of working cycles over the jth component based on age-based preventive maintenances
T_j	Periodicity over preventive maintenance actions [maint./year]
$\mathbb{T}_k$	Periodicity of the preventive maintenance actions of the kth optimal period cluster [maint./year]

a maintenance policy based on a proportional hazard model for multi-component systems, and a policy was established for preventive replacements of spare parts. Subsequently, Liu et al. (2014) formulated a preventive maintenance policy for multi-component systems concerning continuously degrading components. In addition, Zhou et al. (2015) proposed a time window based preventive maintenance model for multi-component systems with stochastic failures and the disassembly sequence involved. Nevertheless, it is possible to identify that the literature has not reported dependence-based models without a pre-established classification (shape, functionality, assembly, etc.), which combines the reliability analysis of the complex systems and the working-life condition of each component.

Other models (Do et al., 2015; Iung et al., 2016; Martinod, Bistorin & Rezg, 2019) have assumed that all members of a group have identical behaviour (i.e. identical working rate, wear ratio, degradation, etc.); therefore, these models are based on hypotheses with simplifications; thus, these models are limited because they do not consider that the same type of components in the system could: (i) come from different suppliers with different quality; (ii) come from different production batches; (iii) have a material quality variation; (iv) have a metrological variation; (v) have different working stress; and (vi) have different working environment. This work shows that it is possible to develop a maintenance policy model which considers a multi-component system affected by multiple types of independent degradation processes. Economic dependencies are common in most continuous operating systems, such as aircrafts, powerplants, or chemical processing facilities. This work focuses on economic dependencies, it means a conjoined maintenance action can yield a lower total cost than maintaining each component separately.

An efficient maintenance policy should consider a long-time period between preventive maintenance actions. Nevertheless, under operational conditions, increasing the period between preventive maintenance actions decreases the reliability function of each component; thus, increasing the maintenance cost by increasing the corrective maintenance actions (Qiu et al., 2017; Yang et al., 2017). If non-identical components are considered in a complex multi-component system, each single component will have different reliability function and a different period between preventive maintenance as well. In this work, an optimisation of maintenance policy process is developed for multi-component systems, where a reliability relationship is considered among different components subjected to each single condition during their working-life. Given a multi-component system comprised of sets with the same type of components, wherein the components are not necessarily identical, and these components may even have: (i) variation of properties, e.g. material quality or metrological variation; (ii) working rate variation due to different operation conditions of the system; and (iii) independent degradation processes. The objective is to minimise the long-term maintenance action cost of complex systems. Main contributions of the article can be summarised as follows:

(i) a dependence-based optimisation model and different maintenance policies (periodic block-type and age-based) are merged to solve the problem of maintenance in complex systems considering the imperfect maintenance actions;
(ii) a stochastic optimisation is developed in order to provide a maintenance plan accounting for the degradation process of each