PhD Proposal at Univ. Grenoble Alpes, France
Multivariate degradation in presence of different types of maintenance
and covariate : modelling, inference and decision making

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Title: Multivariate degradation in presence of different types of maintenance and covariate : modelling, inference and decision making
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Doctoral School: Ecole doctorale Mathématiques, Sciences et technologies de l'information, Informatique (MSTII) - https://edmstii.univ-grenoble-alpes.fr/
Hosting laboratories/research teams : (LJK/ASAR and GIPSA-lab/SAFE) Two research teams are involved in the environment of this PhD project ; they have complementary skills in reliability theory, maintenance modeling, system monitoring and control, and optimization.

- LJK : ASAR Team "Applied Statistics and Reliability" (https://www-ljk.imag.fr/ASAR/ - Laurent Doyen) bringing its competencies in stochastic modelling and statistical inference in reliability and maintenance and in joint modelling of ageing and maintenance efficiency of complex systems.

- GIPSA-lab : SAFE Team " Safe controlled and monitored systems" (http://www.gipsa-lab.fr/ - Christophe Bérenguer) with competencies in deterioration and predictive maintenance modelling, prognosis and remaining useful life estimation, system monitoring and diagnosis, post-prognosis decision making and control systems

Keywords: Reliability Theory, Maintenance Modeling & Optimization, Deterioration modeling, Lifetime analysis, Statistical estimation, Prognosis and Health Management, Post-prognosis Decision Making, Environmental conditions, Data-driven approaches, Information & decision

1 Research topic : context and background

This PhD proposal is part of a broader joint project between LJK and GIPSA-lab. Within this project we consider technological or industrial equipments, or structural components (e.g. dikes, dams, ...) that are subject to degradation because of intrinsic wear, usage imposed by operating conditions or exposure to environmental factors. For such repairable industrial equipments, an issue consists in maintaining the system in working order conditions in accordance with safety, availability and cost constraints, [4]. Nowadays, the wide access to information and data on systems opens new research perspectives to this classical reliability and maintenance issue [8].

Those information and data can be very heterogeneous. They can arise from reliability data base and describe the successive failures, maintenances and inspections of the different parts of the considered systems. Practically, those data base can simultaneously consider several, and possibly correlated, failure mechanisms. Maintenances actions can have different efficiencies and inspections can also be more or less extensive. Information can also be collected thanks to the presence of sensors or modern monitoring techniques and describe the specifics working conditions of each system, such as for example humidity or temperature. But those sensors can also record the severity of the usage conditions of each system and even measure deterioration levels and health indicators. This project aims at exploring solutions and at developing a comprehensive approach to optimally manage the health state of deteriorating systems based on this diversity of available information, and resorting

to a wide range of possible actions from optimal control of the operating conditions to maintenance actions.

To consider these types of issues, two disconnected approaches have been used in reliability literature. One is based on recurrent event models and is centered on the probabilistic lifetime modelling of the successive discrete event times and types. The other one considers stochastic processes (or even dynamic state-space models with some uncertain random parameters) representing continuously time varying degradation, in which failures corresponds to the first reaching of a given threshold. We are convinced that closing the gap between these two "modelling worlds", that describe the same reality from different points of view and using different tools, can be fruitful, but requires to solve several difficulties that are currently under investigation in the joint work of both teams LJK/ASAR and GIPSA-lab/SAFE. To our knowledge, no model has ever been proposed that can take into account simultaneously the effect of maintenance actions and time dependent covariates on multivariate degradation processes. The aim of this PhD project is thus to investigate more in depth the second approach based on an explicit modelling of the time varying deterioration.

2 Methodology and description of work

To complete this project, a methodology implemented through three interlinked and complementary tasks is proposed. These tasks are sequenced in a rather logical way from modelling to inference and finally decision-making ; however several iterations between these tasks will be required : indeed, for example, the performance of the decision-making step might require to revisit the modelling step.

Task 1 - Modelling multivariate wear-out phenomenons Basic assumptions on maintenance efficiency are known as "As Bad As Old" (ABAO) and "As Good As New" (AGAN). In the ABAO case, each maintenance is supposed to restore the system in the same state as it was just before failure. In the AGAN case, maintenances are supposed to renew the system. Obviously, reality falls between these two extreme cases and maintenance is said to be imperfect. The successive failures and maintenances times can be represented by recurrent events model that can be characterized by a random failure intensity. The most usual imperfect maintenance model are the virtual age models [9, 6], which assume that maintenance effect is to rejuvenate the system. Considering environmental conditions, there are only a few papers which consider heterogeneity in reliability and even less in the repairable system literature. Only very recent works have studied how constant or time varying covariates can be introduced in virtual age models [5, 10].

When the deterioration of the system can be observed or quantified, it can interesting to model it by a by a random process (a Gamma [14], monotone Levy or Wiener [16] process for example) and to assume that the failure corresponds to crossing a threshold level for this process. In this approach, most of the prevalent models consider a static operating environment for the system and a unique cause of deterioration. Only very few papers have simultaneously considered multiple and possibly dependent deterioration indicators, influenced by (uncontrolled) environmental conditions and (possibly controlled) operating conditions through covariates effects [13, 15] and also submitted to several types of imperfect maintenances with different efficiencies. In addition, from a practical point of view, the failure mechanism is often more complex than a simple threshold crossing of the degradation process. A few authors have proposed to consider the degradation as a covariate in the lifetime model in order to link both modelling approaches [11]. But, they do not have considered imperfect maintenance actions in this context. The first axe of the PhD will then be to propose such models and to study their probabilistic properties. Different types of processes will be considered : Wiener processes, Gamma processes or inverse-Gaussian processes. The dependence between the different degradation indicators will be taken into account thanks to copulas or Gaussian vectors. Both tools can also be mixed together [7]. In presence of unobserved heterogeneity, additional variability from one degradation path to the other will be added thanks to random effects [15]. The principle of classical imperfect maintenance models for recurrent events, such as virtual age models for example, have to be adapted

for degradation models [12]. The possibility of antagonistic effects of the maintenance will also be considered. In fact, in corrosion phenomenon and may be also for clogging deterioration, maintenance can have an immediate positive effect that reduces the degradation level thanks to the cleaning, but it can also have a long term negative effect that increases for example the degradation slope, because surface treatments have been deteriorate [16].

The originality of the proposed work will also be to consider integrated models that both include multivariate wear-out and also the effects of multiple different types of maintenance and covariate. Maintenance can have different types because they are of different nature (corrective, preventive, planned, condition based, ...) or because they have different effects and efficiencies (inspection, minor repair, major overhaul, ...). All these types of maintenance will be considered, possibly simultaneously, with different modelling of their effects. In particular, we will both considered models in which the effect is to reduce the value after maintenance of a given degradation (for example arithmetic reduction of degradation, age or intensity), and models in which the future evolution of the degradation is affected by maintenance effect. The covariates can both correspond to uncontrolled environment conditions such as for example outside temperature or relative humidity, or to controllable operating conditions like usage rate for example. Covariates can also be of different natures (categorical, constant, time dependent, ...), they can even be represented by function or photo values. We will in particular consider the case where the drift of the degradation process is affected by covariates, for example in the case of linear drift, the corresponding slope parameter is supposed to be a positive function of the covariates value. A challenging issue is also to consider models in which covariates affect maintenance efficiency.

Task 2 - Inference - The statistical inference of imperfect maintenance models has been principally studied for recurrent event models and when only corrective maintenances are considered. Different parameter estimation methods have been introduced: parametric[5], non-parametric or semi-parametric [2] with frequentist or Bayesian [3] approach. Things appears to be not so simple especially in semi-parametric context [1] or when considering time varying covariates.

The second axe of the PhD will be to develop inference methods in order to estimate the model parameters from degradation data bases. Frequentist parametric inference is classically the most natural choice, however in degradation context authors often use Bayesian methods and in particular MCMC algorithms in order to deal with random effects. Nonparametric methods can also be considered. Model parameters estimation enables to forecast for example the remaining useful life of the systems while evaluating also the associated uncertainty. In most of the research articles, authors consider that the different dependent degradation indicators are simultaneously measured. But, for example, the different clogging indicators of steam generators are not measured simultaneously and this is often the case in practical applications. The fact that the different degradation paths are not observed simultaneously induces difficulties for the estimation and specific algorithms have to be developed. To go further an important practical problematic is how a very informative degradation indicator can be forecast from another less informative indicator. For example, failures can be consequences of reaching a predetermined level for a degradation indicator that can never or rarely be measured. But another correlated, but less informative, indicator can be measured sufficiently frequently. The question is then how those measures and the observed failure times can be used to estimate the model parameters and the remaining useful life of the system. Similar problematic has been treated in [11], but authors never considered the problematic of estimating maintenance effects in this context.

In addition to the development of the estimation procedures themselves, the issue of missing or "partial" information and the assessment of the quality of estimation will also be considered.

Task 3 - Decision-Making - For critical systems, the costs associated with deterioration and failure represent very often a high proportion of the overall ownership and operating costs. Maintenance has long been seen has the only way of acting on a system in order to control its deterioration state and mitigate failures consequences,[4]. But, in fact, the deterioration state of a system can be controlled

in many more ways: if a system deteriorates too fast (and faster than expected), it can be possible to schedule dynamically an early predictive maintenance action, but also to modify the way the system is operated in order to modify and slow down its deterioration behavior, or even to determine the optimal combination between a dynamically adapted maintenance schedule and dynamically adapted operating conditions and use of the system. Additionally, the monitoring procedure can also be established in order to optimize the performance of the inference step when identifying the deterioration/lifetime model and the quality of the diagnosis/prognosis step. In this project, we propose to tackle the issue of the control of deterioration from this broader perspective of post-prognosis decision-making: based on the information on the remaining useful life of a system elaborated using deterioration and lifetime models, and the monitoring information, the problem to be solved is to jointly determine the best program for both the operation of the system and its maintenance.

The third axe of PhD will then be devoted to the use of the results of the previous two steps for decision making. The scheduled times for maintenance and degradation measurements can in general be chosen by the system operator. Optimal strategies have then to be developed in order to optimize those times of maintenance and monitoring measurement, with respect to cost criteria for example. Another related problem is to choose which degradation indicator or group of indicators has to be measured with respect to measurement cost and the quantity of information provided by each indicator. In some situations, operators can have an action on some of the covariate values, typically those related to the operating condition or usage of the system. For example, more severe operating conditions, represented by a covariate, can increase the profitability of the equipment but also increase its degradation rate. The problem is then to control the operating condition so as to optimize the system usage for a trade-off between profitability and lifetime.

Expected scientific contributions and expected outcomes of the PhD research work   Each of the three above-described tasks will output its own contribution in terms of new models, inference methods or innovative maintenance decision-making or RUL control structures. We expect that these methodological contributions will lead to the publication of paper in journals in the field of reliability and maintenance (Reliability Engineering and System Safety, IEEE Trans.on Reliability, ...) and communications to scientific conferences in the field.

Besides these methodological contributions, the outputs of the project will also lead to software developments, in the VAM software (developed as a R package VAM (https://rpackages.dyndoc.fr/VAM) by L. Doyen and R. Drouilhet)

3   Application

Please send a CV, a motivation letter, academic transcripts and references to Laurent Doyen (laurent.doyen-at-univ-grenoble-alpes.fr) and Christophe Bérenguer (christophe.berenguer-at-grenoble-inp.fr)
Want to know more about Grenoble and Univ. Grenoble Alpes ? https://www.univ-grenoble-alpes.fr/english/

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