SSM
Scuola Superiore Meridionale

MERC PhD Project Proposal 2023/2024

Title of the research project:

Predictive maintenance models for degrading units in the presence of multiple sources of variability and covariates.

Keywords (up to five)

Stochastic modelling, reliability, remaining useful life, condition-based maintenance.

Supervisors (at least two from two different areas):

Supervisor 1 (name, contact details, homepage, area of expertise)
Massimiliano Giorgio, University of Naples Federico II, Italy, massimiliano.giorgio@unina.it, (Industrial statistics, stochastic modelling, reliability)

Supervisor 2 (name, contact details, homepage, area of expertise)
Inma Torres Castro, University of Extremadura (Spain) *(Reliability engineering and decision making)*

Project description (max 5000 characters)

In recent years, the idea of using degradation and failure data collected (for example sensor data) to implement decision-making strategies that could allow to optimize the overall performance of complex systems is gaining an increased interest. An objective of these models is the formulation of predictive maintenance strategies. Several challenges are still existing for the improvement and the use of such solutions.
One of the tasks of maintenance optimization is the analysis and exploitation of the data or measurements collected by monitoring the state of the system and/or its environment. Here the challenges consist in analyzing large amount of heterogeneous data, performing early diagnosis about the state of health of the system, predicting its future evolution, and integrating all these pieces of information into a complex decision-making procedure.
The purpose of this research project is to develop new prognostic tools that can be used to perform more effective and better informed maintenance decisions.

State of the art
Most of research on maintenance modelling is based on classical lifetime models. These models are usually estimated directly from failure time data. In fact, the standard statistical approach to lifetime distribution modelling consists in selecting a parametric model among a limited list of candidates and determining its unknown parameters. The candidates are usually prepacked black-box models. Model selection is made by means of goodness of fit tests and/or some considerations concerning the ability of the model to capture the aging characteristic of the system under study. Unknown parameters are determined adopting ad hoc estimation procedures. Both these tasks are usually performed on the basis of failure data only. This approach is not always fruitful or, at least, it is not always effective. The main reasons for this inadequateness are the scarcity of failure data and the fact that this approach doesn't allow to directly use other kind information and experimental data that are often available in the applications. In addition, depending on the context,

the needed reliability model may be requested to have specific peculiarities, which standard black box models don't possess. Actually, in all these cases, it may be convenient to adopt modelling solutions which can capitalize on all the other available pieces of information.
In fact, to overcome the limitations of classical approach the recent literature on maintenance optimization is exploring alternative approaches. Part of this literature proposes methods inspired by artificial intelligence, such as machine learning or deep learning. These methods, by taking advantage of the possibility extracting information from large amount of data, allow for very good diagnosis of the state of the degrading systems, being especially suited for the identification of "weak signals". On the other side, these methods show a limited predictive ability, a feature that undermines their usefulness in maintenance optimization. Indeed, the effectiveness of a predictive maintenance policy mainly depends on the predictive/prognostic ability of the mathematical model adopted to plan the maintenance tasks. Another part of the literature focuses on the use of stochastic processes that could guarantee adequate predictive performances. The challenge in this case is being able to properly use all the available data and pieces of information. The proposed research activity will manly focus on these latter aspects.

Experimental framework and motivation
Many technological units are subjected, during their operating life, to a gradual degradation process that, in the long run, causes an inevitable situation of failure, which is (conventionally) assumed to occur when their degradation level passes a given critical threshold. Often these units are very costly and their operational failures produce relevant losses. Thus, to prevent failures, they are usually subjected to condition monitoring and condition-based preventive replacement. As a rule, the earlier is the preventive replacement the lower is the risk of failure. Nevertheless, any preventive replacement has a cost that is directly proportional to the residual life of the replaced unit (i.e., to the amount of operational life lost due to the preventive replacement). The crucial issue in this kind of practices is to identify the replacement time that provides the optimal tradeoff between preventive and corrective maintenance costs. The working principle is to delay the replacement until the risk of failure becomes intolerable. Actually, this task can be more challenging than expected. In fact, in many practical settings the continuous monitoring of degradation is not feasible. Thus, the state of the unit is checked only via periodic inspections. Moreover, the preventive replacement of the unit often requires special equipment and/or special skills. Thus (for example), the replacements can be performed only at specific epochs. This situation creates the need for models that are able to provide accurate predictions of the remaining useful life of the unit of interest, given the information available on its status. Concomitantly, while preventive maintenance (preventing failures) precludes the collection of failure data necessary to estimate the classical lifetime models, condition monitoring allows collecting a great number of degradation data, and maintenance activities provide a valuable insight into the failure causing mechanism.
All these circumstances make the idea of facing the discussed problem by using stochastic models able describe the evolution of degradation over time particularly appealing and convenient.
In fact, this approach permits, at the same time:

- *to formulate models that can incorporate the technological information available on the degradation/failure causing mechanism (which that can be converted in specific features of the stochastic models)*
- *to use historical degradation data to perform estimation procedures and evaluate the fitting ability of the model, and*
- *to use the degradation data collected in real time, via condition monitoring, to implement the requested (condition-based) maintenance strategy.*

Objectives and methodologies

The main objective of project is to formulate maintenance models that can be incorporated into the global project of developing a maintenance-oriented digital twins for a complex system.

The new models should be able to capitalize on all the available pieces of information and should have a simple mathematical structure.

In order achieving this task, we will adopt the following three-step procedure:

- *modelling the stochastic degradation process of the system under study;*
- *obtaining its reliability function as the distribution of the time at which the measured variables passes the failure threshold for the first time (i.e., by solving the first passage time problem);*
- *formulating the maintenance policy by taking advantage of the degradation based reliability model, that allows to treat in an explicit way the dependence of the remaining useful life on the status of the units (key issue in the addressed applications).*

The maintenance models should allow the use of all the available pieces of information and should be able to account in explicit way for all the existing sources of uncertainty as well as on their effect on the degradation process and on the related maintenance model.

Actually, uncertainty on the estimation and prediction of the health state of a degrading unit can be caused by several sources. Some can be endogenous (for example, undetected differences among the units) other can be exogenous (e.g., randomness of environment, which induces difference between degradation paths of identical units). Other sources of uncertainty are the presence of measurement error and/or the fact that monitoring system itself can be subjected to a degradation process.

The attention will be thus devoted to degradation and (related) maintenance models that can (explicitly) account for the presence of all these kind of uncertainties, in order to evaluate their effect on the condition based decision strategy.

It is worth to note that the of presence random effect, randomness in the operational environment, and/or measurement errors (and/or noise) leads to the loss of some mathematically convenient properties (e.g., independence of increments, stationarity of increments, Markovianity) of stochastic models that can be used to analyze the data. This situation exacerbates both modelling, inferential, and computational issues that are (already) usually encountered in this kind of applications. For example, the presence of measurements error prevents from observing the true state of the system. In this experimental situation, both inferential procedures and condition-based prediction of the future state of the system become more challenging. Hidden Markov Theory, Sequential Monte Carlo Methods, Expectation Maximization algorithms are among the theoretical tools that allow to tackle these issues. Obviously, the maintenance model and the inspection strategy are impacted by the presence of these issues. Hence, decision framework and maintenance decision rules should be revised accordingly.

Relevance to the MERC PhD Program (max 2000 characters)

Predictive maintenance is nowadays a major concern for optimizing and controlling complex systems. It is one of the main topics that is promoted in the context of industry digitalization and the advent of the Industry 5.0. This is reflected today in a real commitment between industries and academic researchers. Indeed, the fact that manufacturers are aware of the data's exploitation potential and in particular their interest in a maintenance framework – that has for too long been the poor relation in the search for industrial performance – has led them to look at the results and models produced in an academic context and, conversely, for researchers to draw inspiration from complex industrial real-case problems.

The project is relevant to the MERC PhD program in all its part, concerning the assessment and the mitigation of the risk of failure of complex technological systems by means of stochastic models that allow to estimate and predict the evolution of phenomena whose dynamic cannot be captured by deterministic models. The project also requests an interdisciplinary approach. Indeed, although their research interests are similar, the partners involved in the project have a quite different scientific background.

Key references

Key references

- Zhao X., Fouladirad M., Bérenguer C., Bordes L. (2010). Condition-based inspection/replacement policies for non-monotone deteriorating systems with environmental covariates. Reliability Engineering & System Safety, 95(8), 921-934.
- Mercier S., Castro I.T., (2013). On the modelling of imperfect repairs for a continuously monitored gamma wear process through reduction, Journal of Applied Probability, 50(4):22.
- Castro I.T. (2013), An age-based maintenance strategy for systems subject to multiple internal defects and external shocks, Asia Pacific Journal of Operational Research, 30(05), 1350016.
- Huynh, K.T., Castro, I.T., Barros, A., Bérenguer, C., (2014). On the use of mean residual life as a condition index for condition-based maintenance decision making, IEEE Transactions on Systems, Man and Cybernetics-Part A Systems and Humans, 44(7), 877-893.
- Castro I.T., Caballé N.C., Pérez C.J., (2015). A condition-based maintenance for a system subject to multiple degradation processes and external shocks, International Journal of Systems Science, 46(9), 1692-1704.
- Caballé N., Castro, I.T., Pérez, C., Lanza, J.M., (2015). A condition-based maintenance for a dependent degradation-threshold-shock model in a system with multiple degradation processes, Reliability Engineering and System Safety, 134, 98-109
- Cha, J. H., Sangüesa, C., Castro, I. T., (2016). Maintenance policy for a system with stochastically dependent failure modes with shock-accumulation effect. IEEE Transactions on Reliability, 65(3), 1284-1297.
- Castro, I. T., Mercier, S., (2016). Performance measures for a deteriorating system subject to imperfect maintenance and delayed repairs. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 230(4), 364-377.
- Alaswad S. and Xiang Y. (2016). A review on condition-based maintenance optimization modelsfor stochastically deteriorating system, in Reliability Engineering and System Safety, vol. 157, pp. 54-63.
- Zhu W., Fouladirad M., Bérenguer C. (2016). A multi-level maintenance policy for a multi-component and multifailure mode system with two independent failure modes. Reliability Engineering & System Safety, 153, 50-63.
- Caballé, N. C., Castro, I. T., (2017). Analysis of the reliability and the maintenance cost for finite life cycle systems subject to degradation and shocks Applied Mathematical Modelling, 52, 731-746.
- Giorgio M., Pulcini G. (2018). A new state-dependent degradation process and related model misidentification problems, in European Journal of Operational Research, 267, 1027-1038.
- Mercier, S., Castro, I. T., (2019). Stochastic comparisons of imperfect maintenance models for a gamma deteriorating system. European Journal of Operational Research, 273(1), 237-248.
- Castro, I. T., Landesa, L., (2019). A dependent complex degrading system with non-periodic inspection times. Computers & Industrial Engineering, 133, 241-252.

- Giorgio M., Mele A., Pulcini G. (2019). A perturbed gamma degradation process with degradation dependent non-Gaussian measurement errors, in Applied Stochastic Models in Business and Industry, 35(2), 198- 210.
- Castro, I. T., Basten, R. J., Van Houtum, G. J., (2020). Maintenance cost evaluation for heterogeneous complex systems under continuous monitoring. Reliability Engineering & System Safety, 200, 106745.
- Wu, S., Castro, I. T., (2020). Maintenance policy for a system with a weighted linear combination of degradation processes. European Journal of Operational Research, 280(1), 124-133.
- Esposito N., Mele A., Castanier B. and Giorgio M. (2021), Misspecification analysis of a gamma-with an inverse Gaussian-based perturbed degradation model by using a new expectation-maximization particle filter algorithm, In Proc. of the 31th European Safety and Reliability Conference, 19-23 September 2021, Angers, France.
- Bautista, L., Castro, I. T., Landesa, L., (2022). Maintenance cost assessment for heterogeneous multi-component systems incorporating perfect inspections and waiting time to maintenance. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 236(5), 797-815.
- Bautista, L., Castro, I. T., Landesa, L. (2022). Condition-based maintenance for a system subject to multiple degradation processes with stochastic arrival intensity. European Journal of Operational Research, 302(2), 560-574.
- Esposito N., Castanier B., Giorgio M. (2022), An Adaptive Hybrid Maintenance Policy for a Gamma Deteriorating Unit in The Presence of Random Effect, In Proc. of the 32nd European Safety and Reliability Conference (ESREL 2022), 28th August – 1st September 2022, Dublin, Ireland.
- Esposito N, Mele A., Castanier B. Giorgio M. (2022), A new gamma degradation process with random effect and state-dependent measurement error, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability,
- Ahmadi, R., Castro, I. T., Bautista, L. (2023). Reliability modeling and maintenance planning for a parallel system with respect to the state-dependent mean residual time. Journal of the Operational Research Society, 1-17.
- Fouladirad M, Giorgio M., Pulcini G., A (2023), Transformed Gamma Process for Bounded Degradation Phenomena, Quality and Reliability Engineering International, 39(2), pp. 546-564.
- Giorgio M., Piscopo A., and Pulcini G., A new Wiener process with bathtub-shaped degradation rate in the presence of random effects, Applied Stochastic Models in Business and Industry, 2023 (Early view), pp 1-24, Print ISSN: 1524-1904. https://doi.org/10.1002/asmb.2749
- Esposito N, Mele A., Castanier B. and Giorgio M., (2023), A new gamma degradation process with random effect and state-dependent measurement error, Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 237(5), 2023, pp. 868-885.
- Esposito N, Mele A., Castanier B. and Giorgio M., (2023), A hybrid maintenance policy for a deteriorating unit in the presence of three forms of variability, Reliability Engineering and System Safety, (237, 109320. pp 1-15.
- Giorgio M., Pulcini G., (2024), The effect of model misspecification of the bounded transformed gamma process on maintenance optimization, Reliability Engineering & System Safety, 241, 109569, pp. 1-18

Joint supervision arrangements

The PhD student will be co-supervised by Prof. Giorgio and Castanier. The student will spend about half-time in each institution. Monthly progress meetings will be done through reports and weekly meetings will be done in telematic mode.

Location and length of the study period abroad (min 12 months)

The PhD student will spend 12 months at Extremadura (Spain)

Any other useful information

If needed, we can try involve in the project other academic partners and/or an industrial partner