

ENBIS Spring Meeting 2022



Report of Contributions

Contribution ID: 1

Type: **not specified**

On the time dependent δ -shock model

One of the most popular ways to model an impact of a random environment on system's performance characteristics is via the external shocks that either cause certain damages or immediately result in failures. There is vast literature on this topic with respect to the relevant theoretical properties of the corresponding lifetime models as well as to the various practical applications. One of the widely discussed in the literature and relevant in practice shock models is the δ -shock model that is described by the constant time of a system's recovery after a shock. However, in practice, as time progresses and due to the deterioration of a system, this recovery time is gradually increasing. This important phenomenon was not discussed in the literature so far. Therefore, in this study, we are considering a time-dependent δ -shock model, i.e., the recovery time becomes an increasing function of time. Furthermore, in all studies, it is also assumed that shocks occur according to the HPP or NHPP processes, which is a rather stringent assumption in applications. This is because these stochastic processes are characterized by independent increments, whereas in reality, it is often not the case. Therefore, this assumption is made just for simplicity and mathematical tractability, which can result in substantial errors in assessing the impact of shocks on systems. To remove this limitation, we assume that shocks occur according to the generalized Polya process that contains the homogeneous Poisson process, the non-homogeneous Poisson process and the Polya process as particular cases. For the defined survival model, we derive the corresponding survival function and the mean lifetime and study the related optimal replacement policy along with some relevant stochastic properties.

Primary author: GOYAL, Dheeraj (Indian Institute of Technology Jodhpur)

Presenter: GOYAL, Dheeraj (Indian Institute of Technology Jodhpur)

Session Classification: Withdrawn papers

Contribution ID: 2

Type: **not specified**

Ordering and ageing properties of sequential order statistics governed by the Archimedean copula

In reliability theory, k -out-of- n systems play an important role as these are the basic structures of many technical systems used in real-life. While modeling these systems, we most often assumed that the failure of one component does not have any impact on the performance of the remaining surviving components. This indeed oversimplifies the modelling of such systems. Sequential order statistics are very useful tools for describing the lifetimes of components in a system in which the failure of one component may have severe consequences on the performance of the remaining surviving components. On the other hand, the lifetimes of components in a system are generally assumed to be independent. Being the complex nature of real-life systems, this assumption is not true in most of the scenarios. Copula is a frequently used technique to describe the dependency structure between components of a system. The family of Archimedean copulas is the most popular one among all existing copulas because it captures a wide range of dependency structures. In this study, we consider coherent systems with lifetimes represented by sequential order statistics where the dependence structure is described by the archimedean copula. To be more specifically, we consider the signature representation of a coherent system which is indeed a mixture representation. Using this, we study some stochastic comparisons results for coherent systems (formed by dependent components) with lifetimes described by sequential order statistics. In the process of development of these results, we also derive some ordering properties of sequential order statistics which may be useful in representing the lifetimes of k -out-of- n systems. In addition to this, some ageing properties (namely, ILR, IFR, IFRA, and NBU) of sequential order statistics have also been investigated.

Primary author: SAHOO, Tanmay (Indian Institute of Technology Jodhpur)

Presenter: SAHOO, Tanmay (Indian Institute of Technology Jodhpur)

Session Classification: Withdrawn papers

Contribution ID: 5

Type: **not specified**

Statistical inference for a Wiener-based degradation model with imperfect maintenance actions under different observation schemes

Friday, 20 May 2022 10:50 (20 minutes)

In this article, technological or industrial equipment that are subject to degradation are considered. These units undergo maintenance actions, which reduce their degradation level.

The paper considers a degradation model with imperfect maintenance effect. The underlying degradation process is a Wiener process with drift. The maintenance effects are described with an Arithmetic Reduction of Degradation (ARD_1) model. The system is regularly inspected and the degradation levels are measured.

Four different observation schemes are considered so that degradation levels can be observed between maintenance actions as well as just before or just after maintenance times. In each scheme, observations of the degradation level between successive maintenance actions are made. In the first observation scheme, degradation levels just before and just after each maintenance action are observed. In the second scheme, degradation levels just after each maintenance action are not observed but are observed just before. On the contrary, in the third scheme, degradation levels just before the maintenance actions are not observed but are observed just after. Finally, in the fourth observation scheme, the degradation levels are not observed neither just before nor just after the maintenance actions.

The paper studies the estimation of the model parameters under these different observation schemes. The maximum likelihood estimators are derived for each scheme.

Several situations are studied in order to assess the impact of different features on the estimation quality.

Among them, the number of observations between successive maintenance actions, the number of maintenance actions, the maintenance efficiency parameter and the location of the observations are considered. These situations are used to assess the estimation quality and compare the observation schemes through an extensive simulation and performance study.

Primary authors: LEROY, Margaux (Univ. Grenoble Alpes); GAUDOIN, Olivier (Université Grenoble Alpes); Mr DOYEN, Laurent (Univ. Grenoble Alpes); BÉRENGUER, Christophe (Univ. Grenoble Alpes)

Presenter: LEROY, Margaux (Univ. Grenoble Alpes)

Session Classification: Statistical inference for degradation models

Contribution ID: 6

Type: **not specified**

Imperfect condition-based maintenance for a gamma degradation process in presence of unknown parameters

Friday, 20 May 2022 10:30 (20 minutes)

A system subject to degradation is considered. The degradation is modelled by a gamma process. A condition-based maintenance policy with perfect corrective and an imperfect preventive actions is proposed. The maintenance cost is derived considering a Markov-renewal process. The statistical inference of the degradation and maintenance parameters by the maximum likelihood method is proposed. A sensibility analysis to different parameters is carried out and the perspectives are detailed.

Primary authors: Dr PAROISSIN, Christian (Université Pau et Pays de l'Adour); CORSET, Franck (LJK - Université Grenoble Alpes); Prof. FOULADIRAD, Mitra (Centrale Marseille)

Presenter: CORSET, Franck (LJK - Université Grenoble Alpes)

Session Classification: Statistical inference for degradation models

Contribution ID: 7

Type: **not specified**

A goodness-of-fit test for homogeneous gamma process under a general sampling scheme

Friday, 20 May 2022 11:10 (20 minutes)

Degradation models are more and more studied and used in practice. Most of these models are based on Lévy processes. For such models, estimation methods have been proposed. These models are also considered for developing complex and efficient maintenance policies. However, a main issue remains: goodness-of-fit (GoF) test for these models. In this talk, we propose a GoF test for the homogeneous gamma process under a general sampling scheme.

Primary author: PAROISSIN, Christian (Université de Pau et des Pays de l'Adour)

Presenter: PAROISSIN, Christian (Université de Pau et des Pays de l'Adour)

Session Classification: Statistical inference for degradation models

Contribution ID: 8

Type: **not specified**

Stochastic Drift Model for Discrete Parameters

Thursday, 19 May 2022 10:50 (20 minutes)

In the context of semiconductor reliability, predictive maintenance and calculation of residual useful life are important topics under the greater umbrella of prognostics and health management. Especially in automotive applications, with higher expected usage times of self-driving autonomous vehicles, it becomes more and more important to recognize degradation processes early, so that preventive maintenance actions can be taken automatically. For semiconductor producers, it is important to account for life-time degradation of electronic devices when guaranteeing quality standards for their customer.

For this, accurate and fast statistical models are needed to identify degradation by parameter drift. Typically, electrical parameters have specified limits in which they need to stay over their whole life cycle.

Efficient life-time simulations are performed by so-called accelerated stress tests. In those tests, electrical parameters are measured before, during, and after higher-than usual stress conditions. These stress test data represent the expected life-time behavior of these parameters.

Using models based on these data, tighter limits, so called test limits, are then introduced at production testing to guarantee life-time quality of the devices for the customer.

Based on this data, quality control measures like guard bands are introduced. Guard bands are the differences between specification and test limits and account, amongst others, for lifetime drift effects of electrical parameters.

Models to calculate lifetime drift have to be flexible enough to accurately represent a large number of stress test behaviors while being computationally light-weight enough to run on edge devices in the vehicles.

We present a statistical model for discrete parameters based on nonparametric interval estimation of conditional transition probabilities in Markov chains that allows for flexible modelling and fast computation. We then show how to use the model to formulate an integer optimization problem to calculate optimal test limits. Calculation for both arbitrary parameter distributions at production testing as well as defined initial distributions are shown. Finally, we give an approach to calculate remaining useful lifetime for electronic components.

The work has been performed in the project ArchitectECA2030 under grant agreement No 877539. The project is co-funded by grants from Germany, Netherlands, Czech Republic, Austria, Norway and - Electronic Component Systems for European Leadership Joint Undertaking (ECSEL JU).

All ArchitectECA2030 related communication reflects only the author's view and ECSEL JU and the Commission are not responsible for any use that may be made of the information it contains.

Primary authors: SOMMEREGGER, Lukas (Infineon Technologies Austria AG); Dr LEWITSCHNIG, Horst (Infineon Technologies Austria AG)

Presenters: SOMMEREGGER, Lukas (Infineon Technologies Austria AG); Dr LEWITSCHNIG, Horst (Infineon Technologies Austria AG)

Session Classification: Degradation models

Contribution ID: 9

Type: **not specified**

Phase-type models for competing risks

Friday, 20 May 2022 14:20 (20 minutes)

A phase-type distribution can be defined to be the distribution of time to absorption for an absorbing finite state Markov chain in continuous time. Phase-type distributions have received much attention in applied probability, in particular in queueing theory, generalizing the Erlang distribution. Among other applications, they have for a long time been used in reliability and survival analysis. Particular interest has been in the use of so-called Coxian phase-type models. Their usefulness stems from the fact that they are able to model phenomena where an object goes through stages (phases) in a specified order, and may transit to the absorbing state (corresponding to the event of interest) from any phase. It is noteworthy that Coxian phase-type models have recently, in a number of papers, been successfully applied to model hospital length of stay in health care studies. These authors typically claim the superiority of Coxian phase-type models over common parametric models like gamma and lognormal for this kind of data. Similar models are apparently appropriate for reliability modeling of complex degrading systems.

The main purpose of the present talk is to study how the phase-type methodology can be modified to include competing risks, thereby enabling the modeling of failure distributions with several failure modes, or, more generally, event histories with several types of events. One then considers a finite state Markov chain with more than one absorbing state, each of which corresponds to a particular risk. Standard functions from the theory of competing risks can now be given in terms of the transition matrix of the underlying Markov chain. We will be particularly concerned with the uniqueness of parameterizations of phase-type models for competing risks, which is of particular interest in statistical inference. We will briefly consider maximum likelihood estimation in Coxian competing risks models, using the EM algorithm. A real data example will be analyzed for illustration.

Primary author: LINDQVIST, Bo Henry (Norwegian University of Science and Technology)

Presenter: LINDQVIST, Bo Henry (Norwegian University of Science and Technology)

Session Classification: Reliability models

Contribution ID: 10

Type: **not specified**

On the modelling of dependence between univariate Lévy wear processes and impact on the reliability function

Thursday, 19 May 2022 10:30 (20 minutes)

Univariate Lévy processes have become quite common in the reliability literature for modelling accumulative deterioration. In case of correlated deterioration indicators, several possibilities have been suggested for modelling their dependence. The point of this study is the analysis and comparison of three different dependence models considered in the most recent literature: 1. Use of a regular copula, where the dependence in a multivariate increment is modelled through a time-independent regular copula; 2. Superposition of independent univariate Lévy processes, where each marginal process is constructed as the sum of independent univariate Lévy processes $\{X_j(t), t \geq 0\}$ with possibly common $\{X_j(t), t \geq 0\}$ between margins; 3. Use of a Lévy copula. The three methods are first presented and analysed. As for the model based on a regular copula, it is shown that the corresponding multivariate process cannot have independent increments in general, so that it is not a Lévy process. This means that the distribution of the multivariate process is not fully characterized in this way. The second and third models both lead to a multivariate Lévy process, with a limited dependence range for the second superposition-based model, which is not the case for the third Lévy copula-based model. However, this last model requires a higher technicity for its use and numerical methods (such as Monte-Carlo simulations) have to be used for its numerical assessment. Practical details are given in the paper and two Monte-Carlo simulation procedures are compared.

A two-component series system is next considered, with joint deterioration level modelled by one of the three previous models. Each component is considered as failed as soon as its deterioration level is beyond a given failure threshold. The impact of a wrong choice for the model is explored, based on data simulated from one of the three models and next adjusted to all three models. It is shown that a wrong choice for the model can lead to either surestimate or underestimate the reliability function of the two-component series system, which could be problematic in an applicative context.

Primary authors: MERCIER, Sophie (University of Pau and Pays de l'Adour); VERDIER, Ghislain (University of Pau and Pays de l'Adour)

Presenter: MERCIER, Sophie (University of Pau and Pays de l'Adour)

Session Classification: Degradation models

Contribution ID: 11

Type: **not specified**

Data-driven Maintenance Optimization Using Random Forest Algorithms

Thursday, 19 May 2022 14:40 (20 minutes)

In this paper, a multi-component series system is considered which is periodically inspected and at inspection times the failed components are replaced by a new one. Therefore, this maintenance action is perfect corrective maintenance for the failed component, and it can be considered as imperfect corrective maintenance for the system. The inspection interval is considered as a decision parameter and the maintenance policy is optimized using long-run cost rate function. It is assumed that there is no information related to components' lifetime distributions and their parameters. Therefore, an optimal decision parameter is derived considering historical data (a data storage for the system that includes information related to past repairs) using density estimation and random forest algorithms. Eventually, the efficiency of the proposed optimal decision parameter according to available data is compared to the one derived when all information on the system is available.

keywords: Maintenance Optimization, Data-driven Estimation, Random Forest Algorithm.

Primary authors: MISAIL, HASAN (University of TEHRAN and University of Technology of TROYES); FOULADIRAD, MITRA (Aix Marseille Université et Université de Technologie de Troyes); HAGHIGHI, Firoozeh (University of Tehran)

Presenter: MISAIL, HASAN (University of TEHRAN and University of Technology of TROYES)

Session Classification: Maintenance optimization

Contribution ID: 12

Type: **not specified**

Combining AI with Model based Design: battery State-of-charge estimator using Deep Learning

Friday, 20 May 2022 15:00 (20 minutes)

Across industries, the growing dependence on battery pack energy storage has underscored the importance of battery management systems (BMS) whose role is to monitor battery state, ensure safe operation and maximize performance. For example, the BMS helps avoid overcharging and over discharging, it manages the temperature of the battery and so on, and it does so by collecting information from sensors on the battery for current, voltage, temperature etc. So, this is a closed-loop system by design.

One of the things that cannot be directly measured but is required for many of these operations is the battery state of charge (SOC). So, this quantity needs to be estimated somehow. One way to solve this problem is using recursive estimation based on a Kalman filter. However, the Kalman filter requires a dynamical model of the battery –which may or may not be accurate –and is very time-consuming. Besides, handling just the algorithm is not enough. Models need to be incorporated into an entire system design workflow to deliver a product or a service to the market. The bridge between engineering and science workflows is one of the most important pieces of such an application. Combining Model-Based-Design with Artificial Intelligence will enrich the model and make collaboration between teams robust and more automated.

We will explore, in detail, the workflow involved in developing, testing, and deploying an AI-based state-of-charge estimator for batteries using Model-Based Design:

- Designing and training deep learning models
- Demonstrate a workflow for how you can research, develop, and deploy your own deep learning application with Model-Based Design
- Integrating deep learning and machine learning models into Simulink for system-level simulation
- Generate optimized C code and Performed Processor-in-the-loop (PIL) test

Primary authors: Dr GADO, Moubarak (MathWorks); HAROUIMI, PIERRE

Presenter: Dr GADO, Moubarak (MathWorks)

Session Classification: Reliability models

Contribution ID: 13

Type: **not specified**

Fuel cell stochastic deterioration modeling for energy management in a multi-stack system

Thursday, 19 May 2022 11:10 (20 minutes)

Fuel cells use hydrogen and oxygen as reactants to produce electricity through electrochemical reactions with the only byproduct of water. They are widely used in various applications, e.g. transport, due to their high efficiency, energy density, and limited impact on environmental resources, however fuel cells deployment is held down by multiple barriers such as their high cost or their shorter than required lifetime. To cross over these barriers, using multi-stack fuel cells (MFC) instead of a single one is a promising solution. Firstly, MFC offers improved reliability thanks to the multi-stack structure. Another advantage is that the durability of multi-stack FC can also be increased by optimally distributing the power demand among different stacks by an efficient Energy Management Strategy (EMS), and thus avoiding degraded mode operation [1]. In short, MFC systems are relevant to meet this challenge if properly dimensioned and managed by an appropriate EMS taking into account the deterioration of the cells. In order to implement such a degradation-aware EMS, it is mandatory to build a degradation model that integrates the dynamic behavior of MFC according to the operating conditions. Fuel cell performance degradation is linked to complex electrochemical, mechanical, and thermal mechanisms, which are difficult to model using a “white-box” approach, relying on the exact laws of physics. Within this context, the aim of the present work is to propose a fuel cell degradation model adapted for the energy management of MFC.

The deterioration behavior of an MFC is characterized by two main features : (i) it is load-dependent, i.e. the degradation is affected by the load distributed by the stack ; (ii) it is stochastic and exhibits a stack-to-stack variability. A degradation-aware energy management system allocates a load to deliver to the different stacks of the MFC system as a function of their degradation state and of their predicted degradation behavior. The deterioration dynamics must thus be modeled as a function of the load power. Another specificity of fuel cells is their individual deterioration variability, which can be due to stochasticity in the intrinsic fuel cell deterioration phenomena. This stochasticity varies the deterioration levels even for the identical stacks operating under identical load profiles.

In order to meet these modelling requirements, this work develops a load-dependent stochastic deterioration model for an MFC. First, the overall stack resistance is chosen as the degradation indicator, as it carries the key aging information of a fuel cell stack. Then, a stochastic non-homogeneous Gamma process is used to model the deterioration of the fuel cell, i.e. the increase in the fuel cell resistance. The shape parameter of the considered Gamma process is further modeled by an empirical function of the fuel cell operation load in order to make the resistance deterioration load-dependent. Finally, to model the individual deterioration heterogeneity, a random effect is added to the Gamma process on its scale parameter, taken as a random variable following a probability distribution (a Gamma law is chosen in this work).

Resistance degradation paths can then be simulated based on the proposed deterioration model, based on which the first hitting time distribution of a failure threshold (or equivalently a remaining useful life distribution) can be estimated and the reliability of the system can be analyzed. The proposed model can also be used to optimize the load allocation strategy for an MFC [2].

Keywords: Multi-stack fuel cells, load-dependent deterioration model, stochastic modelling, Gamma process, random effect.

References:

[1] Marx, Neigel, et al. “On the sizing and energy management of an hybrid multistack fuel cell–Battery system for automotive applications.” *International Journal of Hydrogen Energy* 42.2 (2017): 1518-1526.

[2] Zuo, J., C. Cadet, Z. Li, C. Bérenguer, and R. Outbib (2022). Post-prognostics decision-making strategy for load allocation on a stochastically deteriorating multi-stack fuel cell system. To appear in Proc. Inst. Mech. Eng - Part O: Journal of Risk and Reliability.

Primary authors: ZUO, Jian (Phd student); Prof. CADET, Catherine (Gipsa-lab); Prof. LI, zhongliang; BÉRENGUER, Christophe (Univ. Grenoble Alpes); Prof. OUTBIB, Rachid

Presenter: ZUO, Jian (Phd student)

Session Classification: Degradation models

Contribution ID: 14

Type: **not specified**

Change-level detection for Lévy subordinators

Thursday, 19 May 2022 11:30 (20 minutes)

Let

boldsymbol $X = (X_t)_{t \geq 0}$ be a process behaving as a general increasing Lévy process (subordinator) prior to hitting a given unknown level m_0 , then behaving as another different subordinator once this threshold is crossed. We address the detection of this unknown threshold $m_0 \in [0, +\infty]$ from an observed trajectory of the process. These kind of model and issue are encountered in many areas such as reliability and quality control in degradation problems. More precisely, we construct, from a sample path and for each $\epsilon > 0$, a so-called detection level L_ϵ by considering a CUSUM inspired procedure. Under mild assumptions, this level is such that, while m_0 is infinite (i.e. when no changes occur), its expectation $\mathbb{E}_\infty(L_\epsilon)$ tends to $+\infty$ as ϵ tends to 0, and the expected overshoot $\mathbb{E}_{m_0}([L_\epsilon - m_0]^+)$, while the threshold m_0 is finite, is negligible compared to $\mathbb{E}_\infty(L_\epsilon)$ as ϵ tends to 0. Numerical illustrations are provided when the Lévy processes are gamma processes with different shape parameters. This is joint work with Z. Al Masry and G. Verdier.

Primary author: RABEHASAINA, Landy (Laboratoire de Mathématiques, Université Franche Comté)

Co-authors: Mrs AL MASRY, Zeina (FEMTO ST, Université de Franche Comté); Mr VERDIER, Ghislain (LMAP, Université de Pau et des pays de l'Adour)

Presenter: RABEHASAINA, Landy (Laboratoire de Mathématiques, Université Franche Comté)

Session Classification: Degradation models

Contribution ID: 15

Type: **not specified**

Reliability degradation and optimal maintenance for information equipment installed on railway cars

Thursday, 19 May 2022 15:00 (20 minutes)

A Reliability degradation model was developed in a project, which involved LCD TV screens installed on railway. One critical item in the project was an LED strip.

Accelerated Life tests data are the data source for the determination of LED Reliability. The expected life of LEDs being about 10-15 years - testing them until death is not practical.

Luminosity (vs time measurements provided by the manufacturer –were fitted to a degradation model. As opposed to [1] and [2], where an exponential degradation model for the average luminosity was applied our degradation model assumed degradation equations, based on the second law of thermodynamics developed by A. Einstein (1905), Fokker (1919), Planck (1930) and Kolmogorov (1931). The main difference in the approaches is that the degradation function's Taylor expansion contains terms of the first and second derivative, while the models of [1] and [2] contain only the first.

As opposed to [2] we did not fit the results to an assumed Reliability function (Weibull, Normal, Lognormal) and left it in a tabular form. The table allows to determine required reliability and maintenance information.

The following results are derived:

1. PDF of the failure rate as a function of time
 2. Reliability as a function of time and temperature (for simple and complex components)
 3. MTBF for a device used for limited and unlimited life.
- A model developed for maintenance costs and spare parts provisioning allows development Optimal Preventive Maintenance Policy :
1. Optimal preventive maintenance without individual monitoring.
 2. Optimal preventive maintenance based on Rest of Useful Life (with monitoring)

References

1. Ott ,Melanie “Capabilities and Reliability of LEDs and Laser Diodes” Internal NASA Parts and Packaging Publication (1996).
2. J.Fan K_C Yung,M.Pecht Lifetime Estimation of High-Power White LED Using Degradation-Data-Driven Method IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY, VOL. 12, NO. 2, JUNE 2012
3. Si, Xiao-Sheng, et al. “Remaining useful life estimation based on a nonlinear diffusion degradation process.” IEEE Transactions on reliability 61.1 (2012): 50-67
4. Livni, Haim. “Life cycle maintenance costs for a non-exponential component.” Applied Mathematical Modelling 103 (2022): .261-286

Primary author: Mr LIVNI, Haim (Oslo Reliability)

Presenter: Mr LIVNI, Haim (Oslo Reliability)

Session Classification: Maintenance optimization

Contribution ID: 16

Type: **not specified**

Statistical process control versus deep learning for predictive maintenance of power plant process data

Thursday, 19 May 2022 16:30 (20 minutes)

Abstract

This work is motivated by the non-documented, practical learnings gained by a predictive maintenance (PdM) development team in the Danish energy company Ørsted. The team implements PdM solutions for power plant machinery to monitor for faults in the making. Their learnings support the hypothesis that there are not significant enough benefits to be gained from using overly complicated condition monitoring models on selected machinery.

To explore this hypothesis, we set out to compare two different methodologies for detecting faults in process data. We compare a classical latent structure-based method from the field of statistical process control (SPC) with a standard autoencoder deep neural network. Furthermore, we compare the fault detection performance of these methods with two more experimental deep learning models recently proposed in literature [1]. The reason for these specific models is that they a priori seem very well suited for the modelling task the PdM team had undertaken due to the models' alleged ability to automate domain knowledge in a data-driven way.

We benchmark all methods against each other using first the well-known Tennessee Eastman Process (TEP) data, and subsequently data collected from two feedwater pumps (FWP) at a large Danish combined heat and power plant.

The TEP data stems from a simulation tool for generating data from the process, and thus a large number of datasets are generated for each of 20 process disturbances. For the FWP data, six historical faults in the form of leaks are used to test the methods against each other in their ability to detect faults as they develop over time. Each methods' ability to detect faults is measured using a weighted combination of performance metrics such as mean absolute error, ROC AUC and average precision AP.

Preliminary results of the experiments suggest that detection performance is comparable between the different models on both datasets, but that each model seems to come with its own set of advantages in terms of fault detection performance, as in the case of reaction time to certain types of faults.

Based on the mentioned datasets and models, we discuss the quantitative results of these experiments, as well as other pros and cons, such as number of modelling decisions, hyperparameters etc. of each paradigm that may influence the choice of detection model in an industrial setting.

References

1. Schulze, J.-P., Sperl, P., Böttinger, K. 2022, "Anomaly Detection by Recombining Gated Un-supervised Experts", arXiv preprint: <https://doi.org/10.48550/arXiv.2008.13763>

Primary author: Mr HANSEN, Henrik (DTU & Ørsted (Industrial PhD))

Co-authors: Prof. KULAHCI, Murat (DTU); Prof. FRIIS NIELSEN, Bo (Department of Applied Mathematics and Computer Science, Applied Technical University of Denmark)

Presenter: Mr HANSEN, Henrik (DTU & Ørsted (Industrial PhD))

Session Classification: Case studies

Contribution ID: 17

Type: **not specified**

A condition-based maintenance policy in a system with heterogeneities

Thursday, 19 May 2022 14:20 (20 minutes)

Models that describe the deterioration processes of the components are key to determining the lifetime of a system and play a fundamental role in predicting the system reliability and planning the system maintenance. In most systems there is heterogeneity among the degradation paths of the units. This variability is usually introduced in the model through random effects, that is, considering random coefficients on the model.

A degrading system subject to multiple degradation processes whose initiation times follow a shot-Cox noise process is studied. The growth of these processes is modeled by a homogeneous gamma process. A condition based maintenance policy with periodic inspections is applied to reduce the impact of failures and optimise the total expected maintenance cost. The heterogeneities between components are included in the model considering that the scale parameter of the gamma process follows a uniform distribution. Numerical examples of this maintenance policy are given comparing both models, with and without heterogeneities.

Primary authors: BAUTISTA, Lucia (Universidad de Extremadura); CASTRO, Inma T. (Universidad de Extremadura); LANDESA, Luis (Universidad de Extremadura)

Presenter: CASTRO, Inma T. (Universidad de Extremadura)

Session Classification: Maintenance optimization

Contribution ID: 18

Type: **not specified**

Development of an Operational Digital Twin of a Locomotive Systems

Thursday, 19 May 2022 15:50 (20 minutes)

A Digital Twin (DT) is a new and powerful concept that maps a physical structure operating in a specific context to the digital space. The development and deployment of a DT improves forecasting prognostic performance and decision support for operators and managers. , DT have been introduced in various industries across a range of application areas including design, manufacturing and maintenance. Due to the large impact of maintenance on the proper functioning of a system, maintenance is one of the most studied DT applications. In the case of trains, poor maintenance can put the rolling carts out of service or, worse, pose a safety risk to passengers and operators. Implementing intelligent maintenance strategies can therefore offer tremendous benefits. This study addresses the development of an architecture for DT designed to formulate and evaluate new hypotheses in predictive maintenance by iterating between physical experiments and computational experiments. The designed DT supports a broad perspective on statistical aspects of simulations and experiments. In addition, the DT enables real-time prediction and optimization of the actual behavior of a system at any stage of its life cycle. Examples of safety valves and suspension systems will be given.

Primary author: Mr DAVIDYAN, Gabriel (Israel railway)

Co-authors: Prof. BORTMAN, Jacob (PHM Laboratory, Department of Mechanical Engineering, Ben-Gurion University of the Negev); Prof. KENETT, Ron S. (KPA Ltd. and the Samuel Neaman Institute for National Policy Research, Technion City)

Presenter: Mr DAVIDYAN, Gabriel (Israel railway)

Session Classification: Case studies

Contribution ID: 19

Type: **not specified**

Degradation Model Selection Using Depth Functions

Friday, 20 May 2022 11:30 (20 minutes)

Degradation modeling is an effective way for the reliability analysis of complex systems. For highly reliable systems, in which their failure is hard to observe, degradation measurements often provide more information than failure time to improve system reliability (Meeker and Escobar 2014). The degradation can be viewed as damage to a system that accumulates over time and eventually leads to failure when the accumulation reaches a failure threshold, either random or stipulated by industrial standards (Ye and. Xie 2015). Two large classes of degradation models are stochastic processes and general path models. The stochastic-process-based models show great flexibility in describing the failure mechanisms caused by degradation (Lehmann 2009).

The aim of degradation modeling in presence of degradation data is to select a model from a set of competing models, capturing the features of the underlying degradation phenomenon. An efficient statistical tool is able to discard irrelevant models. The concept of statistical depth could be employed as a statistical tool for model selection. A depth function reflects the centrality of the observation to a statistical population (Staerman et al 2020).

Tukey (1975) introduced a data depth to extend the notion of a median to multi-variate random variables. Depth function have been extended by Frairman and Muniz (2001) and Cuevas et al. (2006, 2007) for functional data, the data which are recorded densely over time with one observed function per subject (Hall et al 2006). An alternative point of view based on the graphic representation of curves is proposed by Lopez-Pintado (2009).

In this paper, stochastic processes such as Lévy processes or stochastic differential equations are considered to model the degradation. After model calibration in presence of data, the models that show high values of depth function are compared and a methodology to exploit and analyze the depth function results is proposed.

Primary authors: Ms FOULADIRAD, Mitra (École Centrale Marseille, Marseille, France, Aix Marseille Université (Aix-en-Provence), Université de Technologie de Troyes); Ms ASADI, Arefe (University of technology of Troyes); Mr RODOLPHO TOMASI, Diego (Biofortis)

Presenter: Ms ASADI, Arefe (University of technology of Troyes)

Session Classification: Statistical inference for degradation models

Contribution ID: 20

Type: **not specified**

Quantile Regression via Accelerated Destructive Degradation Modeling for Reliability Estimation

Friday, 20 May 2022 10:10 (20 minutes)

Along with the shortening of production period, manufacturing industry utilizes an accelerated degradation test (ADT) to estimate the reliability of newly developed products as quickly as possible. In ADT, the stress factor which is related to the failure mechanisms is imposed to cause the failure of products faster than those under normal use condition. By increasing the degree of stress such as voltage, temperature, humidity or other external factors, the performance of new products continuously degrades and leads to the failure. In some applications, accelerated destructive degradation test (ADDT) is conducted when testing units should be destroyed to measure the performance of the degrading product.

For general ADT and ADDT models, the mean estimators have been considered as the location measurement. However, the estimation result using mean estimator can be inappropriate for highly skewed data, because the lifetime estimation of degradation data with outliers or irregularity can be distorted.

In this paper, the ADDT modeling based on quantile regression (QR) is suggested as a comprehensive approach for asymmetric observations. QR-based ADDT requires fewer assumptions than the general parametric methods to construct the model, and enables the interpretation to be more flexible. Through the data application, our approach provides a great advantage by inferring a nonlinear degradation path without bias and partiality.

Primary authors: Ms LIM, Munwon (Hanyang University); Prof. BAE, Suk Joo (Hanyang University)

Presenters: Ms LIM, Munwon (Hanyang University); Ms KIM, Gyu Ri (Department of Industrial Engineering, Hanyang University)

Session Classification: Statistical inference for degradation models

Contribution ID: 21

Type: **not specified**

Maintenance policies for items with their repair processes modelled by the extended Poisson processes

Thursday, 19 May 2022 14:00 (20 minutes)

Optimisation of maintenance policies for items with their repair processes modelled by the geometric process (GP) has received a good amount of attention. The extended Poisson process (EPP), one of the extensions of the GP, can be used to model the repair process with its times-between-failures possessing a non-monotonic trend. A central issue in the applications of the EPPs in maintenance policy optimisation is to find when the EPP has an increasing times-between-failures. This paper aims to answer this question. Numerical examples are provided to illustrate the proposed maintenance policies.

Primary authors: YIN, Jiaqi (University of Kent); Prof. WU, Shaomin (University of Kent)

Presenter: YIN, Jiaqi (University of Kent)

Session Classification: Maintenance optimization

Contribution ID: 22

Type: **not specified**

Battery degradation model for mission assignment in a fleet of electric vehicles

Thursday, 19 May 2022 16:50 (20 minutes)

Battery prognostics and health management has recently become a very important and strategic topic specially with the rise of electric vehicles and electric mobility in general, which is seen as a key tool to reduce the impact of global warming. In order for battery health management to be viable, it is necessary to quantify and understand battery state of health (SOH) and its degradation mechanisms. A lot of research has been developed to understand the different degradation processes in a battery [1], to identify and understand the impacts of stress factors [2], and to quantify tendencies of degradation and predict remaining useful life [3]. In this presentation, an overview on battery degradation modelling and prognostics is given, exploring the definitions of the main stress factors, and covering the most common degradation models in the literature. Particular attention is given to an empirical model based on stress cycle decomposition linking the degradation to the history of charge and discharge cycles, which is flexible and accurate [4]. This model can be used to estimate the SoH variation of the battery based on the way the vehicle is driven. A three-step method is thus proposed to develop a comprehensive model for degradation induced by driving conditions, combining the aforementioned degradation model, with battery and vehicle dynamics models, as well as information on road topography and vehicle parameters. The first step of this overall degradation model consists in using the available information topography, speed limits and crossroads to estimate the electrical power required to carry on a given displacement. In the second step, the required electrical power is used to infer a state of charge (SoC) trajectory. Finally, in the last step, the SoC profile is decomposed into stress cycles that serve as input for the degradation model. Such a comprehensive SOH evolution model linking route profiles and driving conditions to battery degradation is suitable for decision-making problems related to the optimal management of electric vehicles. The use of this degradation model is illustrated on a use-case of a fleet of electric vehicles that must perform a set of missions: it is shown how the order of those missions can be decided by optimizing not only energy consumption but also battery degradation.

[1] Anthony Barré, Benjamin Deguilhem, Sébastien Grolleau, Mathias Gérard, Frédéric Suard, Delphine Riu, A review on lithium-ion battery ageing mechanisms and estimations for automotive applications, *Journal of Power Sources*, Volume 241,

[2] Saxena, Saurabh, Darius Roman, Valentin Robu, David Flynn, and Michael Pecht. 2021. "Battery Stress Factor Ranking for Accelerated Degradation Test Planning Using Machine Learning" *Energies* 14, no. 3: 723.

[3] Jiaming Fan et al. "A novel machine learning method based approach for Li-ion battery prognostic and health management". In: *IEEE Access* 7 (2019), pp. 160043–160061, 2019, Pages 680-689,

[4] Xu, B., Oudalov, A., Ulbig, A., Andersson, G., and Kirschen, D.S. (2018). Modeling of lithium-ion battery degradation for cell life assessment. *IEEE Transactions on Smart Grid*, 9(2), 1131–1140. doi:10.1109/TSG.2016.2578950

Primary author: DIAS LONGHITANO, Pedro (Volvo Group)

Co-authors: Mrs TIDRIRI, Khaoula (Gipsa-lab); BÉRENGUER, Christophe (Univ. Grenoble Alpes); Mr ECHARD, Benjamin (Volvo Trucks)

Presenter: DIAS LONGHITANO, Pedro (Volvo Group)

Session Classification: Case studies

Contribution ID: 23

Type: **not specified**

A new approach to the mean residual lifetime (MRL) stochastic modeling of a parallel system

Through incorporating a bivariate state process, this paper explores an approach to the stochastic modeling of MRL for a failure-prone parallel system operating in a random environment. The bivariate state-dependent MRL (BSDMRL) model outperforms the ordinary MRL and other state-dependent MRL models in the actual circumstance that it incorporates not only the age factor, but also two basic processes: the number of failed components and the operating environment. Such mature model helps in two ways: (i) the correct evaluation of the system state; (ii) accurate decision-making by the use of the BSDMRL as a decision variable.

Primary author: Dr AHMADI, Reza (Iran University of Science and Technology)

Presenter: Dr AHMADI, Reza (Iran University of Science and Technology)

Session Classification: Withdrawn papers

Contribution ID: 24

Type: **not specified**

On the Number of Failed Components in a System and Its Application in Maintenance Models

In a failed system, the number of failed components at a particular time or at the time of system failure might be useful for understanding the stochastic behavior of the system. In this talk, we investigate the role of this quantity in scheduling optimal maintenance strategies for a multi-component system. The system has different types of independent components, and the components are assumed to be subject to both internal failures and fatal shocks. The system may fail due to the aging of its components, or it may fail due to fatal shocks arriving from external sources. We first study the probability of having a specific number of failed components of each type at the time of system failure. Then, under the above mechanism of system failure, we propose some optimal age-based and block preventive maintenance models. We provide some formulas for the average long-run cost rate of the proposed strategies. In addition, Monte Carlo simulations are carried out to evaluate the cost functions of the proposed maintenance models. Our derivations rely on the concept of survival signature.

Primary authors: Dr HASHEMI, Marzieh (University of Isfahan); Dr TAVANGAR, Mahdi (University of Isfahan)

Presenter: Dr HASHEMI, Marzieh (University of Isfahan)

Session Classification: Withdrawn papers

Contribution ID: 25

Type: **not specified**

Optimal Maintenance Models for Coherent Systems Sold with Warranty

In this talk, we will consider maintenance strategies for coherent systems consisting of n components. The system is under a warranty policy with two consecutive phases under which the manufacturer's commitment goes in two different forms. In Phase I, upon the system failure, the failed components are replaced with new ones and a corrective maintenance is performed on the whole system. If the system failure occurs during Phase II, only minimal repair is performed on the components. Following expiration of the warranty time, the customer is solely responsible for maintaining the system who, for a fixed length of the time period, replaces the failed components and preventively maintains the system at the end of such period. During the maintenance period, the same maintenance as that of Phase I of the warranty period is conducted. Such a maintenance model was considered in our previous work for a coherent system consisting of identical components. Here, we consider the systems consisting of heterogeneous components which is a more realistic assumption in some practical situations. We investigate, from the manufacturer's and customer's perspectives, the optimal length of each phase in the warranty period, and the optimal planned time of preventive maintenance based on some imposed cost functions, respectively. The results were developed by using the survival signature-based reliability representation of the system lifetime. This representation enables us to propose the cost functions such that at time of the performance of the maintenance action, the repairs/replacements are carried out not only on the entire system but also on each component.

Primary authors: Dr TAVANGAR, Mahdi (University of Isfahan); HASHEMI, Marzieh (University of Isfahan)

Presenter: Dr TAVANGAR, Mahdi (University of Isfahan)

Session Classification: Withdrawn papers

Contribution ID: 26

Type: **not specified**

The long road from data collection to maintenance optimization of industrial equipment

Thursday, 19 May 2022 16:10 (20 minutes)

In the coming years, with the development of intermittent renewable energy sources and the gradual phasing out of coal-fired power plants, combined cycle gas turbines (CCGT) will play an essential role in regulating electricity production. This need for flexibility will increase the demands on the equipment of these CCGT and the issue of optimizing their maintenance will become increasingly important. To this end, the use of statistical tools to enhance the value of data from the operation and maintenance of these plants' equipment is a possible approach to provide decision support elements.

It is in this industrial context that an important collection of data was carried out for several conventional repairable equipment (turbines, pumps...) of three EDF CCGT. The second step consisted in a pre-processing / cleaning of these raw data with the support of field experts, an essential requirement for the statistical modeling stage. A wide range of imperfect maintenance models implemented in the free R VAM (for Virtual Age Models) package (<https://rpackages.imag.fr/VAM#>) was tested to evaluate the ability of these models, on the one hand to reproduce the field reality, on the other hand to bring useful insights to help the development of equipment maintenance plans. The communication will present this work, illustrating it on a piece of equipment and insisting on its industrial application dimension.

Primary author: REMY, Emmanuel (EDF R&D)**Co-author:** LE BRIS, Yves (EDF DTEAM –CIST INGEUM)**Presenter:** REMY, Emmanuel (EDF R&D)**Session Classification:** Case studies

Contribution ID: 27

Type: **not specified**

System reliability modeling with dependent degradation paths: a review of models including clustering and machine learning

Models are reviewed for systems of degrading components that exhibit dependent degradation paths, including distinct clusters of components which have similar behaviors. When component degradation models are extended to complex systems with multiple components, more complex reliability behaviors are often exhibited. As an example, consider a smart railway station, which exhibits multiple dependent failure processes and cluster of components. The main functionality of the railway station is to supply the electricity demand from the loads in the railway station and trains. Component degradation paths can form clusters because of external stresses that influence only a subset of components or physical proximity of a subset of components or many different reasons. For the railroad system, to reduce the CO₂ emission, two additional external energy sources can be used, e.g., a braking power recuperation system that recuperates the electricity generated during the braking of the trains, and a photovoltaic generation system that produce renewable energy supplies to the system. The energy storage system degrades as the battery in the system ages, and concurrently, the photovoltaic generation systems suffer from performance degradation. These two components form a cluster because the degradation of the photovoltaic system are accelerated by the degradation of the energy storage system, as when the energy storage system degrades, the power generated from the photovoltaic system cannot be absorbed rapidly, creating additional stresses to the photovoltaic system that could increase its aging rate.

Different approaches for modeling the reliability for systems with dependent failure processes or degradation processes are reviewed, and stochastically dependent component degradation processes are specifically studied and extended. Models for dependent failure and/or degradation processes can be formulated by approximating joint multivariate distributions using copula functions. The copula function can be applied directly to the joint distribution of the degradation measures or to a joint distribution of the parameters of a degradation model. Alternatively, in the new model, gamma or Weiner process parameters are defined as a function of a vector of random variables and sensitivity coefficients, with specific random variables within the vector corresponding to individual clusters. Furthermore, machine learning models will be beneficial or even necessary when there are dynamic data sets and changing conditions.

Primary authors: COIT, David (Rutgers University); Dr ZENG, Zhiguo (CentraleSupélec); Mr LI, Zhanhang (Rutgers University); Dr BARROS, Anne (CentraleSupélec)

Presenter: COIT, David (Rutgers University)

Session Classification: Invited speaker: David Coit

Contribution ID: 28

Type: **not specified**

Modeling Spatially Clustered Failure Time Data via Multivariate Gaussian Random Fields

Friday, 20 May 2022 14:00 (20 minutes)

Consider a fixed number of clustered areas identified by their geographical coordinate that monitored for the occurrences of an event such as pandemic, epidemic, migration to name a few. Data collected on units at all areas include time varying covariates and environmental factors. The collected data is considered pairwise to account for spatial correlation between all pair of areas. The pairwise right censored data is probit-transformed yielding a multivariate gaussian random field preserving the spatial correlation function. The data is analyzed using counting process machinery and geostatistical formulation that led to a class of weighted pairwise semiparametric estimating functions. Estimators of models unknowns are shown to be consistent and asymptotically normally distributed under infill-type spatial statistics asymptotic. Detailed small sample numerical studies that are in agreement with theoretical results are provided. The foregoing procedures are applied to leukemia survival data in Northeast England.

Primary authors: ADEKPEDJOU, akim (University of Missouri); Dr DABO, Sophie; Mrs SAINUL, zarah

Presenter: ADEKPEDJOU, akim (University of Missouri)

Session Classification: Reliability models

Contribution ID: 29

Type: **not specified**

RELSYS : A new method based on damage physical-chemical processes with uncertainties and hazard.

Friday, 20 May 2022 14:40 (20 minutes)

Jerome de Reffye

Engineering Degrees from Gustave Eiffel University (ESIEE)

and Pierre et Marie Curie University (Paris VI)

PhD in applied mathematics and theoretical physics

from Pierre et Marie Curie University

On opposite way of empirical approaches we develop an analytic method in Reliability - Maintainability - Availability - Safety (RAMS) area which led to the RELSYS model, (RELIability of SYStems), allowing to take into account all the physical-chemical parameters of the degradation models of the system components as well as their uncertainties in a model of randomized physical-chemical evolution allowing the complete calculation of the probabilities of their failures. This calculation is sufficiently complete to be compatible with the actuarial calculation of insurance, both of which allow the association between the RAMS and the calculation of the guarantee of the system costs. We show that it is possible, with precise calculations, to evaluate the risks of uninsurable systems by time series because of the lack of data due to the rarity of the feared events. The probabilities of occurrence of these events being very low, the calculations must be based on justified models. It uses the Langevin's equation for phenomena that evolve slowly over time. The notions of Limit State in Service and Ultimate Limit State are introduced.

This model gives access to dynamic reliability which studies time-dependent phenomena and provides failure probabilities as functions of time through numerical simulation.

We obtain random functions of time whose parameters are themselves random. The uncertainties are thus divided into two parts according to their origin: Uncertainties on the physical-chemical parameters (randomness concentrated at the origin) and uncertainties on the realization of the degradation processes (randomness distributed in time).

We thus obtain the failure probabilities with their confidence intervals. The numerous examples show that RELSYS can be applied to any man-made system. We show the importance of taking into account the probabilistic aspect of the problem from the beginning of the modeling and to develop determinism within the random model. Finally, for the solution of particular problems, one will find original methods in signal processing.

The RELSYS application into system maintenance is using classical theory of random processes. The preventive maintenance parameters can be calculated by RELSYS from the failure probabilities and the technical specifications about the residual failure probabilities. The corrective maintenance cost can be deduced from the previous analysis.

The application of RELSYS to the calculation of the cost of the commitments of guarantees of a program uses the concept of Value at Risk. The used techniques are derived from reinsurance.

We will show numerous examples illustrating the theory by practice in engineering. RELSYS supplies a whole tool to dynamical RAMS analysis.

Primary author: DE REFFYE, Jerome (individual researcher (retired))

Presenter: DE REFFYE, Jerome (individual researcher (retired))

Session Classification: Reliability models

Contribution ID: 30

Type: **not specified**

About some extensions of the gamma process and their applications in reliability and maintenance

According to the failure threshold model, degrading units are typically assumed to fail when their degradation level exceeds an assigned threshold limit. Consequently, the reliability function of these units is defined in terms of the first passage time distribution of their degradation process to the assigned threshold.

This degradation process-based approach to reliability modelling offers two main advantages: i) allows estimating the lifetime distribution from degradation data, even in absence of failure; ii) provide a very natural way for making degradation-based of residual reliability estimates and remaining useful life predictions.

Within this framework, this talk discuss three generalizations of the very popular gamma degradation process, which allows to account for the presence of random effect and measurement error, and shows how this models can be used to implement a recently proposed simple and effective hybrid age/condition-based maintenance policy.

Presenter: Prof. GIORGIO, Massimiliano (Universita' degli Studi di Napoli, Federico II)

Session Classification: Invited speaker: Massimiliano Giorgio