ENBIS Spring Meeting 2026

Report of Contributions

Contribution ID: **2** Type: **not specified**

Imperfect diminishing maintenance modelling and reliability analysis for a multi-process degradation system

This work proposes a framework for analysing reliability and optimizing maintenance in a system subject to multiple degradation processes. Unlike models that assume perfect maintenance, this study incorporates an imperfect maintenance mechanism with diminishing efficiency, where the ability to reduce accumulated degradation decreases with each successive maintenance intervention.

Analytical survival functions and failure-time distributions for two distinct failure scenarios are derived. The first one is an aggregate-threshold scheme modelled via Wiener processes, where system failure is driven by a linear combination of all the degradation processes. In the second scenario, an aggregate-or-critical scheme modelled using Gamma processes is considered, where failure occurs if either the total degradation or a specific critical component exceeds its respective threshold. These mathematical derivations explicitly account for the discontinuities in degradation paths caused by imperfect repairs.

Building on these reliability models, our work develops two condition-based maintenance (CBM) strategies: one using the conditional Residual Useful Life (RUL), and another based on direct degradation thresholds. Numerical experiments show that optimizing the inspection intervals and decision thresholds of these policies provides significantly lower long-run average cost rates compared to traditional periodic maintenance strategies.

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Track Classification: Spring Meeting

Contribution ID: **3** Type: **not specified**

A Geometrical Method for High Dimensional On-line Process Monitoring

I will review recent work where we take an extrinsic manifold fitting point of view, contrary to a manifold learning (i.e., embedding) approach, to develop an on-line monitoring scheme with a simple geometric interpretation which requires neither decorrelation of process dynamics nor dimensionality reduction. The new monitoring framework for online or "phase II"SPC monitors deviations from the reconstructed manifold using a novel univariate (scalar) distribution-free control chart. The average run length performance of the new method is compared to manifold learning methods that first embed the data into a lower-dimensional space before monitoring the embedded observations via explicit out of sample extensions. The manifold fitting SPC method has a provable controllable Type I error probability and, contrary to manifold learning SPC methods, it can operate in a high-dimensional regime where the ambient dimension exceeds the number of "phase I" in-control observations. An application to image data will be presented as well directions for further research.

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Track Classification: Spring Meeting

Contribution ID: **4** Type: **not specified**

Modeling a Human-Centric Framework to Link Cognitive Factors and Maintenance Reliability in HRC Systems

In the Industry 5.0 transition, Humans and Collaborative Robots (Cobots) work together in different operations.. In maintenance ,the role of Human-Robot Collaboration (HRC) is becoming increasingly crucial for achieving sustainable efficiency and human-centered automation. While Collaborative Robot (Cobot) design takes into account worker safety, ergonomics, and process precision, it is necessary to consider aspects such as psychological stress in human operators that may lead to uncorrect operations and uncertainty. In maintenance activities, this stress can compromise the operations and the related quality, leading to increased defect rates, accelerated component degradation, and economic losses. Despite many studies on Human Reliability Analysis (HRA) and Human–Robot Interaction (HRI), there is no integrated quantitative framework that connects trust, stress, and repair reliability within maintenance operations.
The ongoing study proposes a dynamic model linking operator trust and stress to maintenance performance and post-repair degradation in HRC environments. The model will consider and quantify the effect of trust level on operator stress, determine the probabilistic relationship between stress and repair accuracy, and evaluate the overall economic implications, including rework and downtime costs. The analytical core of the framework is based on a Weibull reliability formulation extended with a cognitive stress factor. The resulting equations describe the probability of repair failure as a nonlinear function of trust-induced stress.

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Track Classification: Spring Meeting

Contribution ID: **5** Type: **not specified**

Integrating Real-Time Fatigue Monitoring into Adaptive Human–Robot Collaboration Systems

The increasing use of collaborative robots in warehouse logistics is changing intralogistics systems, improving productivity, but is also creating significant challenges for operator safety, ergonomics, and operational reliability. The introduction of new technologies implies continuous cognitive and physical pressures on operators in modern warehouses, increasing the impact of human fatigue on system performance and the risk of accidents. In this context, traditional models of human-robot collaboration are mostly static and unresponsive to changes in workers' psychophysiological states. To overcome this gap, an integrated approach will be proposed by combining real-time biometric fatigue monitoring with adaptive robotic behavior and dynamic risk assessment.

The development and validation of a socio-technical framework will allow estimating operator fatigue using specific indicators derived from non-invasive eye-tracking data; hence, a quantitative cognitive fatigue index will be defined and integrated into a decision-making model that dynamically adjusts task assignment and robot behaviour in collaborative warehouse operations. Unlike traditional Human Robot Collaboration (HRC) systems that rely on fixed safety thresholds, a model enabling the robot to proactively adapt its contribution to the task in response to changing human conditions and the relative Risk Assessment will be proposed.

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Track Classification: Spring Meeting

Contribution ID: **6** Type: **not specified**

A Data-Driven Optimization Framework for Joint Reliability and Energy Efficiency in 5G Smart Factory Monitoring

Ensuring both the safety and operational continuity of smart factories requires reliable real-time hazard detection and energy-efficient predictive maintenance. This work addresses the joint challenge of guaranteeing ultra-reliable, low-latency communication for safety-critical sensors (Factory Safety Detectors - FSDs) while minimizing energy consumption for a large-scale network of equipment health monitors (Equipment Monitoring Units - EMUs). We propose the Factory Resource Optimization (FRO) framework, a data-driven iterative algorithm that dynamically allocates 5G network and edge computing resources. By decomposing the problem into optimal channel pairing and power allocation, FRO ensures that stringent latency bounds for safety-related data are never violated, thereby enhancing system reliability and safety. Simultaneously, it significantly extends the operational lifespan of EMUs by minimizing their transmission energy, directly supporting sustainable predictive maintenance cycles. Simulation results demonstrate that our approach achieves over 40% energy savings for monitoring units while fully meeting sub-millisecond latency targets for safety detectors. This work provides a scalable model for integrating communication optimization into data-driven reliability and maintenance strategies for Industry 5.0.

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Track Classification: Spring Meeting

Contribution ID: **7** Type: **not specified**

Anomaly Detection in Knitting Machines for Medical Compression Socks Using Performance Indicators based on Quadrant Analysis, and PCA-Based K-means Clustering

Chronic Venous Insufficiency (CVI) affecting the lower extremities is common among adults. Compression textile products, such as compression socks, play a crucial role in the treatment and prevention of CVI and other lower-limb disorders [1], [2]. By applying controlled external pressure, these products support venous return and alleviate symptoms such as pain, edema, and venous hypertension [2], [3], [4]. Since the clinical effectiveness of compression therapy depends on an appropriate pressure profile and patient adherence, manufacturing defects that affect fit, comfort, or pressure distribution may compromise therapeutic performance and user comfort [5], [6].
This study originates from a practical industrial issue: the occurrence of appearance-related and dimensional defects in medical socks detected during quality inspections. Identifying the causes of these defects is essential to improve product quality and optimize quality control procedures.
The analysis is based on annual production data from circular knitting machines used to manufacture compression socks, including total production, number of defects, and number of machine events. From these data, three performance indicators were derived: defect rate, event rate, and defect rate per event. Together, these indicators describe quality outcomes, operational stability, and the severity of machine-related events.
As a first level of analysis, an engineering-oriented quadrant analysis was developed using event rate and defect rate per event. Quadrant-based approaches are widely used in engineering and management as intuitive tools for performance assessment, prioritization, and anomaly detection, particularly when combining frequency- and impact-related metrics [7], [8], [9]. Reference thresholds based on mean values enabled the classification of machines into four categories: critical, high risk, inefficient, and optimal. This representation provides a transparent tool for anomaly detection and constitutes the first set of results of the study.
To improve and complete the quadrant-based analysis, Principal Component Analysis (PCA) was applied to the performance indicators. PCA is widely used in engineering and industrial contexts to capture latent multivariate structures and support visual classification of complex systems [10]. Previous studies have shown its effectiveness in identifying machine clusters and validating grouping results across datasets [11], [12]. In this study, the first two principal components explained more than 96% of the total variance, representing overall operational burden and event severity. The PCA projection revealed coherent machine groupings as well as borderline and extreme behaviors not evident in univariate analyses.
Subsequently, K-means clustering was applied to the PCA scores to obtain a data-driven classification of machine performance. The resulting clusters consistently isolated machines with anomalous behavior, such as high event severity or frequency, while also identifying machines with stable and near-optimal performance.
The proposed methodology represents an essential step toward improving quality control in compression sock manufacturing. By providing a reliable classification of machine behavior, this work lays the groundwork for future studies on defect-specific correlations, reprocessing monitoring, and predictive quality control strategies. More broadly, it demonstrates how performance indicators and multivariate analysis can support continuous improvement in the production of medically relevant textile products. Finally, feedback from industrial experts supports the interpretation of the results and their practical significance.

[1] Y. Shi, R. Liu, J. Lv and C. Ye, “Biomedical therapeutic compression textiles: Physical-mechanical property analysis to precise pressure management,” Journal of the Mechanical Behavior of Biomedical Materials, vol. 151, 2024.
[2] E. Akçagün, F. Siddique and A. Yilmaz, “Development of seamed compression socks and com-

parison with class i socks using existing mathematical models," Journal of The Faculty of Engineering, vol. 28, no. 3, 2023.
[3] C. S. Lim and A. H. Davies, "Graduated compression stockings," Canadian Medical Association Journal, vol. 186, no. 10, pp. 391-398, 2014.
[4] B. Sarı and N. Oğlakcıoğlu, "Analysis of the parameters affecting pressure characteristics of medical stockings," Journal of Industrial Textiles, vol. 47, no. 6, p. 1083–1096, 2018.
[5] B. Yang, Y. Xiong, S. Liu, F. Wang and X. Tao, "Assessment of spatial and temporal pressure distribution of compression stockings during 8-hour wear by using a smart bionic morphing leg mannequin," Measurement, vol. 262, p. 120057, 2026.
[6] J.-M. Gong, J.-S. Du, D.-M. Han, X.-Y. Wang and S.-L. Qi, "Reasons for patient non-compliance with compression stockings as a treatment for varicose veins in the lower limbs: A qualitative study," PLoS One, Public Library of Science, vol. 15, no. 4, pp. 1-11, April 2020.
[7] H. Pires Ferreira and P. Odete Fernandes, "Importance-performance Analysis Applied to a Laboratory Supplies and Equipment Company," Procedia Computer Science, vol. 64, pp. 824-831, 2015.
[8] J. Sarker, J. Hong and C. Im, "Innovation Strategies for Textile Companies in Bangladesh: Development Using Quadrant Analysis Based on a Productivity Index," Sustainability, vol. 14, no. 24, pp. 1-15, December 2022.
[9] A. Shahin and T. Hamidreza, "Investigating the supplier-producer relationship quality: a gap-quadrant analysis approach," Research in Production and Operations Management, vol. 14, no. 4, pp. 31-48, 2024.
[10] F. Alves de Almeida, G. Ferreira, P. Balestrassi, G. Belinato, R. P.A.R and M. Achilles, "Principal Component Analysis: An Overview and Applications in Multivariate Engineering Problems," in Uncertainty Modeling: Fundamental Concepts and Models, Brasília, DF, Brazil, University of Brasília, 2022, pp. 172-194.
[11] M. Chattopadhyay, S. Mazumdar, P. K. Dan and P. S. Chakraborty, "Application of principal component analysis in machine-part cell formation," Management Science Letters, vol. 2, no. 4, pp. 1175-1188, 2012.
[12] W. Hachicha, F. Masmoudi and M. A. Haddar, "Principal component analysis model for machine-part cell formation problem in group technology," Applications, 2006.

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Track Classification: Spring Meeting

Contribution ID: **8** Type: **not specified**

Advanced FIT-Rate Estimation for Serial Systems

FIT(failures in time)-rates are a typical reliability measure for the constant part of the bathtub curve for non-repairable systems. The FIT-rate is the parameter of the exponential distribution in units of 109 hours. It is the inverse of the mean times between failures (MTBF). It is assessed at so-called MTBF-tests. For a serial system, FIT-rates of the individual components are added up. Frequently, individual FIT-rates are given as interval estimations at a certain confidence level (CL), e.g., 60% or 90% CL. Although it is common practice, adding up such FIT-rates can lead to an overly conservative estimation of the overall FIT-rate for a serial system.

We introduce a novel method to calculate FIT-rates at a given CL for serial systems. This method is based on data pooling. Raw data from individual MTBF-tests are combined. Situations of MTBF-tests with different durations are covered as well. Corner cases of various lengths of MTBF-tests, like balanced and unbalanced cases, are investigated. This data pooling forms the basis for the further FIT-rate calculation of a serial system. This new estimator is substantiated by a probability theoretical model. Statistical properties of this new estimator are examined. Special focus is put on the coverage probability of this new estimator, such that it ensures the stated CL.

The novel method is applied to multi-chip semiconductor products and supported by simulations. We see wide range of potential of this method for further applications where the raw data of MTBF-tests are available. This enables manufacturers of complex systems to achieve a competitive FIT-rate based on existing data.

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Track Classification: Spring Meeting

Contribution ID: **9** Type: **not specified**

Maximum Likelihood Inference for Non-Linear Wiener Processes under Multiple Arithmetic Reduction of Degradation (ARD) Maintenances

As time passes, complex industrial systems suffer degradation phenomena that will inevitably lead them to failures. Several degradation models have been proposed to model these phenomena [5]. The most usual ones are based on stochastic processes such as the Wiener process, the Gamma process or the Inverse Gaussian process. In the case of complex systems that must operate without interruptions for long periods of time, waiting for a failure to initiate a repair process is not a viable option. Hence, industrial agents need to carry out preventive inspections, in which they assess the degradation level of the system, along with preventive maintenances, aiming to reduce the degradation level.

Overall, the goal of degradation data analysis is to estimate the lifetime of industrial assets. Mathematically, this is done by estimating the residual time before the degradation level hits a certain threshold after which the product will be unable to perform its task. In order to do so, it is crucial to have a good estimation of the model parameters. In the case of systems for which inspections and/or maintenance actions are expensive, it is harder to estimate the effect of the maintenance actions as less data means less precision. Furthermore, in some cases, the degradation may present non-linear patterns that need to be considered. For instance, the degradation might be accelerating [4], deccelerating or hit a plateau [2]. Thus, it is important to develop general modelling frameworks capable of taking into consideration as much information as possible.

The present work presents a maximum likelihood based inference method for a degradation model where the underlying degradation process is a Wiener process and the maintenance effect is modelled by an Arithmetic Reduction of Degradation (ARD) model [1] [3]. The originality of this work is that the drift and volatility of the Wiener process are both assumed to be non linear. The ARD framework stipulates that each maintenance reduces the degradation level by a quantity proportional to a certain amount accumulated in the history of the studied asset. We consider multiple maintenance types and associate each of them to a coefficient representing their efficiency. Indeed, the same piece of system may be subject to different types of maintenance actions. For instance chemical treatments may have different efficiencies depending on the used product. It is worth to note that the present method covers all possible schemes of observation.

The presentation is divided in four parts. Firstly, we introduce our model in a framework where we assume both the drift and the volatility to be as general as they can be and we deduce the expression of the likelihood for an arbitrary dataset. Secondly, we assume a parametric shape for the drift and volatility that lead to a set of estimators for the model parameters.
Thirdly, the estimators are implemented with the Julia language and their quality is assessed through simulations. Finally, the estimators are applied to real data from energy production systems.

References

[1] L. Bautista, I. T. Castro, C. Bérenguer, O. Gaudoin, and L. Doyen. Parameter estimation in an ARD∞ wiener degradation and maintenance model under different observation schemes. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 240(1):261–277, 2026.

[2] M. Fouladirad, M. Giorgio, and G. Pulcini. A transformed gamma process for bounded degradation phenomena. Quality and Reliability Engineering International, 39(2):546–564, 2023.

[3] S. Mercier and I. T. Castro. Stochastic comparisons of imperfect maintenance models for a gamma deteriorating system. European Journal of Operational Research, 273(1):237–248, 2019.

[4] G. A. Whitmore and F. Schenkelberg. Modelling accelerated degradation data using wiener

diffusion with a time scale transformation. Lifetime Data Analysis, 3(1):27–45, 1997.
[5] Z.-S. Ye and M. Xie. Stochastic modelling and analysis of degradation for highly reliable products. Applied Stochastic Models in Business and Industry, 31(1):16–32, 2015.

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Track Classification: Spring Meeting

Contribution ID: **10** Type: **not specified**

Reliability Verification with Economic Constraints

The verification of a reliability target is one of the last and most expensive steps in the development process of a technical product. It ensures a certain level of product reliability prior to market release and provides a limit for expected warranty costs. Depending on product complexity and diversity as well as production volumes, a sufficient verification of a challenging target may become economically impossible. In such cases, current industrial practice is to select critical product variants and determine for this choice an unconstrained reliability verification plan without consideration of economic consequences.
This talk discusses the role and importance of reliability verification in product development and shows how economic constraints can be considered in stochastic reliability models for planning of optimal reliability verification. An example from the automotive industry illustrates the practical applicability of this innovative approach.

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Contribution ID: **11** Type: **not specified**

A Finite-Time Prescriptive Maintenance Policy for Systems Exhibiting Bathtub-Shaped Degradation Rates

Real-world degradation processes often exhibit three distinct phases, namely a running-in (accommodation) phase, a steady-state (normal) phase, and a catastrophic wear phase. As a consequence, the degradation rate function, here intended as the first derivative of the mean degradation function, is typically bathtub-shaped: it decreases during the first phase, remains approximately constant during the normal phase, and increases again during the last phase. In such settings, maintenance policies should explicitly account for this behavior, since model misspecification can lead to systematically suboptimal decisions and, in turn, increased expected costs. Motivated by these considerations, we introduce a non-homogeneous gamma degradation process inspired by Giorgio et al. (2023) that accounts for a bathtub-shaped degradation-rate function, and we use it to develop a prescriptive maintenance policy. In this work, we consider a prescriptive maintenance policy for a degrading system in which degradation is influenced by a usage rate, that represents the operating intensity of the system, and where prescriptive actions include its adjustment.
We consider a nominal usage level corresponding to standard operating conditions. At each inspection, the usage rate is selected from a finite set for the next interval, where reductions slow degradation but incur a per-unit-time cost that increases with the deviation from nominal. The system is planned over a finite operating mission with periodic, perfect inspections and non-self-announcing failures. At each inspection, the policy selects the next usage rate and may perform preventive or corrective replacement.
The problem is formulated as a finite-time Markov decision process and solved via backward recursion. Numerical studies vary the number of available usage rate levels and the length of the operating mission. Results, compared to those obtained by adopting a simpler policy that allows for corrective and preventive replacements only, show that within the considered experimental scenarios, allowing for usage rate reductions significantly reduces the expected cost. Moreover, the results suggest that the optimal action at each inspection strongly depends on the degradation phase experienced by the system at that time.

Keywords: *prescriptive maintenance, non-homogeneous Gamma process, bathtub-shaped degradation rate, finite-horizon maintenance policy, average total cost.*

Esposito, N., A. Piscopo, B. Castanier, and M. Giorgio (2024). Adaptive Maintenance Policy For Gamma Degrading Units With Bathtub-Shaped Degradation Rate Function In The Presence Of Random Effect. In Advances in Reliability Safety and Security, Cracow (PL), 29–37.
Gertsbakh, I. B., and Kh. B. Kordonskiy (1969). Models of Failure. Springer.
Giorgio, M., A. Piscopo, and G. Pulcini (2023). A new Wiener process with bathtub-shaped degradation rate in the presence of random effects. Applied Stochastic Models in Business and Industry 40, 574–597.
Meissner, R., A. Rahn, and K. Wicke (2021). Developing prescriptive maintenance strategies in the aviation industry based on a discrete-event simulation framework for post-prognostics decision making. Reliability Engineering & System Safety 214, 107812.
Sun, Q., P. Chen, X. Wang, and Z. Ye (2023). Robust condition-based production and maintenance planning for degradation management. Production and Operations Management 32, 3951–3967.

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Track Classification: Spring Meeting

Contribution ID: **12** Type: **not specified**

Variable-Domain Multivariate Functional PCA for PHM and RUL Prediction

Functional data analysis methods are increasingly used in Prognostic Health Management (PHM) to model degradation from multi-sensor systems. Multivariate Functional Principal Component Analysis (MFPCA) is effective in this context, but its standard formulation assumes that all units are observed over a common time domain. In practice, operational data often exhibit variable domain lengths due to heterogeneous usage conditions and lifespans. We propose a Variable-Domain Multivariate Functional Principal Component Analysis (vd-MFPCA) framework that extends MFPCA to handle multivariate functional observations defined over unit specific domains. By estimating a domain dependent covariance structure, the method extracts principal components that adapt to the observed operational domain of each unit. This enables more flexible modeling of degradation trajectories across heterogeneous units. The proposed method is applied to the NASA C-MAPSS aircraft engine dataset. Results show that vd-MFPCA improves Remaining Useful Life prediction accuracy compared to conventional MFPCA while offering clearer functional interpretations of degradation patterns. The approach provides a practical and interpretable framework for PHM applications and RUL predictions involving variable-length, multi-sensor functional data.

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Track Classification: Spring Meeting

Contribution ID: **13** Type: **not specified**

Hybrid modelling through Latent Differential-Regression Analysis (LDRA) for predicting long-term equipment degradation in the Chemical Process Industry

Long-term equipment degradation decisively affects production cycles of chemical process industries (CPI), and has a major impact on plant safety, operation and economy. Equipment degradation is caused by underlying phenomena that evolve over time with a rate of change that depends on the operating conditions. To tackle this problem, a Latent Differential Regression Analysis (LDRA) methodology is introduced to predict and analyze long-term equipment and process degradation in CPI. As the degradation state is typically not observable, LDRA follows a hybrid modeling approach that combines knowledge-based feature engineering to infer an Equipment Health Indicator (EHI) and data-driven models to find the process variables related to EHI degradation.
The LDRA methodology was tested using real data from an industrial plant, where fouling takes place in several heat exchangers located in the reaction section. The case study illustrates how the proposed methodology unfolds in a real and challenging application and the results that it provides.
For this case study, LDRA successfully identified the concentration of a key component as being critically related to fouling. Furthermore, the models showed good prediction capabilities during both steady and unsteady operation periods, strengthening the hypothesis that fouling is caused by the accumulation of the identified component. Therefore, the results provided useful insights into the fouling phenomenon and allowed the plant personal to narrow down troubleshooting on a specific component of the process.
The methodology is general and can be applied to other long-term degradation modes commonly found in the CPI, such as catalyst deactivation, corrosion, mechanical degradation of packing beds and catalysts, coking, among others. We thus foresee that the proposed modeling approach based on LRDA and a case-dependent EHI can find wide application in CPI.

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Contribution ID: **14** Type: **not specified**

Connections between information measures and activation functions

In this work, we introduce a generalized measure of uncertainty, namely the cumulative information ψ-measure, in order to provide a unified perspective to the uncertainty framework. Indeed, it is a variability measure which reduces to several well-known information measures for appropriate choices of the function ψ. In particular, cumulative versions of Shannon and Tsallis entropies, Gini's dispersion indices, cumulative information generating functions, and additional new classes of uncertainty measures arise as special cases. We also investigate a suitable relative version, referred to as the relative cumulative information ψ-measure. We establish fundamental properties of the proposed measures, including monotonicity properties, bounds, and a set of related inequalities. We derive covariance-based and quantile-based representations, too. Illustrative examples are presented to clarify the behaviour of the measures under different model assumptions and choices of ψ. A notable feature of the proposed approach is the natural connection between the function ψ and certain increasing activation functions, commonly employed in neural networks. For instance, the function ψ associated with the cumulative paired Shannon entropy can be derived from the sigmoid activation function, and conversely. Motivated by this link, we introduce the generalized logistic-linear family of activation functions, which include classical models such as sigmoid and linear activations as particular cases within a parametric structure. Finally, we develop an application motivated by a neural network scenario to demonstrate the flexibility and novelty of the proposed framework. The results highlight the potential of the cumulative information ψ-measure as a bridge between information theory and modern neural networks.

References:
M. Capaldo, A. Di Crescenzo, and A. Meoli,
"Cumulative information generating function and generalized Gini functions," *Metrika*, vol. 87, pp. 775–803, 2024.
DOI: 10.1007/s00184-023-00931-3.

M. Capaldo, A. Di Crescenzo, and G. Pisano,
"Information measures and activation functions," *submitted*, 2026.

A. Di Crescenzo and M. Longobardi,
"On cumulative entropies," *Journal of Statistical Planning and Inference*, vol. 139, no. 12, pp. 4072–4087, 2009.
DOI: 10.1016/j.jspi.2009.05.038.

M. Rao, Y. Chen, B. C. Vemuri, and F. Wang,
"Cumulative residual entropy: A new measure of information,"
IEEE Transactions on Information Theory, vol. 50, no. 6, pp. 1220–1228, 2004.
DOI: 10.1109/TIT.2004.828057.

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Track Classification: Spring Meeting

Contribution ID: **15** Type: **not specified**

Unsupervised Anomaly Detection in AIS Data from Fishing Vessels

The increasing availability of AIS (Automatic Identification System) data in the fishing sector offers new opportunities for monitoring and statistical analysis of maritime activity, but it also poses significant methodological challenges. We present an open problem motivated by the study of fishing vessels operating along the coast of Norway, aiming to promote the development and discussion of rigorous statistical approaches in a real industrial context.

The dataset integrates heterogeneous information at the vessel level: structural characteristics (length, tonnage, engine power, etc), target species, and declared catch volume. From a statistical perspective, this defines a multivariate problem with mixed-type covariates and potentially complex dependence structures. As an initial approach, we apply Isolation Forest to detect anomalous catches conditioned on vessel characteristics. This unsupervised method is scalable and flexible but raises relevant issues in industrial contexts, such as result stability, interpretability of anomaly scores, and uncertainty quantification.

Additionally, complete vessel trajectories obtained from AIS signals are available. These trajectories are treated as functional data, representing space–time curves over fishing campaigns. Functional Isolation Forest is used to identify atypical navigation patterns.

The main difficulty arises when attempting to analyze jointly both types of detected anomalies: on one hand, those related to vessel characteristics and catches and, on the other, those associated with navigation trajectories. To date, both analyses have been conducted separately. However, in an industrial context, it makes more sense to study both aspects in an integrated manner, as an anomalous catch may be linked to an unusual navigation pattern.

Therefore, it is necessary to develop a common framework that combines information from both sources. This involves integrating different anomaly measures into a single analysis framework, taking operational context into account (such as fishing area, season, or target species), and defining clear criteria for evaluating results, particularly in settings where reliable labels indicating true anomalies are unavailable.

We propose this case as an open challenge intended to foster discussion and collaboration on anomaly detection in complex and heterogeneous data. The goal is to advance toward more robust and well-founded methods that can be reliably applied in real industrial contexts, combining methodological contributions with proposals to improve result interpretation and validation.

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Track Classification: Spring Meeting

Contribution ID: **16** Type: **not specified**

Risk informed inspection and maintenance in refineries

Safety and reliability of industrial equipment in the process industries are substantially influenced by degradation processes such as corrosion, erosion, deposits and blocking of pipes. To that end Risk-Based Inspection and Maintenance (RBIM) methodologies are progressively adopted using prediction models that depict the yearly corrosion rate of piping & equipment groups.
Indeed, piping and equipment corrosion can trigger serious failures, which eventually lead to large economic loss, sometimes combined with environmental pollution or personnel losses, together with unpredictable and costly shutdowns of industrial facilities owing to repair and /or replacement. Additionally, the increasing importance of Hydrogen (H2) as an alternative marine fuel makes the study of its handling very topical right now.
The analysis described in this work is performed in a Hydrogen (H2) steam-reforming unit of a Greek refinery for its diesel desulphurization process, under different operating conditions; namely temperature, pressure, fluid speed, metallurgy and more related physicochemical variables that have been gathered in a file. Wall thinning measurements by ultrasonic scanning equipment performed by the refinery personnel were grouped by period, unit section, steel alloy type, fluid type, and nature; the latter have been processed by multivariable regression analyses.
The outcome of these analyses is an extensive family of multivariable functions describing, with a predefined accuracy, the yearly corrosion rate for each corrosion loop and for each examined part of it. This analysis provided the basis for the design and development of a tailor-made software with user-friendly data entry and reporting system to be used as an additional loss prevention tool by the refinery management team. An overview of the results regarding the tool implementation will be presented.

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Track Classification: Spring Meeting

Contribution ID: **17** Type: **not specified**

A maintenance policy for a partially observable parallel system with two components subjected to stochastically dependent degradation processes]{A maintenance policy for a partially observable parallel system with two components subjected to stochastically dependent degradation processes

Degradation modelling based on stochastic processes has become a key tool in reliability analysis and condition-based maintenance of engineering systems. While a large body of literature addresses single-component systems, many practical assets consist of multiple components whose degradation processes are influenced by common environmental or operational factors. In such systems, component deterioration is often correlated, and maintenance decisions become particularly challenging when only partial information on the system state is available. This situation arises when some components can be directly inspected while others remain hidden or inaccessible, requiring maintenance policies that account for both dependence among components and incomplete state observability.

This paper investigates maintenance decision-making for a parallel two-component system in which one component is fully observable and the other is latent. The degradation of both components is modelled through stochastic degradation processes driven by a shared random effect, capturing the influence of unobserved environmental or operational conditions and inducing correlation between the two degradation trajectories. At inspection times, the degradation level of the observable component is perfectly known, whereas the state of the latent component must be inferred indirectly from the information provided by the observable one.

The system is assumed to operate over a finite time horizon with a single inspection and maintenance opportunity. At the inspection time, the decision-maker observes the degradation state of the accessible component and selects an optimal maintenance action. System failure is defined through a threshold-based degradation model, linking component deterioration to system lifetime. The objective is to determine the optimal inspection timing and the corresponding maintenance action that minimise the expected cost per unit of time over the system lifetime.

The analysis focuses on a one-inspection policy in order to clearly isolate and characterise the informational contribution of the observable component to the maintenance decision process. This modelling choice allows the role of correlation and partial observability in supporting optimal decisions to be examined in a transparent way. Nevertheless, restricting the number of inspection can also provide operational and/or economic benefits in some industrial applications (such as, for example, offshore energy or large-scale plants) where the mobilisation of specialised inspection teams and the downtime associated with maintenance interventions may justify policies with limited inspection opportunities.

Obtained results offer insights into the value of indirect information in condition-based maintenance policies.

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Track Classification: Spring Meeting

Contribution ID: **18** Type: **not specified**

TTS R Package: Non-parametric Time-Temperature Superposition for Materials Lifetime Prediction

We present a novel non-parametric method (MNAT) within materials reliability studies to apply the Time-Temperature Superposition (TTS) principle, enabling prediction of long-term viscoelastic material behavior from short-term accelerated tests—critical for polymers, composites, adhesives, and advanced materials where full-scale durability testing spans decades.
This work presents the TTS R package (CRAN) implementing the MNAT methodology, a non-parametric approach based on first-derivative curve shifts that outperforms traditional Arrhenius/WLF models across glass transition regions. Unlike parametric methods requiring restrictive temperature assumptions, MNAT delivers smooth master curves via GAM regression with bootstrap confidence bands, following Explainable AI principles for full model transparency.
The open-source TTS package democratizes accelerated lifetime testing for Industry 4.0 materials engineering, from adhesives to composites. Real Ocean Engineering validation confirms adhesive viability vs. welding (weight/emissions reduction).

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Track Classification: Spring Meeting

Contribution ID: **19** Type: **not specified**

Bayesian Hierarchical Modeling for Reliable Large-Scale Sensors Deployments and Applications

Reliability of large populations of sensors is a major challenge in modern industrial production and applied functional monitoring systems. The massive deployment of low-cost Micro-Electro-Mechanical Systems (MEMS) sensors across several technological domains requires calibration strategies that ensure metrological reliability while remaining feasible at industrial scale. However, traditional laboratory calibration procedures become impractical when sensors are produced in very large quantities, motivating the development of statistical approaches for large-scale calibration.

This work develops a Bayesian statistical framework for the virtual calibration and actual applications of large sensor batches. A earlier published model exploits information from a reference, laboratory-calibrated batch to infer the calibration properties of new lots of the same production process. By calibrating only a small subset of sensors from each batch, the model estimates key parameters that characterize the entire lot, providing robust reliability assessments while drastically reducing direct calibration effort. Building upon this formulation, a hierarchical extension of the model is developed by introducing a Beta hyperprior distribution on the probability of detecting out-of-tolerance sensors, enabling the integration of prior industrial knowledge with explicit control of parameter variability. This approach softens prior deterministic assumptions about batch quality and enhances the flexibility and robustness of reliability estimates. The choice of hyperprior parameters therefore plays a crucial role in ensuring that the model coherently reflects prior industrial knowledge.
The study evaluates sensor batch reliability metrics under varying model parameters and introduces alternative metrics to address identified limitations. Model validation was conducted on a case study of 100 digital MEMS accelerometers calibrated at INRiM. Models based on weakly informative hyperpriors rely more strongly on the information conveyed by the likelihood. Consequently, when the observed data indicate a smaller percentage of defective sensors than that expected according to the prior, higher batch reliability and lower uncertainty associated with the statistically calibrated sensors are obtained. Conversely, when the data suggest a higher percentage of defective sensors, the same models produce a substantial increase in the associated uncertainty. This result highlights how the agreement between the prior assumption and the data-driven evidence plays a fundamental role in the assessment of the batch reliability and uncertainty.

Future research will extend the model by including utility and cost functions to formally represent the producer's risk in rejecting a batch and the consumer's risk in accepting it, integrating probabilistic calibration results with decision-making criteria. These studies will be crucial for balancing the benefits of using less informative hyperpriors, which may lead to higher estimated reliability of lots, against the drawback of a larger posterior variance, that is, a reduced confidence in the estimation of the true number of defective sensors.

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Track Classification: Spring Meeting

Contribution ID: **20** Type: **not specified**

Data-Driven Condition-Based Maintenance Optimization

Studies on condition-based maintenance optimization typically consider systems with known deterioration processes. In this talk, we make the often more realistic assumption of an unknown deterioration process and we discuss various approaches for determining when to carry out preventive maintenance based on limited condition data. Contrary to many existing studies that consider a certain parametric form for the deterioration process with uncertainty its parameters, we also assume that the parametric form of the deterioration process is unknown, making the approaches fully data-driven.

For the approaches that we consider, the maintenance policies are determined based on observed condition data of K runs-to-failure. We use logistic regression to estimate the failure probability of the system as a function of its condition, and based on this we determine in which states to carry out preventive maintenance. We compare the resulting policies to the oracle policies under the assumption that the exact deterioration process is known, and analyze how the performance of our approaches depends on the amount of data that we have.

In addition to only using available condition data, we analyze to what extent the data-driven policies can be improved by creating additional, synthetic runs-to-failure. We generate these additional runs-to-failure by resampling from the deterioration increments that have been observed in the past. It turns out that this leads to improved accuracy and reduced variance compared to existing methods.

Another extension that we consider is that of a system with two condition indicators, i.e., the system deteriorates according to a bivariate deterioration process. For each run-to-failure, the two conditions are measured periodically, until the system fails. In this case, the failure probability is estimated as a function of the two condition indicators. We also address how a suitable maintenance policy can be determined in the setting with two condition indicators.

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Track Classification: Spring Meeting

Contribution ID: **21** Type: **not specified**

Discretization of the Gamma Process: Structural Properties and Reliability Applications

The discretization of the gamma process plays an important role in both theoretical investigations and practical implementations of stochastic modeling. The gamma process is a continuous-time, non-decreasing Lévy process with independent increments and is widely used in applications such as reliability engineering, survival analysis, and degradation modeling.

In practice, however, observed degradation data are often collected in a categorized or discretized form. In many engineering applications, the data must also be categorized in order to apply decision-making frameworks such as Markov decision processes (MDPs). For this reason, studying the discretized gamma process becomes essential for linking theoretical models with real-world data.

Discretization enables the approximation of continuous-time dynamics while attempting to preserve the key probabilistic properties of the original process. In particular, it is important to examine whether fundamental characteristics—such as the Markov property, independent increments, stationarity of increments, and infinite divisibility—are maintained after discretization. Understanding the preservation or alteration of these properties is crucial for ensuring model validity and analytical consistency.

Furthermore, analyzing these structural properties provides insight into transition behavior, dependence structure, and long-term dynamics, all of which directly influence statistical inference and predictive performance. Therefore, a rigorous study of the discretized gamma process and its characteristic properties serves as an important bridge between continuous-time stochastic theory and practical modeling applications. Additionally, the impact of this discretization will be investigated in the context of maintenance and reliability analysis, where degradation modeling plays a central role.

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Track Classification: Spring Meeting

Contribution ID: **22** Type: **not specified**

Efficient Post-Shrinkage Estimation Strategies in High-Dimensional Cox's Proportional Hazards Models

Regularization methods such as LASSO, adaptive LASSO, Elastic-Net, and SCAD are widely used for variable selection in statistical modeling. However, these approaches primarily focus on variables with strong effects and often overlook weaker signals, which may lead to biased parameter estimates and reduced predictive performance. To address this limitation, corrected shrinkage strategies have been proposed to incorporate both strong and weak signals within the estimation process. Nevertheless, existing developments have largely been restricted to linear models, and their applicability to survival data has received limited attention, despite the common presence of both strong and weak covariate effects in biomedical survival studies.

To bridge this gap, we propose a novel class of post-selection shrinkage estimators within the Cox proportional hazards model framework. We establish the asymptotic properties of the proposed estimators and evaluate their performance through simulation studies that explicitly account for weak signals. The results demonstrate improvements in estimation accuracy and predictive performance. Finally, we illustrate the practical utility of the proposed approach using two real-world datasets, highlighting its advantages over existing methods.

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Track Classification: Spring Meeting

Contribution ID: **23** Type: **not specified**

Process Analytical technology by ultrasounds for industrial product control

Abstract

Process Analytical Technology (PAT) is a regulatory and scientific framework introduced by the Food and Drug Administration (FDA) to promote innovation and efficiency in pharmaceutical manufacturing by enabling in-line, real-time process monitoring and quality control, consistent with quality by design (QbD) principles, rather than solely through conventional laboratory testing (quality by testing approach). In this work, a new PAT tool was developed for implementation in an injectables manufacturing plant. Considering the sterility and cleanliness constraints associated with injectable products, a non-invasive ultrasound technique, using a pulse-echo configuration, was selected as the most suitable approach. Additional advantages include rapid analysis, robustness and straightforward implementation. Herein we present a method for quality control of saline physiological solution for infusion (NaCl 0.9%) developed with the new PAT.

Keywords: Injectables, Process Analytical Technology (PAT), Quality by Design (QbD), Ultrasound

Introduction

In modern pharmaceutical production, PAT is a key enabler of continuous manufacturing, supporting automated feedback and feed-forward control loops that ensure product consistency 1. PAT is closely aligned with to QbD principles, which emphasizes proactive quality assurance based on process knowledge and identification of Critical Quality Attributes (CQAs) and Critical Process Parameters. By establishing relationships between CQAs, CPPs and product quality, manufacturers can operate within a design space approved by regulatory authorities, ensuring consistent quality while allowing flexibility in process optimization 2.
Regulatory agencies, including FDA and EMA encourage PAT adoption, especially when associated with Real-Time Release Testing (RTRT) [3]. Aligned with these principles, our team developed an acoustic PAT tool and applied it to determining NaCl concentration in physiological saline solution for infusion.

Setup

The experimental setup (Figure 1) includes an ultrasonic probe operating in pulse-echo mode, a pulser-receiver to send an electrical pulse to the probe and receive the echoes after propagation in the solution, a temperature probe, a signal-processing board, and dedicated software. This configuration enables non-invasive, real-time measurement of acoustic velocity in the solution.

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Results

To evaluate the CQA NaCl concentration, calibration was performed using solutions ranging 0.45-1.35% (w/v) NaCl, at temperatures from 15 to 40 °C (1°C increments). Sound speed was measured under each condition. The data was fitted under a full quadratic 3D polynomial model. The resulting response surface (Figure 2) shows excellent predictive performance, with an RMSE of 0.032 and an adjusted R^2 of 0.99.

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Conclusion

The ultrasound-based PAT tool proved robust and reliable for determining NaCl concentration in physiological saline solution for infusion. The strong predictive performance confirms acoustic velocity as a suitable surrogate for this CQA. The non-invasive nature, compatibility with sterile and closed systems, and rapid data acquisition make this PAT highly advantageous for the pharmaceutical industry, particularly for injectables. Moreover, the method aligns with regulatory priorities for PAT adoption and supports future integration into automated control strategies and RTRT. Overall, our ultrasound PAT represents a practical, scalable technology capable of enhancing process understanding, improving quality control, and supporting the transition toward next-generation pharmaceutical manufacturing.

Acknowledgements:

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References

1. FDA, CDER, CVM, ORA. Guidance for Industry: PAT –A Framework for Innovative Pharmaceutical Development, Manufacturing and Quality Assurance (2004). https://www.fda.gov/downloads/drugs/guidanc last accessed 2026/01/05.
2. Henriques J, Sousa J, Veiga F, Cardoso C, Vitorino C. Process analytical technologies and injectable drug products: Is there a future? Int J Pharm 10 (554), 21-35. 2019.
3. EMA. Guideline on Real Time Release Testing (formerly Guideline on Parametric Release). EMA/CHMP/QWP/811210/2009-Rev1 (2012) https://www.ema.europa.eu/en/documents/scientific-guideline/guideline-real-time-release-testing-formerly-guideline-parametric-release-revision-1_en.pdf, last accessed 2026/01/05.

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Track Classification: Spring Meeting

Contribution ID: **24** Type: **not specified**

Optimal repair policies for monotone systems with simultaneous failures

Industrial systems composed of multiple interacting components are often exposed to external events that can simultaneously affect several parts of the system. Such events, commonly referred to as common shocks, introduce strong dependence between component failures and significantly complicate maintenance planning. When multiple components fail at once, the system may experience large operational disruptions and costly repair interventions, making the design of efficient maintenance policies a challenging problem.

In this talk we show optimal repair strategies for multi-component systems subject to dependent failures. The dependence structure is modeled using the Lévy–Frailty Marshall–Olkin (LFMO) distribution, which captures both individual component failures and simultaneous failures caused by common shocks through an underlying stochastic degradation process..

The maintenance decision problem is formulated as a sequential decision-making problem. Starting from the continuous-time reliability model, we construct a Semi-Markov Decision Process (SMDP) under an average-cost performance criterion. The SMDP is then transformed into an equivalent discrete-time average-cost Markov Decision Process (MDP), allowing the use of dynamic programming methods to compute optimal or near-optimal maintenance policies.

Because the transition dynamics of the system can be complex or analytically intractable, we also develop a simulation-based approach to approximate the underlying MDP. In particular, we employ reinforcement learning techniques based on the Stochastic Approximation Value Iteration Algorithm (SAVIA) to estimate optimal policies using simulated trajectories of the LFMO process.

In addition to the policies obtained through the MDP formulation, we also study and compare several alternative maintenance strategies. These include simple rule-based policies that depend on aggregate system indicators, such as the number of failed components. Although such policies are generally less optimal than those derived from the MDP framework, they are computationally inexpensive and scale well to larger systems. Simulation experiments show that, despite their simplicity, these heuristic policies can sometimes achieve competitive performance, making them attractive practical alternatives when solving the full MDP becomes computationally challenging.

Computational experiments illustrate how the dependence structure among failures affects maintenance decisions and demonstrate the effectiveness of the proposed framework for designing and evaluating maintenance policies in complex reliability systems.

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Track Classification: Spring Meeting

Contribution ID: **25** Type: **not specified**

A Data-Driven Health Indicator for Condition Monitoring of Electric Vehicles

The increasing availability of high-frequency telemetry data in electric vehicles (EVs) creates new opportunities for monitoring system health. Within the broader context of Prognostics and Health Management (PHM), these data streams have the potential to facilitate the transition from reactive maintenance to evidence-based condition assessment. However, in real-world industrial settings, reliable labels for faults, maintenance interventions or remaining useful life (RUL) are often incomplete, inconsistent or unavailable. This restricts the effectiveness of supervised predictive modelling and necessitates the development of statistical approaches that can operate without explicit degradation benchmarks.

This work proposes a data-driven framework for developing a Vehicle Condition Indicator (VCI): an interpretable, synthetic measure of vehicle health derived from heterogeneous, multisensory telemetry. The framework's primary methodological contribution is the definition of a statistically robust indicator that can capture deviations from normal behaviour while remaining stable under different operating conditions.

The framework integrates multivariate statistical monitoring and unsupervised learning techniques into a consistent modelling approach. In particular, baseline operating regimes are identified through dimensionality reduction and clustering to characterise nominal system behaviour. This modelling step enables normal variability due to usage conditions to be separated from structurally atypical behaviour. Any deviations from these patterns are quantified using metrics based on distance and density, and their temporal evolution is analysed to distinguish persistent shifts, which may be associated with degradation processes, from transient anomalies.

The resulting VCI is not intended to be a black-box score. It is designed to be interpretable and can be broken down into subsystems, such as the battery, power electronics or braking system. This breakdown provides diagnostic proxies that support engineering analysis, even when labelled failures are absent. Rather than directly estimating RUL, the indicator provides a continuous, comparable measure of relative condition which can be monitored over time and across vehicles operating under different duty cycles, thus supporting PHM decision processes without relying on fully supervised degradation models.

A case study based on real-world EV telemetry data illustrates the statistical properties and practical relevance of the proposed indicator. The analysis shows how the VCI captures emerging behavioural changes before explicit faults are recorded, enabling consistent health ranking across vehicles with different usage profiles. Although it was developed for EVs, the framework can easily be transferred to other complex industrial systems characterised by high-dimensional telemetry and scarce labels. By basing condition monitoring on interpretable multivariate statistics rather than purely predictive modelling, this work aims to stimulate discussion within the business and industrial statistics community on robust and scalable approaches to data-driven health assessment.

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Track Classification: Spring Meeting

Contribution ID: **26** Type: **not specified**

Monotonicity-Based Parent-Child Inference for the Efficient Computation of Signatures and Minimal Cut/Path Sets in Coherent Systems

In binary reliability systems, the minimal cut-sets, path-sets and signature vector [1, 2], provide the basis for computing key reliability measures, such as the survival function and the mean time to failure [1, 3]. However, these quantities are typically obtained by exhaustive evaluation of the structure function over the Boolean state space 1, whose size grows exponentially with the number of components: if n is the number of components in the system, there are 2^n possible states of the system 2. Thus, as system size increases, this becomes computationally burdensome, and exact calculation becomes practically impossible even for moderate-sized systems.

In this work, we propose a new method to compute minimal cut-sets, path-sets and the signature vector for monotonous binary systems. We make no assumptions about the structure of the system and consider its structural function a black box. The proposed approach explores the Boolean state space by failure level, defined as the number of failed components. At each iteration, a level is selected from an adaptive biased distribution, then an "unchecked"state within that level is sampled uniformly at random and evaluated using the structure function, and then its status (working or failed) is propagated through the state lattice using monotonicity-based parent-child inference 2. Indeed, if the sampled state is working, all of its ancestors toward lower failure levels are inferred working; and if it is failed, all of its descendants toward higher failure levels are inferred failed. In this way, a single exact evaluation can determine the status of many additional states without further structural-function calculations. With this, we propose confidence intervals for the signature vector. And in the cases where all states can be checked, we can compute the minimal cut- and path-sets, and also the signature of all intermediate states.

Preliminary results across multiple tested systems indicate a substantial reduction in computation time when using our algorithm.

1 F. Samaniego, System Signatures and their Applications in Engineering Reliability. Springer, 2007.

2 J. Navarro, Introduction to System Reliability Theory. Springer, 2022

[3] J.-L. Marichal, P. Mathonet, and T. Waldhauser, "On signature-based expressions of system reliability,"Journal of Multivariate Analysis, vol. 102, no. 10, pp. 1410–1416, 2011.

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Track Classification: Spring Meeting

Contribution ID: **27** Type: **not specified**

Implementation of Automatic differentation on Maintenance optimization problems

Abstract

Automatic Differentiation (autodiff or AD) is a technique for computing derivatives that differs from both symbolic and numerical differentiation. It relies on the implementation of the chain rule to functions composed of simpler smooth functions whose Jacobian matrices are known.

Given the implementation of a function composed of smooth operations, Automatic Differentiation enables the computation of its partial derivatives by propagating derivatives through the computational graph of the program. Using this approach, we can differentiate a function that is part of a code and does not have an explicit mathematical expression.

In this work, we demonstrate the application of this technique to basic maintenance optimization problems, where the objective is to identify maximum or minimum points of a cost function approximated using Monte Carlo methods. This approach enables efficient gradient-based optimization even when the cost function is estimated through stochastic simulation. The implementation is carried out using modern automatic differentiation libraries such as JAX and Autograd.

References

1. Atilim Gunes Baydin, Barak A. Pearlmutter, Alexey Andreyevich Radul, and Jeffrey Mark Siskind. Automatic differentiation in machine learning: a survey, 2018.
2. Waltraud Kahle, Sophie Mercier, and Christian Paroissin. Degradation Processes in Reliability. Mathe- matics and Statistics Series, Mathematical models and methods in reliability set, Vol. 3. June 2016.
3. Charles C. Margossian. A review of automatic differentiation and its efficient implementation. WIREs Data Mining and Knowledge Discovery, 9(4), March 2019.
4. Toshio Nakagawa. Maintenance Theory of Reliability. Springer Series in Reliability Engineering. Springer Science & Business Media, London, 2005.

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Track Classification: Spring Meeting

Contribution ID: **28** Type: **not specified**

Data-Driven Model Selection and Performance Assessment of Solar Chimney Systems Using CFD and Multivariate Analysis

The increasing complexity of engineering systems and the growing demand for sustainable energy solutions require robust data-driven approaches for performance evaluation and decision-making. Solar Chimney Power Plants (SCPPs) constitute a promising renewable energy technology; however, their optimal design remains challenging due to the interaction of multiple physical and environmental variables, as well as external operating conditions.

In this work, we propose a methodology that combines Computational Fluid Dynamics (CFD) simulations with multivariate statistical analysis to support model selection and performance assessment of different SCPP configurations. A dataset is generated from numerical simulations considering key variables such as air velocity, temperature, pressure, and mass flow rate, along with geometric design parameters of the system.

The proposed approach focuses on the joint analysis of multiple performance indicators in order to identify the most suitable configuration under different operating conditions. Statistical techniques, including correlation analysis and multivariate exploratory methods, are used to study the relationships among variables and to evaluate the global behaviour of each design alternative. Additionally, the methodology allows the detection of dominant factors influencing system performance.

In particular, Chernoff faces are employed as an integrative visualisation tool to represent multiple variables simultaneously, enabling an intuitive and comprehensive comparison of competing models. This approach facilitates the identification of patterns that may not be evident through traditional univariate or bivariate analysis.

The results provide a practical and interpretable framework for model selection in complex engineering systems, supporting decision-making based on multiple criteria. This methodology is aligned with current trends in data-driven engineering and offers potential extensions to reliability assessment, uncertainty analysis, and optimisation in other industrial applications.

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Track Classification: Spring Meeting

Contribution ID: **29** Type: **not specified**

A Piecewise Hidden Markov Model for Degradation and Maintenance

Hidden Markov Models (HMMs) are increasingly recognized in reliability engineering as valuable tools for monitoring systems where the true operational state is not directly observable and must be inferred from certain indicators provided by a control system. Accurate estimation of these hidden health states and prediction of failures are crucial for minimizing unexpected downtime and optimizing operational costs. While recent literature has demonstrated the utility of HMMs in estimating dependability measures, such as identifying failed components and assessing system reliability, the explicit integration of maintenance actions into these models remains an evolving area of study.

Traditional HMM applications often assume time-homogeneous transition dynamics, which may not capture the discontinuous physical effects of a maintenance intervention. Specifically, a maintenance action introduces an instantaneous restorative shock and often alters the subsequent aging rate of the system, which does not agree with the homogeneous degradation assumption.

To address this gap within a structured probabilistic framework, this paper presents a piecewise, time-inhomogeneous HMM approach designed to incorporate trend changes in system degradation. We model the degradation level over a finite state space, partitioned into functional and failure states. The system's operational evolution is decomposed into distinct chronological phases.

For robust parameter estimation, we propose an adapted Expectation-Maximization (EM) algorithm. A new algorithm is discussed to decode the hidden state trajectory across these varying temporal regimes. The proposed piecewise framework allows for the modeling of systems where the transition matrix structurally changes due to external occurrences. This framework provides a practical method to isolate natural degradation from repair actions, for instance, facilitating a rigorous evaluation of maintenance effectiveness in HMM-based reliability studies to determine the optimal timing for future scheduled interventions. Furthermore, this approach can be considered for other situations where the transition matrix changes due to external events, such as the arrival of a disruptive shock.

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Track Classification: Spring Meeting

Contribution ID: **30** Type: **not specified**

Adaptive Spare Parts Inventory Control under Stochastic Degradation

Efficient control of spare parts inventory is essential for maintaining the availability of engineering systems operating under progressive degradation. This paper proposes an adaptive decision-support framework that integrates stochastic degradation modeling with data-driven control policies for inventory management. By continuously updating the risk of failure and its implications for future demand, the approach enables dynamic assessment of stockout risk in the presence of supply lead times.The problem is formulated as a sequential decision-making task under uncertainty, in which replenishment actions are guided by the evolving condition of the system and the current inventory status. A reinforcement learning approach is employed to learn effective inventory policies that balance availability and cost considerations in a stochastic environment. The proposed framework provides a flexible and scalable solution for condition-informed inventory control, highlighting the potential of combining degradation modeling and artificial intelligence to improve decision-making in maintenance-intensive systems.

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Reinforcement Learning-Based Decision Support for Maintenance Optimization in the Steel Industry

Scrap-based steel production plays an essential role in promoting sustainable industrial practices by significantly reducing energy consumption and greenhouse gas emissions compared with conventional ore-based steelmaking. Despite these benefits, maintaining high operational efficiency, reducing the costs associated with recycling operations, and ensuring product quality in scrap-based production lines remain challenging. In particular, critical machines such as shredders and processing units operate within interconnected production systems, where failures or maintenance interventions can affect the overall performance of the system. This study proposes a deep reinforcement learning (DRL) framework to support inspection and maintenance decision-making in a scrap-based steel production line modeled as a multi-component system with interdependent components. The proposed approach dynamically recommends inspection time and maintenance actions based on the observed operational conditions of the production system, including machine productivity, buffer levels, and production demand. To represent the stochastic behavior of the production line, a simulation environment was developed incorporating practical industrial features such as variable production rates, uncertain maintenance durations, and component degradation processes. This environment enables the training of DRL agents capable of learning adaptive maintenance policies under dynamic operating conditions. The effectiveness of the DRL-based policies is evaluated by comparing them with commonly used maintenance strategies, including corrective maintenance, time-based maintenance, and condition-based maintenance. Results from the case study demonstrate that the DRL approach can effectively learn adaptive maintenance strategies that balance inspection frequency, maintenance timing, and production requirements. Compared with conventional maintenance policies, the DRL approach demonstrates strong potential to reduce operational costs while enhancing system reliability and production efficiency. These results highlight the potential of reinforcement learning as a decision-support tool for maintenance management in complex industrial systems. By enabling adaptive and data-driven maintenance planning, the proposed framework contributes to improving both the operational performance and sustainability of scrap-based steel production.

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Estimation of return levels with the generalised F distribution #5

The generalised F distribution (GenF) has been called an "umbrella"that covers several conventional distributions. In this work, we compare GenF with the Generalised Extreme Value (GEV) distribution with focus on estimation of return levels. Upper-tail asymptotics of the GenF are examined in relation to GEV. Potential numerical challenges in fitting the GenF are discussed. Data sets of river discharge and significant wave height data are analysed, as well as synthetic data from simulation studies.

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