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Reliability modeling challenges for systems with dependent failures or component degradation

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System reliability models and analyses involving multiple failure processes are challenging research topics, particularly when the failure processes, such as degradation failures and random shocks, are competing and dependent. For reliability modeling of complex multiple component systems, component failure time and/or degradation are often assumed to be independent as a simplifying assumption, although this is not always the case for actual engineering systems. If one component in the system degrades or fails prematurely, it is possible or even likely that other components also degrade or fail prematurely given the shared working environment or other reasons. This provides evidence of dependent component failure times or failure processes. When component degradation models are extended to complex systems with multiple components, different perspectives are needed for system reliability modeling, considering this dependency. These different approaches for modeling the reliability for systems with dependent failure processes or degradation processes are reviewed, and a new model is presented based on extended random effects gamma processes. Models for dependent failure and/or degradation processes can be formulated using Markov chains, copula functions, joint multivariate distributions or shared shock exposure models. Furthermore, machine learning models will be beneficial or even necessary when there are dynamic data sets and changing conditions. Each approach has specific advantages considering model fidelity, precision, ability to generalize or extend, and practicality. Stochastically dependent component degradation processes are specifically studied, and extended gamma process models are proposed to model the dependent degradation process. Based on these new reliability models, different maintenance policies can be derived to provide cost effective maintenance plans.

Speaker Bio: David Coit is a Professor in the Department of Industrial & Systems Engineering at Rutgers University, Piscataway, NJ, USA, with visiting professor positions at Universite Paris-Saclay, Paris, France and Tsinghua University, Beijing, China. His current teaching and research involves system reliability modeling and optimization, and energy systems optimization. He has over 130 published journal papers (h-index 61) and over 90 peer-reviewed conference papers. He

is currently an Associate Editor for *IEEE Transactions on Reliability* and *Journal of Risk and Reliability* and for 15 years was a Department Editor for *IIE Transactions*. His research has been funded by USA National Science Foundation (NSF), U.S. Army, U.S. Navy, industry, and power utilities. His NSF grants included a CAREER grant to develop new reliability optimization algorithms considering uncertainty. He was also the recipient of the P. K. McElroy award, Alain O. Plait award and William A. J. Golomski award for best papers and tutorials at the Reliability and Maintainability Symposium (RAMS). Prof. Coit received a BS degree in mechanical engineering from Cornell University, an MBA from Rensselaer Polytechnic Institute, and MS and PhD in industrial engineering from the University of Pittsburgh, and he is a member of IIE and INFORMS.

Battery degradation incorporated on fleet management optimization

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Historically, internal combustion engine vehicles have been the norm in terms of transportation.

However, to attenuate global warming, different actions to popularize Electric Vehicles (EV's) have been taken. In this transportation paradigm, the importance of understanding and improving battery lifetime has important economic consequences since this component is responsible for 35% to 50% of the total vehicle cost.

Since vehicle usage has a direct influence on battery lifetime, incorporating battery degradation on vehicle decision-making problems can lead to different insights and solutions that extend lifetime [1,2,3] However, to achieve practical degradation-aware decision-making, optimization models must realistically describe State of Charge (SoC) of the [4] and most works on decision making problems related to EV's use oversimplified SoC models. Including such models in optimization problems remain a challenge and therefore, simplified alternatives, that may lead to infeasible solutions in real applications.

In [5] a realistic degradation model and a realistic SoC model were used in a formulation of the shortest path problem. Now, we extend this concept to a whole fleet of vehicles, solving a new version of the Electric Vehicle Routing Problem (EVRP), which consists of assigning missions to an ensemble of vehicles according to an optimization criteria.

In our version of the EVRP, we include battery degradation and decision variables related to partial charging, maximum vehicle speed and maximum vehicle acceleration. Due to its computational complexity, heuristic optimization algorithms are proposed to solve it

Our approach is compared to other state of art models and the benefits of incorporating degradation in EVRP's are shown through numerical experiments and a sensitivity analysis is performed to identify which of those decisions lead to more impact on battery health and the overall exploitation cost of the fleet.

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Keywords: Electric Vehicle, decision-making, multi-objective optimization, degradation and degradation models, automotive sector.

First hitting time distribution in a two-component system subject to a degradation and imperfect maintenance

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Multivariate models are essential to assess the maintenance of complex degrading industrial systems. Some models for multi-component degradation systems assume that the components degrade independently. Although such an assumption allows tractable mathematical models, it remains unrealistic for systems where stochastic dependence is indeed present.

This work is focused on the study of a system consisting of two dependent components. The dependence is modelled with the so-called trivariate reduction method as follows: two dependent degradation processes are created from three independent degradation processes. Imperfect preventive maintenance actions are periodically performed and the overall degradation of the system is reduced in a fixed percentage. We assume that the system fails when the degradation of a component crosses a predetermined threshold. Under these assumptions, the first hitting time distribution is developed using a recursive procedure. Furthermore, the analytical cost model is obtained, and the expected cost rate is minimized considering the repair efficiency and the time between preventive maintenance actions as optimization parameters.

Keywords: *bivariate degradation, maintenance, imperfect repairs, first hitting time.*

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Title: Degradation model selection based on a comparison with the depth values of the median and the outlier of the functional data

Aref Asadi

Abstract:

Degradation modeling is a paramount issue in failure time prediction or maintenance planning of complex systems. The aim of degradation modeling is to select a model from a set of competing models capturing the features of the underlying degradation process. The stochastic-process-based models show great flexibility in describing the failure mechanisms caused by degradation. However, collected data and stochastic processes used for the modeling do not always satisfy the classical properties required to apply goodness of fit tests. The statistical depth could be considered a statistical tool for degradation model selection. A depth function reflects the centrality of the observation for a statistical population. Depth Function has been introduced to extend the notion of the median to multi-variate random variables as well as functional data. A Depth Function assigns the highest value to the median and the lowest value to the outlier of the functional data. The idea is to compare the depth value of the degradation trajectory with the median and outlier of the model respectively. A model will be selected if the degradation trajectory behaves more like the median of the model rather than the outliers. This model will be employed to predict the failure time of the system under study.

A GIS based approach to predict pavement deterioration on the UK road network

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The UK road network is a complex and dynamic system, managed by a federated network of organisations, often with stringent constraints on resourcing. Remediating deterioration of the network is both costly and politically sensitive; resilience, sustainability, and utilisation impacts must be constantly balanced by asset managing organisations.

An approach for localised prediction of deterioration is developed in this paper, combining remote sensing, automated survey, and IoT data into a GIS-based data model to support decision making. In addition, predictive models are proposed in this paper, based on random forest regression and classification approaches, which use the proposed data model to create localised deterioration profiles. The machine learning model has been trained with and validated against data from a 21km length of the UK Major Roads network, using ~10 years of condition data and authoritative traffic, cartographic, and environmental data from several UK government agencies. Both the regression model and the classifier is able to accurately predict industry standard condition metrics.

This approach could allow for early detection and mitigation of pavement failure and support maintenance operations on the network whilst minimising disruption and maximising return on investment.

Railway Track Degradation Modelling Using Dynamic Multi-Regression to Predict Failure Patterns

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Abstract

Railway track systems are constantly used and are also exposed to environmental factors leading to frequent degradation and subsequent failure. The review of relevant literature indicate that railway tracks, switches and level crossings are safety critical assets for trains operation, and failure can lead to significant impact on service operations as well as increase in the cost of maintenance resources and budget. This paper presents the modelling of track geometry defects due to increase dynamic of loads, and maintenance undertaken when degradation accumulates over time, and eventually leading to failure. The use of degradation signals indicates a potential way for modelling the reliability of safety-critical systems with a longer lifetime requirement. The paper focuses on used of stochastic dependence approach in which the failure of some system components can influence the failure or degradation of other system components. A twelve-year actual historical infrastructure field maintenance data record and estimates from Network Rail is used. An attempt is made to model the railway system degradation process using dynamic multi-regression model to predict failure Patterns. Simulation of the data and results gives an insight into control-limit thresholds for periodic inspection, appropriate maintenance interventions to increase critical asset availability, and hence performance improvement.

A condition-based maintenance policy for degraded solar farms under multiple environmental factors

Abstract

In this paper, a condition-based maintenance policy for a degraded solar farm is considered. This work investigates the effect of the dust accumulation and temperature on the photovoltaic (PV) panel working under varying environmental conditions. The PV panel suffers from dust accumulation and inner temperature increasing while the power generation efficiency decreases. The dust accumulation process is described by non-homogeneous compound Poisson processes (NHCPP). The effects of wind speed and rainfall on the deterioration rate are modeled by covariates via the Cox proportional hazards model. The covariates process is assumed to be a two-dimensional time-continuous Markov chain with finite state space. In the framework of the system under consideration, an appropriate condition-based maintenance policy leading to the minimal cost criterion is obtained. Both preventive and corrective replacement are considered according to the results of periodic system-state inspections. The preventive maintenance threshold F_p and inspection interval τ are selected as optimization parameters. Numerical implementations are presented to illustrate the performance of the proposed model.

Keywords

Solar farm, Condition-based maintenance, Degradation model, Dust accumulation, inner temperature, NHCPP, Covariates

A general approach for evaluating SHM system reliability with sensor failures

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Structural health monitoring (SHM) systems involve implementing damage identification strategies to determine health states of structures. However, it is important to pay close attention to the degradation of the SHM itself, especially the effect of sensor degradation on the reliability of the SHM. This paper aims to formulate a general framework for evaluating SHM reliability that takes sensor failures into account. The framework involves modelling the degradation process of sensor network using Petri nets (PNs) and calculating the expected information gain/loss of the sensor network based on Bayesian inverse approach. The PNs allow for taking account of the sensor location and the number of sensor failures. A Bayesian inverse procedure is used to calculate the expected information loss due to sensor failures, which integrates a damage localization and a damage identification scheme to update information about model parameters. The proposed framework is demonstrated for a plate with a part-thickness hole, monitored by an ultrasonic guided wave monitoring system. The given framework could be adapted to other monitoring systems. The proposed model is able to predict the health condition state of the SHM, which can be included in asset management models for various industries.

Managing Energy Resource Upgrading Decisions under Government Regulation and Emerging Technologies

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To mitigate the effects of long-term climate change, more governments are setting carbon emission targets. One of the sectors with the highest carbon emissions is the electricity production sector. Power producers can curb their carbon emissions by replacing old dirty technologies with cleaner new ones. We introduce a novel mathematical model to study how government regulations and emerging technologies influence power producers' capacity-related choices, such as keeping, upgrading, or decommissioning their power plants. Our model uses real options theory to value these capacity-related choices. If the value of a capacity-related choice becomes high enough, the company chooses this action. Governments can increase the value of upgrading to a cleaner energy source using the right incentives, such as a carbon tax. The uncertainty related to emerging clean energy technologies lowers the value of upgrading and can lead to companies waiting until clean energy technology is further matured before making the investment. We study what drives companies from dirty to clean energy sources in a numerical experiment. We study the optimal policy structure for power plant upgrading and how this is affected by external factors, such as government interventions or electricity price changes.

Title:

Integrated Planning of Usage-Based Maintenance and Condition-Based Load-Sharing for Engines of a Vessel

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Abstract:

In the literature, the effect of operations planning and maintenance planning on each other and the benefit of making these plans in an integrated way have been stated by many researchers. Recently, it has been realized that these two planning problems have not just an effect on each other, but they can be a way to control each other. Many researchers have focused on multi-unit systems due to the dependency between units, such as economic and resource dependencies. Although this problem is investigated by researchers numerically and analytically, the effect of the usage levels of the units on the operating cost has hardly been studied. Our research is motivated by the problem of integrated planning of load-sharing and usage-based maintenance for the engines of a ship. In this problem, for every time period, the engines will be used to produce the energy required for the use of the systems of the ship. In this study, this problem is investigated with the consideration of fuel consumption which is directly related to the amount of energy produced by each engine. The aim is to determine (near) optimal policies that minimize the total average maintenance costs for an infinite planning horizon.

On the use of a marker process for CBM in case of a latent degradation

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Abstract: Condition-based maintenance (CBM) suggests preventive actions to avoid failures, considering the system's state. The question which arises is what can be done whether the state of the system is not directly measurable due to some difficulty. Here, we try to deal with such a question. The degradation of the considered system leads to its failure. Consider it is latent, which means not observable. Meanwhile, we can measure and track the progress of a 'marker process' which is correlated with the latent degradation process. Thus, observations of the marker process provided in inspections allow inferences about the degradation process. To model the information gathered from such a system, we consider a bivariate gamma process where one univariate process represents the latent degradation process, and the other is the marker process. This paper presents two condition-based maintenance policies based on the measurement of the marker process. In one of the policies, the decision-making is directly based on the marker process while the other policy requires the inference of the actual degradation level given the information of the marker process. The performance of proposed policies depends on the strength of the relationship between degradation and marker processes. A simulation study is conducted to demonstrate the implementation of the two proposed policies, investigate their efficiency and identify the best option.

Keywords: Bivariate gamma process, condition-based maintenance, degradation process, marker process.

Model of Condition-based Maintenance with Multiple Imperfect Inspections

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Proactive maintenance that is done in accordance with the system's condition is known as condition-based maintenance. For the case where the system has a single component structure, the type of imperfect inspection corresponds to condition-based maintenance, the perfect repair is used, and only hidden failures occur in the system, we developed mathematical equations in this study to calculate maintenance effectiveness indicators, such as achieved availability, inherent availability, mission availability, and average maintenance costs per unit of time. Mathematical models have been derived for the scenario of multiple imperfect inspections and an arbitrary time-to-failure law. For condition-based and corrective maintenance, the optimal number of inspections for a particular stochastic degradation process was determined. The implementation of condition-based maintenance significantly increases availability and decreases the number of inspections, as demonstrated by our research.

Stochastic RAM Analysis of a Novel CO2 Capture Facility with Multiple Dependencies

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Evaluation of a CO2 capture demonstration in an industrial setting revealed multiple dependencies for resolution by stochastic discrete event modeling. A detail of the problem and the required input requirements for an open source R package are to be presented. Insight will be given to the object oriented program design for solution of such dependency models.

A nested Petri Net – Fault Tree approach for modelling complex failure behaviour in engineering systems

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Fault Trees (FTs) lack the capability to model complex features of engineering systems, e.g., complex maintenance strategies or asset management, that introduce dependencies between basic failure events.

The D2T2 methodology [1] overcomes such limitations through the tailored integration of Petri Nets (PNs) and Markov Models (MMs) with the Fault Tree framework. Such combination is provided maximizing modelling flexibility, while minimizing the size of more sophisticated models, which are restricted to the only dependent events [2].

Nevertheless, the modelling of dependencies involving entire subsets of components, as often encountered in real-world applications, may require the construction of large Petri Nets or Markov Models, putting strain on the analyst.

This research focuses on the generalization of the D²T² methodology, aiming at simplifying the dependency modelling of multiple components. The approach consists of the computation of subtrees involved in the dependency and the subsequent input of the analysis results into a PN model capturing the dynamic of their relationships. This is in turn computed and the results fed back into the FT framework, resulting in a nested PN-FT framework.

The solution proposed is described and demonstrated through its application to a simple case study involving a safety critical subsystem.

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THE NUMBER OF FAILED COMPONENTS IN A SYSTEM OF MULTIPLE TYPES OF COMPONENTS USING SURVIVAL SIGNATURE AND APPLICATION TO THE REPAIR KIT PROBLEM

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The number of failed components when the system fails is an important quantity in many aspects such as preparing for stocking or replenishing spare parts. A few studies of similar quantities have been investigated in the literature. However, they are restricted to systems with a single type of components or to specific system structures. Furthermore, the known periods of correct system function leading up to failure have not received more attention. This condition is realistic since the number of failed components when the system fails may vary depending on how long the system was working for. Several related events are considered, the probabilities for these events are derived using the survival signature. We consider the number of failed components of multiple types at the future moment at which the system fails, given that the system was functioning at some point in time. We also consider the number of failed components at system failure time, assuming the system will fail in a specific future time interval.

The results of these events are applied to several settings of the repair kit problem. Specifically, we use the probability of the number of failed components when the system fails, in the cost model, to quantify the cost of a possible second visit when there is a penalty cost if a kit cannot repair all failures. Moreover, the derived probability is used as a constraint to express the service level required by the customers in the service model.

Title: Spatial Reliability Importance Measures

Abstract: Reliability importance measures are used to quantify and rank components with respect to the influence they have on system reliability. The most widely used include the Risk Achievement Worth, Risk Reduction Worth, Birnbaum, and Criticality importance measures. However, there are applications where measuring and ranking the influence that parts of a system within bounded regions of the physical space it occupies, instead of named components, on system reliability may be more useful. Examples of such applications include measuring the influence on system reliability of fire zones in an offshore oil platform and “behind armour debris” zones from projectile impacts on an armoured fighting vehicle. Spatial reliability importance measures are introduced as ways of measuring the influence on system reliability from this perspective. These can be used for decision support in analogous ways to traditional component importance measures, such as for focusing improvements on the region with greatest reliability effect or prioritising regions for fault-finding in a failed system, as well as new ones such as optimising the physical layout of system components. They also enable the visualisation of system reliability over the three-dimensional Euclidian space occupied by its geometry, which brings new insights.

Extension of Common Measures of Importance for Dynamic and Dependent Tree Theory (D²T²)

John Andrews and Sally Lunt

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Abstract

Traditional Fault Tree Analysis (FTA), known as Kinetic Tree Theory (KTT), was derived by Vesely [1] in the 1970s to model and analyse engineering systems. The tree structure provides a clear visual representation of the causes of system failure in terms of component and software failures and human errors. One limitation of KTT is the necessary assumptions of constant component failure and repair rates and independence of component failure and repair rates. Both assumptions limit KTTs ability to model modern engineering systems effectively.

In 2023 Andrews and Tolo [2] published the D²T² methodology designed specifically to address these limitations in the most efficient manner. The methodology retains the tree structure and combines the use of BDDs, Markov Methods and SPN models to analyse engineering systems involving non-constant failure and repair rates and component dependencies as efficiently as possible. The methodology ensures that no matter how far apart the dependent events are in the tree structure, the dependency model only features these components. As such, the dependency models are minimal, maximising efficiency. The methodology enables the calculation of both the system unavailability and the system failure frequency. However, in order to obtain the full range of output, the methodology needs to be extended to calculate measures of importance. This paper suggests an extension that enables the calculation of the following key measures of importance:

- Birnbaum's measure of importance
- The Criticality Measure of Importance
- Fussell-Vesely's measure of component importance (possibly a suitable approximation)
- Fussell-Vesely's measure of Minimal Cut set importance
- Barlow and Proschan's measure of enabler importance
- Lambert's measure of enabler importance.

Keywords: Fault Tree Analysis, D²T² methodology, importance Measures, dependencies

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Wrangling Lots of Data to Enable Warrantee Analysis

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Abstract. A large data set, admittedly synthesized, was provided for demonstration of analysis techniques to be used to satisfy management requests for warrantee analysis. Discussion will be given to the specific challenges that can occur with such big data and particular management demands. Modeling is performed in the open source R environment.

Modeling Alternative Inspection Protocols for Latent Failures

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Abstract. Fault Tree analysis has a history in modeling risks in many industrial instances. A focus is given to the use of Conditional Gates and Dormant Events to explore the inspection protocols for several points on a single system. Inspections on dormant components vary in complexity and cost, such that identifying an appropriate inspection protocol requires sensitivity to these costs. The free open source R package FaultTree is used to demonstrate an example problem to illustrate this kind of modeling.

Phil Scarf

Title: Modelling for maintenance planning: some reflections

This keynote presentation will be partly an opinion piece about the role of mathematical modelling in maintenance planning and partly a description of a recent project to develop a digital twin (DT) of a reverse-osmosis desalination pressure-vessel. This DT uses a mathematical model of wear and repair of membranes in such a pressure-vessel to assess the feasibility and cost of various potential repair policies. It is not practical to assess such policies directly on the system. My experience on this project and others will be reviewed in the opinion-piece. The talk will also discuss a framework for mathematical modelling in maintenance planning. This framework is a fusion of what the academic literature says about maintenance planning, mathematical modelling and optimization, and what I think works and is useful and what doesn't and isn't.

Optimization of Life-time Extension with an application to PC upgrading.

Rommert Dekker

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In this presentation we consider a system consisting of multiple components with different deterioration rates. One has the option to replace one or multiple components if the state of the system is below a certain threshold. We derive the optimal policy which minimizes long-term costs under quality constraints. This policy however is not workable in practice, as it is a state-dependent policy. Hence, we present a heuristic policy which has a clear interpretation, thus facilitating applications. We next investigate when this heuristic is optimal and when it produces inferior solutions. We apply the approach to the case of upgrading PC components, like CPU, GPU and HDD. We show how we obtain deterioration rates from Passmark data and indicate what kind of upgrade may be cost efficient.

After-sales services during an asset's lifetime: Collaborative planning of system upgrades

Geert-Jan van Houtum, Fiona Sloothaak, Alp Akcay, Matthieu van der Heijden

We consider a single technical system (e.g., a radar system) that is part of an asset (e.g., a frigate) with a long, but finite lifetime. We study the upgrade decisions for the technical system, which has a much shorter lifetime than the asset. In our model, we capture the key critical factors that drive the upgrade decisions: increasing functionality requirements due to evolving technology, age-dependent maintenance costs, a predetermined overhaul plan of the asset, and the lifetime of the asset. A system upgrade is less costly if it is executed jointly with an asset overhaul. We analytically characterize the structure of the optimal upgrade policy for different types of cost functions for the key critical factors and under the assumption that there is no extra cost for an upgrade outside an overhaul interval. We then use these results as a building block for the case that such an upgrade involves an extra cost. Finally, we show how the optimal costs and optimal number of upgrades depends on the various input parameters.

Data-Driven Condition-based Maintenance Optimization: Conservative Maintenance Decisions with Limited Data

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Unexpected failures of operating systems can result in severe consequences and huge economic losses. To prevent these unexpected failures, preventive maintenance based on collected condition data can be performed. A recent study has suggested a data-driven approach to estimate the failure probability at each observed deterioration level, and to use an optimality condition to select one of the observed deterioration levels as the condition threshold for performing preventive maintenance. Although this approach performs quite well if a lot of condition data is available, it has the drawback that only deterioration levels that have been observed in the past can be detected as the condition threshold. This typically leads to overly optimistic maintenance policies. To overcome this issue, we propose using a sigmoid function to estimate continuous failure probability and adapting the optimality condition to determine the preventive maintenance threshold from continuous deterioration levels. Numerical results for a stationary gamma deterioration process show that the maintenance thresholds resulting from the proposed approach converge to the optimal threshold faster, particularly when only a limited number of runs-to-failure data are available.

Keywords: Condition-based maintenance, Data-driven, Limited data problem, Control limit policy

Joint reliability assessment and adaptive control for a balanced system considering actuators degradation

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Abstract. The effect of control action is crucial to system reliability. However, it has been not significantly investigated in the literature, particularly for balanced systems which require strict control to maintain balance restriction. The purpose of this paper is to present a reliability assessment and adaptive control for a balanced system considering actuators degradation. The degradation state of an actuator process affects vice versa to the control actions by forcing them to increase generating stress on the actuator in order to maintain the desired setpoint. In that way, first we propose a novel degradation model for actuators considering the impact of control actions. An adaptive control allowing considering the degradation state of actuators is then developed. Illustrated with the use case of quadcopter, the reliability of the system has been analyzed and effects of proposed control policy have been demonstrated with simulation.

Maintenance recommendation for photovoltaic systems using
Markov Decision Process and Machine Learning

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Solar energy production has grown annually at a rate of 40%, and the associated technology and the configuration of the plants themselves are changing in a disruptive way. Large-scale photovoltaic (PV) systems present configurations with hundreds of MW installed and various technologies involved. Currently, we face the challenge of optimising the profitability of these assets due to the significant increase in installed power, the difficulty of accessing the panels, the significant amount of employee hours needed for data analysis, and the need for adequate management tools. In this context, our work aims to increase the operational performance of PV systems by improving current practices in O&M. We develop a condition-based maintenance approach using Markov Decision Process. Our methodology can prioritize actions, advise asset replacement, and schedule preventive maintenance tasks based on past experiences. With the use of predictive algorithms, we can identify the current operational state of the PV system. As a result, we generate economic improvement through downtime reduction and early detection of system underperformance.

Reinforcement learning for maintenance decision-making and optimization: a literature review

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Abstract. Nowadays, maintenance managers are looking for ways to design more efficient approaches for maintenance decision-making and optimization. In this regard, Reinforcement Learning (RL) is proved to be an efficient tool due to its flexibility and adaptability which allow converging for an optimal policy, especially in dynamic environments. RL is an iterative learning-based machine learning paradigm. It might be characterized as a sequential decision-making process, in which one or more agents interact with their environment to learn a repertoire of ideal actions that maximize a long-term reward based on the observable environmental states. The capacity to manage complicated scheduling tasks and optimization problems in dynamic systems, together with the natural ability for data-driven decision-making, have made RL a hot topic in maintenance field. It has demonstrated effectiveness in delivering a more adaptable and flexible maintenance policy for complex and modern systems, with the potential to improve some performance metrics, including availability, reliability, and cost. Deep Reinforcement Learning (DRL), which combines RL and deep neural networks, has more recently given this tool the ability to address data complexity that is typically present in sensor monitoring data and solve maintenance optimization problem in large-scale systems. Recent RL and DRL implementations, however, place a greater emphasis on maintenance features like prognosis and diagnosis rather than on decision-making and planning. To provide researchers and practitioners with a holistic view of the existing applications, this work conducts a literature review on the use and application of RL in finding optimal maintenance planning. A string search was defined, and the related papers were collected from different databases such as Scopus, Web of Science, and IEEE Xplore. The main contribution is to give a general understanding of where and how RL has been applied for maintenance decision-making and optimization and identify the main knowledge gaps.

Keywords. Reinforcement learning, Maintenance decision-making, Maintenance optimization

Deep learning for Remaining useful life prediction of proton exchange membrane fuel cell of an electro-hydrogen generator

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The proton exchange membrane fuel cell (PEMFC) is a critical and essential component of zero-emission electro-hydrogen generator. The accurate prediction of its Remaining Useful Life (RUL) is important for the optimal operation management and preventive maintenance of the system. However, the system's RUL is strongly affected by the PEMFC working conditions such as temperature, cell current, hydrogen pressure, etc. The RUL prediction becomes a very challenging task and should be investigated. In our paper, we develop a new prognostic model based on deep learning, considering the dynamic working conditions for the PEMFC's RUL prediction. The proposed model is then tested and compared to other methods, such as the backpropagation neural network (BPNN) and the long short-term memory (LSTM), by considering a real dataset collected from an electro-hydrogen generator.

Title: Engineering informed ML models for improved condition-based monitoring of wind turbines.

Aaron Kang, Onyx Insight, William Higham, Onyx Insight, Dr Joshua Greenslade, Onyx Insight

Machine learning models are becoming more frequently adopted recently within the wind industry due to their ability to provide predictive maintenance solutions, which can significantly reduce maintenance costs, increase system reliability and availability, and improve overall performance.

This paper presents case studies on the development and validation of two machine learning models for condition-based maintenance of wind turbines. The first model is used to determine main bearing health. In the model, the expected main bearing temperature is predicted based on various sensor readings, which are selected and filtered using engineering knowledge to maximise model performance. The second model implements a deep learning approach to assess pitch accumulator health. Pitch accumulator failure is a common failure with no pre-existing monitoring solution. The approach provides early warning for potential failures and reducing operational risk.

In addition to presenting the development and validation of the machine learning models, this paper also discusses the challenges associated with maintenance record data, data quality, and failure data. The case study highlights the importance of high-quality data for developing accurate and reliable machine learning models for condition-based maintenance.

Overall, the results demonstrate the potential of machine learning models in improving the efficiency and effectiveness of condition-based maintenance in the wind energy industry. The developed models can be used to estimate remaining useful life, reduce maintenance costs and improve system reliability and availability, leading to significant economic and environmental benefits.

MIMAR 2023 Tool Condition Monitoring in Turning with Artificial Intelligence

Lorenzo Colantonio, Lucas Equeter, Pierre Dehombreux & François Ducobu

Machining operations are widely used, but as the cutting tool degrades, the quality of the machining decreases. As a result, machining tolerances are no longer met which can result in parts being rejected. It is therefore necessary to monitor the degradation of cutting tools in order to replace them at the best time and thus avoid the production of poor-quality parts. To achieve this, artificial intelligence methods can be used to monitor tool degradation in real time. A neural network approach is presented to monitor tool wear in real time based on data collected during instrumented turning tests. The signals recorded during the tests are pre-processed and used to train a neural network to estimate the cutting tool degradation. The results cover the entire acquisition chain, from the data collected by the sensor and its processing to its use in the neural network.

Prescriptive Maintenance Optimization under Heteroscedasticity in Lifetime Distribution of Components

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In industrial production, maintenance is crucial, and age-based maintenance policies focus on developing maintenance strategies based on estimating the lifetime distribution of components. In this study, we focus on a single-component system and aim to determine the optimal maintenance time that minimizes the cost rate in a replacement cycle by leveraging prescriptive maintenance strategies that predict the lifetime using data-driven methods. The feature of the component determines its lifetime distribution, making the variance of the distribution critical. However, existing studies use homoscedasticity regression models, neglecting the heteroscedasticity of the data, leading to a significant gap between the policy obtained from their model and the theoretical optimal strategy. To overcome this gap, we propose a heteroscedasticity-captured regression model to estimate the lifetime distribution. We estimate the mean and variance functions using the Kernel method and obtain the estimated optimal strategy based on these functions. We demonstrate the consistency of the mean function, variance function, and estimated strategy and provide the rate of convergence for each to their true values. Additionally, we show that the proposed model is competitive against other homoscedasticity regression models under data uncertainty by extending to distributionally robust optimization. Our proposed model and solution approaches offer an effective and robust approach to maintenance decision optimization that considers heteroscedasticity's impact on the lifetime distribution of components. The numerical experiments support the attractiveness and advantage of our approach.

Opportunistic condition-based maintenance for sea water pumps in a nuclear power plant

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The objective of this paper is to study the effectiveness of opportunistic condition-based maintenance strategy for the sea water pumps in a nuclear power plant. For the presented study a primary seawater system consisting of four sea water pumps, supplied by three water chambers, have been considered. There exists the functional dependency and state interaction between these pumps due to the operation policy. This results in the degradation of the pumps at different rates. In order to ensure the availability of the pumps for the effective operation of the plant, an optimal maintenance strategy is required. In this paper, both functional dependency and state interactions between the components are firstly modelled. An opportunistic condition-based maintenance strategy considering these dependencies between the components is then proposed. The proposed opportunistic maintenance policy takes into account the quality of the maintenance actions (perfect and imperfect). A cost model is then developed to evaluate the performance of the proposed opportunistic maintenance policy. Long term simulation results show the effectiveness of the proposed model and opportunistic maintenance policy.

keywords: Nuclear reactor, degradation, failure rate, sea water pump, Imperfect maintenance, perfect maintenance, opportunistic maintenance.

Optimization of imperfect condition-based maintenance

Bram de Jonge

Industrial systems are in general subject to deterioration, ultimately leading to failure, and therefore require maintenance. Due to increasing possibilities to monitor, store, and analyze conditions, condition-based maintenance policies are gaining popularity. We consider optimization of imperfect condition-based maintenance for a single unit that deteriorates according to a discrete-time Markov chain. The effect of a maintenance intervention is stochastic, and we provide reasonable properties for the transition matrix that models the effect of maintenance. Because maintenance does not always bring us back to the as-good-as-new state, we are dealing with a semi-regenerative process rather than a regenerative process. We provide different methods to determine the optimal maintenance policy and aim to prove that the optimal policy is of the control-limit type.

Joint optimization of reallocation and maintenance policies for 1-out-of-2 pairs: G balanced system

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Abstract. In a physical system consisting of multiple functionally exchangeable components, differences in components degradation levels due to various random factors, such as workloads and external operating environment, can significantly affect the system's performance. The dynamic reallocation of these components among different installation positions can be an effective way to explore the full use of all components, and hence, prolong the lifetime of the system. In this study, we quantify the benefit of incorporating reallocation into a condition-based maintenance framework for a 1-out-of-2 pairs: G balanced system, where the system balance is defined based on component positions. Component degradation is modeled as a Gamma process and is inspected per time unit. A Markov decision process model is developed to determine the optimal joint reallocation and replacement strategy that minimizes the long-run average cost. A numerical investigation and sensitivity analysis are conducted by varying degradation and cost parameters. Key insights into the structure of the optimal policy are obtained, including the fact that reallocating two units, particularly when the degradation level of the forced-down units is relatively low, is often more cost-efficient than replacing failed units. Policy comparison shows that the proposed joint reallocation and replacement policy can significantly outperform other policies, including reallocation-only and replacement-only policies.

Reducing Turnaround Duration for Sea Water Plant Treatment Modules

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Turnaround events are unique type of maintenance projects that has limited duration and resources. Thus, it is crucial to ensure these projects have the planning and execution streamlined to adequately address such challenges. This work is a case study of how chronic schedule slippage of turnaround of water treatment modules was analyzed and addressed. The study followed DMAIC methodology to identify and analyze the root causes of the repetitive slippage, come up with an improvement plan and establish a control process in place. As a result of following the study recommendations, the average treatment module turnaround duration was reduced from 179 to 91 days. Consequently, annualized USD 580,00 of around was accomplished. Also, the reduction in duration helps in reducing the risk of unsafe events associated with turnaround maintenance activities.

A framework for evaluation and fair comparison of the performance of maintenance teams

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We present a framework for evaluation and fair comparison of the performance of maintenance teams, even when they work under different conditions, dealing with technical systems with different reliability properties. The research was motivated by a situation faced by a maintenance manager of a Brazilian company: he seeks to identify maintenance teams that have implemented the best practices, aiming to establish internal benchmarking and a policy of rewarding results. However, most maintenance indicators presented in the literature fail to provide a way to fairly compare the performance of maintenance teams dealing with very different systems. We then developed a framework based on the idea that for each technical system we can define a minimum level of performance, which could be achieved with the optimal implementation of a standard maintenance policy, designed to be widely adaptable. To estimate the reference performance level, we propose a knowledge elicitation protocol, within the scope of the Evidence Theory of Dempster-Shafer. Additionally, we considered uncertainty propagation with Monte-Carlo simulation. The framework was initially tested with simulated scenarios, and then an application with real systems was carried out, showing a reasonable discrimination when comparing the performance of different maintenance strategies in medium- and long-term.

A maintenance policy for a bi-component system under internal deterioration and external shocks

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Abstract: We propose a maintenance policy for a bi-component system (C1 and C2) with stochastic dependence. C1 suffers internal degradation and fatal external shocks. Failure of C1 results in immediate defect of C2. If the defect is not induced, C2 defect occurs because of internal deterioration. The deterioration of both components is modelled via the delay time concept. Shocks arrive at C1 according to a non-homogeneous Poisson process, leading it to immediate failure. The shock rate depends upon the state. The defect and failure of C1, as well as the defect of C2, are only detected by an inspection, whereas the failure of C2 is immediately revealed. Inspections are triggered every time interval T to identify the state of C1, replacing it if it is in the defective or failed state. If C1 is defective, an inspection is immediately performed on C2 to preventively replace it if it is defective. After M inspections, the system is replaced preventively. Therefore, the objective of this study is to determine the interval between inspections and the age for preventive replacement in order to minimise the cost-rate in the long run of the whole system. A case study is presented to study the cost effectiveness of the maintenance policy.

Preventive maintenance policy in photovoltaic systems using Reinforcement Learning

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The development of new technologies and the improvement of systems made solar photovoltaic (PV) energy generation grows exponentially in the last years. Research into failure and degradation mechanisms has become necessary for obtaining efficient and reliable systems. However, unsolved challenges remain concerning safety, unforeseen outages, and high operation and maintenance (O&M) costs. Early detection of problems is essential to provide reliability and avoid production losses over time. Performing preventive maintenance can anticipate faults and limit unplanned downtime as it is based on history and probability of failure. This work aims to increase PV plants' operational performance by improving the methodologies for O&M in PV systems. A Markov Decision Problem model is adapted to a Reinforcement Learning approach to recommend preventive maintenance actions in PV systems considering equipment degradation, such as cables and switches in the inverter. The methodology allows to explore the economic and energy production benefits of the detection, prevention, and mitigation techniques applied to PV power production. Case studies consider large-scale scenarios and show that the approach can be applied to create a long-term horizon planning maintenance policy

System Inspection and Maintenance Planning using the Survival Signature

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The survival signature was introduced just over a decade ago, to enable quantification of reliability of large systems with relatively few different types of components. It is a summary of the system structure function, based on the key assumption that failure times of components of the same type are exchangeable. In recent years, it has attracted much attention with a range of illustrative and real-world applications being presented. Furthermore, several generalized survival signatures have been presented for a range of system scenarios, including phased missions and multiple systems which share components. Recently, the first attempts to use the survival signature for planning of inspection and maintenance activities have been proposed. In this presentation, the possibilities and problems for such attempts are discussed, and one scenario considering preventive maintenance for multi-state systems with multi-state components is presented in some detail.

This presentation is based on joint work with Mahdi Tavangar, Marzieh Hashemi (both University of Isfahan, Iran) and Tahani Coolen-Maturi (Durham University, UK).

A scalable maintenance optimization model for multi-state multi-component systems.

Authors: Ipek Kivanç, Claudia Fecarotti, Néomie Raassens, Geert-Jan van Houtum.

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Abstract:

Nowadays most original equipment manufacturers provide after-sale service, and as such they aim to develop customized service contracts. To support them in this practice, we develop a quantitative approach to craft maintenance policies which strike a trade-off between system *maintenance costs* and *output performance*. We consider a system of multiple heterogeneous components subject to degradation thus causing the system to operate at different levels of performance. Hence, we model the system and its constituent components as multi-state, and we characterize the contribution of the components to the overall system performance. The maintenance decision problem consists of determining the interval between scheduled visits at system level, and the thresholds triggering preventive replacement at component level. To respond to the degradation of system performance, we optimize two replacement thresholds with different urgency levels. We employ a decomposition approach based on which we optimize the maintenance policy per component by solving a Markov decision process via dynamic programming, and use an iterative procedure to optimize the interval of scheduled visits for the system. We investigate the structural properties of the optimal policies and then apply our model to a real case study to derive customized optimal maintenance policies.

Title: Spare parts decision model of marine hoses: a case study for offshore terminals in the Brazilian coast

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Abstract:

Exports and imports of oil and derivatives have high strategic relevance in Brazil and in the world. The movement of these hydrocarbons between ships and maritime terminals is a high-risk activity, given the possibility of leakage at sea and environmental impacts. Therefore, good physical assets management is of paramount importance and, for that, one of the points of attention is the proper management of spare parts that support the maintenance management of maritime terminals. Among the main spare parts of offshore terminals are maritime hoses. There is a lot of research on mechanical strength, construction materials and computer simulations on these components, but no studies were found in the literature on determining the optimal amount that should be kept in stock. Given this context, this work presents a decision support model for the optimization of the amount of spare hoses and exposes the application in offshore terminals responsible for supplying regions with millions of people along the Brazilian coast. The developed model proved to be easy to use and reduced the risk of economic, social and environmental impact on the company in which it was applied. The social impact is due to the reduction of the risk of oil shortages and derivatives in several regions of the country, which would result in a considerable increase in the cost of food, among others that depend on logistics with diesel trucks. The environmental impact is due to the reduction in the risk of environmental accidents caused by the increase in the level of service of oil transfer lines that cross kilometers at sea. And, finally, the economic impact due to the reduction in the cost of investment in fixed assets of approximately R\$ 20 million compared to what was expected before the application of the methodology, as well as the annual reduction in the cost of maintaining inventory by approximately R\$ \$5 million. In addition to the possible reduction in lost profit and the improvement of the budget estimate for the following years, the optimal point calculated for each type of hose resulted in a decrease in the risk of average out of stock by more than 22%.

Keywords: Spare Parts, Marine Hoses, Maintenance Management

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Since its introduction, the geometric process (GP) has been widely studied in the literature of reliability and maintenance. Many methods to extend the GP have been proposed. One strand of those extensions aims to extend it to describe the nonmonotonicity of the failure processes. Nevertheless, it is known that preventive maintenance only takes effect on items with increasing failure rates, which causes confusion between the monotonicity of failure rate functions and that of failure processes (described by a geometric-like process). As such, there is a need to discuss the relationship eliminate this confusion. This motivates this research. The paper also aims to perform sensitivity analysis for the expected cost ratio of two maintenance policies where the failure processes are geometric-like processes. Numerical examples are provided.

Title: A Novel Approach to the Optimisation of Blade Defect Repair Workflows Based on Drone Inspections.

Aaron Kang, Onyx Insight, Dr Susie Naybour, Onyx Insight

Maintenance planning is an essential step in the PdM process, but it's often the least digitised, leaving little room for optimisation. The traditional approach involves manually reviewing blade drone images and creating a turbine-by-turbine repair plan. However, algorithm-assisted maintenance planning can streamline the process by allowing engineers to make data-driven decisions, save time, and optimise repair plans.

This talk presents an automated approach to maintenance planning that uses current and historical drone inspection data to create a model for defect severity. The model includes factors like defect size, position, type, and progression, which are weighted using an optimisation algorithm trained by expert blade engineers. By automating the defect repair selection process, the approach can save up to 75% of the time required for a fully manual process, and it provides a more consistent selection of defects for repair across multiple sites.

The approach is validated using data from numerous wind farms and compared with historic repair plans created by expert blade engineers. It provides a promising platform to increase blade maintenance efficiency further through repair strategies optimised for reducing cost. The automated approach allows engineers to fully consider the benefits and drawbacks of different maintenance strategies, and it gives rise to the opportunity to rapidly iterate different scenarios and optimise repair plans.

In conclusion, an algorithm-assisted approach to maintenance planning can help engineers make more efficient and data-driven decisions, reduce the time required to plan maintenance, and optimise repair plans. The automated defect repair selection process provides a more consistent and time-saving approach to maintenance planning, and it has the potential to further increase blade maintenance efficiency by optimising repair strategies.

Developing effective maintenance policies for systems with high equipment access costs

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Abstract: In this article, the main objective is to propose maintenance models for systems where access to equipment is costly. This is especially relevant for systems in which long distances need to be travelled for maintenance actions to be carried out, or where logistical difficulties or adverse conditions can arise during access. It is crucial to take advantage of events or circumstances that provide opportunities for cost-effective maintenance actions, while also considering possible impediments that may prevent the execution of planned maintenance. We develop, compare and numerically analyze policy outcomes in order to show under what circumstances the use of policies that consider opportunities and impediments are useful for complex access systems. The models are simple to implement and therefore has the potential to provide cost-savings for maintainers of such systems.

Imprecise statistical inference based on robust Bayesian analysis for step stress accelerated life testing data

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Abstract

A new imprecise statistical method is developed for step stress accelerated life testing data, where the Arrhenius link function is implemented for the data analysis. This function expresses the relationship between the lifetime and the applied stresses in terms of temperature to link the scale parameters at different stress levels. This method consists of two steps. First, it transforms failure times occurred by different strategies of experimental settings at higher stress levels to the normal stress level. Secondly, it creates imprecision based on robust Bayesian analysis for the acceleration parameter. This imprecision allows to transform failure times into interval values at the normal stress level where it is assumed that these transformed failure times are not distinguishable from failure times occurring at the normal stress level. This method leads to more imprecision if data are used from higher stress levels or in case of model misspecification. The performance of this method is evaluated by simulation studies.

Keywords: imprecise statistical inference; step stress accelerated life testing; Arrhenius link function; robust Bayesian analysis.

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Bayesian analysis for virtual age model

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Abstract

During the lifetime of a system, repairs are performed when the system fails. The Renewal Process (RP) represents perfect repair or as good as new, and Nonhomogeneous Poisson Process (NHPP) represents minimal repair or as bad as old. However, the repair sometimes will be between minimal repair and perfect repair, which is called imperfect repair. Kijima's type I virtual age model can be used to model these types of repairable systems. This model contains a parameter q which reflects the restoration level after each repair. The value $q = 0$ indicates perfect repair, while $q = 1$ reflects minimal repair. Values of q between 0 and 1 model repair results in between these two extreme scenarios. Bayesian analyses are presented for this model, including consideration of the system's overall time to failure if a given number of repairs is possible, and some related decision scenarios are also considered.

Improving the Modelling Capability of an Integrated Fault Detection and Diagnostic Petri Net Methodology for Dynamic Systems

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ABSTRACT

The existing Generalised Stochastic Petri Net and modified Bayesian Stochastic Petri Net (GSPN-mBSPN) methodology has demonstrated an improved modelling capability of using Bayesian-supported Petri net approaches for fault diagnosis in a dynamic system with feedback control loops. However, the GSPN-mBSPN approach uses predefined input prior and conditional probability tables (CPTs) for fault diagnosis. Thus, this limits the usage of the approach for dynamic fault diagnosis. Hence, this paper presents an improved GSPN-mBSPN modelling approach for automatically generating the CPTs tables for the fault diagnosis of dynamic systems. First, the elements (places and transitions) of a GSPN-mBSPN model of a system are analysed and structured into the system components (C) and interactions (I) Petri net modules (PMs) to create data structures for the CPTs tables. The CPMs and CIPMs describe the system components' working and failure state(s) and the causal relationships between the system components' states and the observable system process parameters. Through the model simulation, the entries of the CPTs tables are populated accordingly. The results of applying the methodology to the operation of a water tank level control system demonstrate an improvement in the modelling capability of the existing GSPN-mBSPN approach for system fault diagnosis under time-varying dynamic conditions.

Explainable Artificial Intelligence (XAI) for non-conforming product detection: an application to fuel tank manufacturing

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Abstract: Artificial Intelligence (AI) techniques have been recently developed and successfully applied to the quality control domain. These techniques analyze the product data (image, weight, dimensions, ...) to detect non-conforming products automatically. They can help significantly reduce quality control-related costs and control time; however, their “black-box” effect (the lack of the results’ interpretability) limits them in many applications. In this context, Explainable Artificial Intelligence (XAI) helps to explain why an AI arrives at a specific decision and makes it more reliable. Through a real case study of fuel tank manufacturing, the paper compares the different XAI techniques, such as Gradient-weighted Class Activation Mapping (Grad-CAM) and Local Interpretable Model-Agnostic Explanations (LIM). The obtained results confirm the performance of the Grad-CAM when compared to other XAI techniques.

A systematic literature review on dependencies and resource constraints in opportunistic maintenance modeling: bibliometric results

L. Equeter*, P. Do **, P. Dehombreux* and B. Iung** (11pt font, single spacing, 6pt after)

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Abstract. Opportunistic maintenance (OM) is an effective maintenance strategy that allows reducing downtime and maintenance costs by performing several maintenance actions together by taking advantage of dependencies between components. The impact of various types of dependencies (economic, stochastic, structural, etc.) between components on the benefits of OM leads to strong yet scattered hypotheses in the literature. Existing reviews of OM either do not explore the variety of hypotheses, or are not specific to OM modeling. In this study, the current advancement in the consideration of dependencies, resource constraints and maintenance skill in OM modeling and optimization are reviewed using a systematic literature review protocol. Four relevant research questions are used to select publications on the topic. These questions focus on how workers' skills, dependencies, and resource constraints are considered in OM modeling, how OM is defined in the literature, how economic dependency, the most used dependence, is modeled, and identifying the optimization objectives. The bibliometric results show that, besides the economic dependence, the structural and stochastic dependence are predominant in the corpus, while there is a scarcity of workers' skills modeling. The study highlights the need for further research to enhance the models' comprehensiveness and adaptability to the industrial world's diversity.

Title: A disaster risk management model for situations of intense rainfall: a case study for a Brazilian city

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Abstract:

Public administration, whether at the local or national level, faces new challenges in adapting human life to alarming trends such as: an increase in the extent and frequency of natural disasters, threats to food and water supply, inadequate energy distribution and migration crises. Given this context, the worsening of the climate crisis forces policymakers to adopt a new perspective to combat its damaging impacts on urban functioning, especially concerning the quality of life under the occurrence of hydrological events. This problem is multifaceted so usually conflicting objectives impose hard dilemmas to decision-makers (DMs) once heavy precipitations can potentially promote fatalities, displacements, contamination of water bodies, economic losses, and others. This paper aims to propose a novel multicriteria decision model for assessing and monitoring flood disasters, using the DM's subjective preferences to establish value judgements under risky situations. A numerical application in a Brazilian municipality is performed with the aid of a Decision Support System (DSS) with views to validate the new approach. By integrating statistical, graphical, and tabular information, this model is replicated in other urban areas in which the model assumptions are assumed. Moreover, the model results can be analyzed by DMs not only for taking preventive actions against floods, but also for enhancing early warning systems to reduce disasters.

Keywords: Disaster Risk Management, Multi Criteria Decision-Making, Flood Risk, Natural Hazards

A simulation-based life cycle cost model for track form selection-implementation

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This work presents the implementation result of a simulation-based model proposed previously with simplification. The model is to evaluate life cycle cost of a given track form. It is based on known degradation conditions and life time distributions of track components and thresholds for initiating relevant maintenance actions. Based on published experience, the concrete slab is taken as maintenance-free for ballastless track. Maintenance costs only arise from preserving the conditions of other superstructure components. In contrast, ballast constitutes a substantial part in the maintenance demand of ballasted track apart from the superstructure components common to those of ballastless track. Monte Carlo simulation is applied in the model. Data from various sources are sought for the relevant track components which were collected under different application contexts due to lack of complete data sets for individual applications. The purpose of the study is to demonstrate the feasibility of the proposed approach. It is expected that with increasing availability of supporting data, the model can grow into a useful decision support tool which the rail industry can use for the selection of the appropriate track form for a specific application situation.