MAINTENANCE RESEARCH DAY

4 February 2016

NS Trefpunt - Utrecht

Organised by

TU/e Technische Universiteit Eindhoven University of Technology

UNIVERSITY OF TWENTE.

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Welcome

A lot of research on maintenance is being performed in the Netherlands and in Flanders, ranging from research on wear and failure behaviour to optimization of maintenance intervals or spare parts logistics, and from research on power generation and distribution, to transportation, and to manufacturing equipment. We felt that we were missing the overview; your attendance today suggests that you share that feeling.

Today, we believe we have together all the relevant groups involved in maintenance topics. We have two excellent plenary speakers from the Delft University of Technology and the University of Groningen to open and close the day, and twenty speakers in parallel sessions from seven different universities. Since the primary aim is to know what others are doing, we have scheduled only two parallel streams of sessions. This should give you, and us, the opportunity to also see presentations that you would not see at your regular conference.

After lunch, we re-energize in a more interactive session. We have a speaker introducing an interesting topic, followed by a discussion with the audience. There is further ample time to discuss with colleagues who you already know and to meet new colleagues.

We hope that you will enjoy the day!

Dr.ir. Rob Basten,
Eindhoven University
of Technology

Dr.ir. Alberto Martinetti,
University of Twente

Marc Coumans, BSc,
Eindhoven University
of Technology

Program

09.00-09.30	**Entry**
09.30-09.50	**Welcome by organization** **Introduction by prof.dr.ir. Leo van Dongen**
09.50-10.30	**Plenary session by prof.dr.ir. Rinze Benedictus**
10.35-11.15	**Parallel session 1** **1A** Bram de Jonge & Richard Ruitenburg **1B** Feng Fang & Roland van de Kerkhof
11.15-11.40	**Coffee and tea**
11.40-13.00	**Parallel session 2** **2A** Viswanath Dhanisetty & Nils Knofius & Sajjad Rahimi Ghahroodi & Loe Schlicher **2B** Szilárd Kálosi & Stella Kapodistria & Engin Topan & Minou Olde Keizer
13.00-14.00	**Lunch**
14.00-15.00	**Discussion session by dr.ir Jos Thalen**
15.05-16.25	**Parallel session 3** **3A** Qianru Ge & Andrea Sanchez Ramirez & Sha Zhu & Gero Walter **3B** Peter Kipruto Chemweno & Filippos Amoiralis & Joeri Poppe & Kim Verbert
16.25-16.45	**Coffee, tea and soda**
16.45-17.25	**Plenary session by prof.dr. Ruud Teunter**
17.25-17.40	**Conclusion by prof.dr. Henk Akkermans** **Farewell by organization**
17.40-18.30	**Drinks**

Plenary session speakers

Prof.dr.ir. Rinze Benedictus
Delft University of Technology
Plenary session

Maintenance: Task or Functionality?

Abstract

Designing a new aircraft today costs around 20-30 billion euros and buying an aircraft costs in the range of 20-300 million euros (depending on the size, and you need more than one to operate an airliner). These are huge numbers, and operating costs are not even yet included. Huge investments are needed and the increasing competition makes that an aircraft needs to be operated 24/7: disrupting issues like maintenance are not wanted. From a safety point of view it is the opposite. Using the aircraft will result in deterioration of the health of the aircraft. This can be restored by maintenance and if you would like to fly always with maximum safety, continuous maintenance is wished for.

These are two opposite views on the wish for maintenance, but there is way of making this one single view that will deliver both: continuous operation and continuous maintenance. If we can design objects (materials, structures or complete aircraft) that can monitor their own health, that can do self-reporting, that can communicate, and that can do self-repair, then we can have maintenance during operation. Then we achieve maximum safety combined with maximum operation time.

Some of the ingredients needed for this are already developed (and are being used to minimise downtime), others still need a lot of research and development. This talk will address some of those developments like self healing materials, structural health monitoring, and big data (how to get from data towards useful information). But also how there are interesting connections towards smart manufacturing.

Prof.dr. Ruud Teunter
University of Groningen
Plenary session

Various Aspects of Planning Condition-based Maintenance

Abstract

I will provide an overview of the research on maintenance that my group has been doing in recent years. Key research questions addressed include the following:

- How does Uncertainty about failures rates affect Time-based and Condition-based Maintenance planning?
- Under what general conditions is Condition-based Maintenance preferred to Time-based maintenance?
- How to perform Cost-effective Condition-based Maintenance in a Multi-unit System?
- When to inspect Multi-unit Systems for which Condition-based Maintenance is applied?
- How to schedule Condition-based Maintenance for systems with redundancy?

It may be clear that our core focus has been on Condition-based Maintenance, but also with a critical view of its downsides compared to other types of maintenance. One reason for this focus is that many companies currently perform corrective and Time-based maintenance, but see Condition-based Maintenance as the way ahead. We are currently involved in two major research projects where this is the case: Rail Infrastructure maintenance with ProRail and Off-shore Wind farm maintenance with a number of firms involved. Both projects are still at an early without much research

Discussion session speaker

Dr.ir. Jos Thalen
Invocate
Discussion session

The Art of Collaboration

Abstract

It can be quite challenging for researchers to really understand what is going on in practice. The other way around may me even more challenging: practitioners do not always understand what you are doing (and why). Especially when a project is relying on practical issues or case studies, effective and efficient communication and collaboration between researchers and practitioners is of vital importance.

In this talk I will share some examples of communication and collaboration between researchers and practitioners. In particular, a case study on the development and use of a serious game in a recent maintenance-related research project will be discussed. In addition to serious gaming I will also discuss the use of two other techniques, co-design sessions and virtual reality.

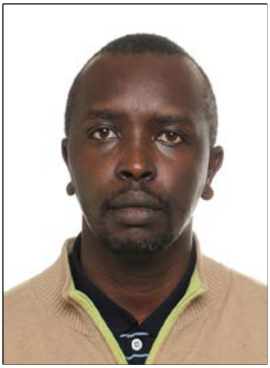
Parallel session speakers

Filippos Amoiralis
University of Twente
Session 3B

Application of Physics Based Maintenance in Maritime Applications

Abstract

Considering that in the maritime industry scheduled maintenance is extensively applied, there is a great potential for modernization. This can be achieved by the implementation of physics based predictive maintenance, which has the advantage of requiring a minimum amount of failure data. The suitable components are to be selected based on a generic methodology that will take into account their criticality, modeling feasibility, usage profile and impact on maintenance program. As a first case, the cylinder liner from the diesel engine was selected. The main degradation mechanism is abrasive wear, due to the sliding contact with the piston rings, loaded by the cylinder pressure. A commonly used equation to describe the mechanism of material loss through abrasive wear is called the Archard's law. The equation describes the cumulative volume loss as a function of the sliding distance (S), the normal load (L) and the material loss probability factor (k). The probability factor (k) depends on the lubricant and material properties and is determined experimentally. The sliding distance (S) for a specific liner position is related to the passage times of the piston rings and the thickness of the oil film. The passage times are proportional to the time that the engine is run at a certain speed profile. The oil film thickness is a function of the piston speed and the oil properties. The oil properties also vary with the cylinder temperature and pressure as well as oil age. Finally, the normal load (L) is proportional to the cylinder pressure, which exerts a force behind the piston rings, against the liner surface. These parameters are directly depended on the engine usage profile and can be related to the liner wear status. After completion of the model, the model results in combination with the usage history can be used to predict the just-in-time interval for replacing the liner. Additional cases shall be made on propulsion systems components with the ultimate aim of establishing a predictive maintenance framework for the maritime industry.



Peter Kipruto Chemweno
KU Leuven
Session 3B

Maintenance Decision Support: a Simulation Approach

Abstract
In today's industries, the need for optimizing maintenance decisions has gained prominence, more so, with respect to formulating maintenance strategies best suited for the organization. Often, such strategies mitigate the impact of unnecessary downtimes attributed to equipment failure. However, formulating such strategies is not straightforward owing to several challenges. Firstly, optimal spare parts provisioning performs a critical role towards sustaining the equipment's operational capabilities, owing to the fact that, the spare part demand is usually initiated by equipment failure. Here, sub-optimal replenishment lead times often imply unnecessary production losses. Moreover, the provisioning strategy is dependent on the reparability of the component where, component reconditioning is feasible depending on the degradation level at the time of repair. Invariably, this influences the stocking policy and by extension, the provisioning strategy adopted by the organization. To realistically model complexities associated with, on the one hand, the equipment maintenance strategy, and on the other hand, the spare parts provisioning strategy, simulation approaches are often explored, thus the subject of this study. The simulation approach evaluates the impact of alternative spare part provisioning strategies on repairable systems, and here, a multi-echelon provisioning system is mimicked. The approach further mimics' alternative maintenance policies, for instance, reactive maintenance, and condition based maintenance, where, depending on the type of policy adopted, varying equipment deterioration is influenced. The approach is implemented in the empirical case of thermal power plant engine failures and the results underscore the importance of component reconditioning on spare part provisioning for repairable systems, and moreover, in instances where both the reactive and condition based maintenance approach are implemented.

Viswanath Dhanisetty
Delft University of Technology
Session 2A

Multi-level Repair Decision-making Process for Composite Structures

Abstract

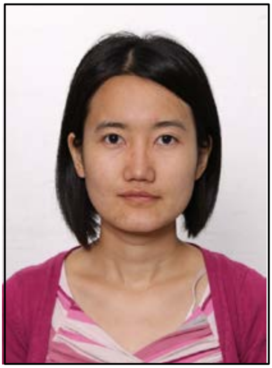
As next generation civil aircraft include progressively more composite materials in their designs, there exists a need for designing a comprehensive process for monitoring and maintaining such structures. The application of composites on a large scale in aircraft design is relatively new compared to the 70 plus years of expertise acquired from the use of metal. This presents a critical challenge for maintenance repair organisations that have comparatively limited historical failure data to support maintenance management and substantiate changes to limits for composite repairs. However, an opportunity can be seized in the decision-making process regarding the type and time of repair performed by an inspector based on the usage and the damage level of the structure of interest.

The research delves into developing a decision-making model evaluating the multiple repair levels that a composite structure can undergo, each with inherent achievable reliability and consequence to operations in terms of availability, costs, and scheduling. The goal of this model is to provide the maintainer an integrated approach to all feasible repair solutions within the operational and structural integrity constraints, applicable to any given damage levels found during monitoring. At its core, the model incorporates various stochastic processes to model different types of repairable behaviour: the non- homogeneous Poisson process, homogeneous Poisson process, and the general renewal process. Additional driving factors for the final repair decision such as maintenance resources and criticality are introduced. A case study on the carbon-fibre reinforced polymer flaps of a Boeing 777 is performed to verify and validate the proposed decision- making model. With the case study providing the means for application of the model in an operational context, a standardised decision making process is delivered that is adaptable to any given failure scenario and implementable in practice.

Feng Fang
Tilburg University
Session 1B

Learning to Adapt: the Case of Operation & Maintenance Service Outsourcing

Abstract
The paper investigates the learning mechanism in the development of contracting capabilities based on a longitudinal case study in the context of Dutch water authorities. The results show that organizations learn to adapt to unanticipated contingency in the contract execution stage through a deliberate learning mechanism. The adaptation process consist of three major steps: proactive information search (knowledge accumulation: information about technology and partners), sense-making (knowledge articulation: root cause analysis of problem and goodwill & competence analysis of partners), solution development (knowledge integration and codification: contract redesign).



Qianru Ge
Eindhoven University of Technology
Session 3A

Reliability Optimization for Multi-components System in the Design Phase

Abstract

We develop an optimization model to determine the optimal failure rate of critical components in a system. Since the system is under a service contract, a penalty cost should be paid by the OEM when the total system down time exceeds a predetermined level, which complicates the evaluation of the life cycle costs. Furthermore, in the design phase for each critical component, the failure rate can be chosen from a certain range.

Bram de Jonge
University of Groningen
Session 1A

Innovative Individualized Education on Time-based Maintenance Planning

Abstract

An innovative automated approach to generate individualized assignments on time-based maintenance planning is presented. The assignment learns students to determine optimum time-based maintenance strategies using familiar spreadsheet software based on historical failure and preventive maintenance data. Topics covered by the assignment include censored data, Kaplan-Meier estimations, maximum likelihood estimations, (mixtures of) Weibull distributions, bathtub-shaped failure rates, visual goodness-of-fit tests, numerical integration, and optimization of the maintenance age. The assignment is currently used within various study programs at the University of Groningen in the Netherlands. When time allows, other developed education on maintenance planning will also be discusses.

Szilárd Kálosi
Eindhoven University of Technology
Session 2B

Condition-based Maintenance at Both Scheduled and Unscheduled Opportunities

Abstract

This research is part of a bigger maintenance project in which we look at how to exploit event data of healthcare systems for a better maintenance concept leading to less system downtime and a lower total cost of ownership for hospitals. The aim of our research is to turn outcomes of predictive models into better maintenance decisions.
Motivated by the OEM service and maintenance practices we consider a single component subject to replacements at failure instances and two types of preventive maintenance opportunities:

- Scheduled, which occur due to scheduled system downs for periodic reviews of the equipment, and
- Unscheduled, which occur due to other components in the system failing.

Modeling appropriately the state of the component and incorporating a realistic cost structure for corrective maintenance as well as preventive maintenance based on the condition of the component, we derive the optimal maintenance policy. In particular, we show that the optimal policy for the model at hand is a control-limit policy, where the control limit depends on the time until the next scheduled system down. Whereas, in the cases of only the scheduled or the unscheduled opportunities, we assert that it is optimal to employ a time-independent control-limit policy. Finally, we discuss the issues arising in the calculation of the long-run average cost as well as in the derivation of the optimal policy.

Stella Kapodistria
Eindhoven University of Technology
Session 2B

Integrating Statistical Process Control into Condition Based Maintenance

Abstract
We are interested in maintenance optimization concepts for high-tech medical systems, where the challenge lies in maintaining high availability times of the equipment at hand, while scheduling maintenance activities in such a way that it does not interfere with the patient-doctor schedules. Due to this conundrum, it is pivotal to define and execute smart maintenance strategies. Typically, this is achieved by the creation of a model for the condition of the asset based upon which condition based maintenance (CBM) approaches are performed. Such analyses can be either data driven or stochastic: two approaches that within the field of maintenance have mainly developed independently. In this talk, we will explore this relatively unexplored idea and show how to bridge these two approaches. In particular, we will use statistical concepts stemming from SPC (Statistical Process Control) and we will show in the context of CBM how to make the connection between the statistical view of SPC and the stochastic view of first passage times. To this purpose, we will use as a paradigm, mainly for illustration and simplicity purposes, the connection between the Shewhart control charts with the "On-Off" stochastic process.

Roland van de Kerkhof
Tilburg University
Session 1B

Knowledge Lost in Data: Organizational Impediment to Condition-Based Maintenance in the Process Industry

Abstract

In this presentation we report on a pilot study of Condition-Based Maintenance (CBM) in the process industries, such as the steelmaking- and chemical industries, and propose a framework for systematically analysing the challenges to the successful implementation and execution of a CBM program. Although the field of predictive maintenance is growing and considerable research effort has been targeted to the technical aspects of CBM, we observe that many firms in the process industry do not yet systematically use advanced CBM approaches. This research therefore aims to contribute to our understanding of the contextual barriers (beyond the technical issues) that hinder organisations from employing condition-based maintenance programs to improve their asset management.

Nils Knofius
University of Twente
Session 2A

Implications of Additive Manufacturing for After Sales Service Logistics

Abstract

Expensive slow moving spare parts with a long (replenishment or repair) lead time cause a lot of costs for holding inventories, and for discarding unused parts at the end of the life cycle. The technology of Additive Manufacturing (AM) is developing rapidly. When applied to spare parts, this could offer benefits in the medium to long term, for example by printing parts on demand and on location (Make-To-Order) rather than stocking those parts (Make-To-Stock).

AM is a computer-controlled production process, in which a complete item is build up layer by layer from basic materials. In practice 3D printing is an established synonym for AM. Various institutions attribute AM a bright future. In general, AM technologies are becoming faster, cheaper, safer, more reliable, and environmentally friendly (Gibson et al., 2010). This clearly demonstrates the value to get acquainted with the technology and its opportunities.

In our presentation, we give an overview of options to improve spare part supply chains with AM and outline a method to identify promising spare parts for AM in practice. Furthermore, we propose a conceptual model in order to quantify the value of integrating assemblies into one-piece part (monolithic design) with AM. This is motivated by the development that companies begin to exploit the design freedom of AM in order to consolidate parts. Apart from eliminating assembly times, this allows them to improve part characteristics like failure rate or weight. Logistical consequences however, are not considered yet.

Minou Olde Keizer
University of Groningen
Session 2B

Clustering Condition-based Maintenance for Systems with Redundancy and Economic Dependencies

Abstract
Systems that require maintenance typically consist of multiple components. In case of economic dependencies, maintaining several of these components simultaneously can be more cost efficient than performing maintenance on each component separately, while in case of redundancy, postponing maintenance on some failed components is possible without reducing the availability of the system. Condition-based maintenance (CBM) is known as a cost-minimizing strategy in which the maintenance actions are based on the actual condition of the different components. No research has been performed yet on clustering CBM tasks for systems with both economic dependencies and redundancy. We develop a dynamic programming model to find the optimal maintenance strategy for such systems, and show numerically that it can indeed considerably outperform previously considered policies (failure-based, age-based, block replacement, and more restricted (opportunistic) CBM policies). Moreover, our numerical investigation provides insights into the optimal policy structure.

Joeri Poppe
KU Leuven
Session 3B

A Hybrid Opportunistic Condition-based Maintenance Policy for Continuously Monitored Components with Two Degradation Thresholds

Abstract

Condition-based maintenance (CBM) is a maintenance strategy that makes use of the actual condition (degradation level) of the component to decide when the maintenance and/or the replacement of the component needs to be executed, thereby maximizing the lifetime of the machine, while minimizing the number of maintenance interventions. In this paper, we suggest a hybrid opportunistic maintenance policy, combining CBM on one (monitored) component, with preventive maintenance (PM) and corrective maintenance (CM) on the other components of the same machine/system. The CBM policy relies on two thresholds of the degradation level. When the degradation level of the monitored component surpasses a first ‘opportunistic’ threshold, the monitored component will be maintained as soon as either a PM intervention occurs (which is planned for other components), or when another component breaks down and requires a CM intervention. In case none of these opportunities have occurred, and the degradation level surpasses a second ‘intervention’ threshold, an extra maintenance intervention is executed after a planning period to prevent breakdown of the machine. Both thresholds are subject to optimization to minimize the total maintenance cost of the monitored component, or to minimize the downtime of the machine due to maintenance on the monitored component. We perform an extensive numerical experiment to find the key drivers that determine the performance of this hybrid policy compared to using a traditional periodic PM policy. We also benchmark our results when only one threshold is implemented.

Sajjad Rahimi Ghahroodi
University of Twente
Session 2A

Integrated Planning of Service Engineers and Spare Parts in Maintenance Logistics

Abstract

We consider an integrated spare parts inventory and service engineers planning in a service logistics system consisting of K spare parts and a team of service engineers. When a failure happens, a spare part and a service engineer will be requested for the repair call. In case of a stock-out at spare parts inventory, the repair call will be satisfied entirely by an emergency channel. However, when there is no available service engineer, the spare part will be reserved and the repair call waits for a service engineer to become available. We are interested to find the optimal stock levels and the optimal number of service engineers to minimize the average total cost under a maximum total average waiting time constraint. We analyze this problem using queueing models. An exact and two fast approximation methods for the evaluation of a given policy are presented. We exploit the evaluation methods in a heuristic procedure for the spare parts base stock level and the number of service engineers determination. Furthermore, we show that the integrated planning of spare parts and service engineers can lead to considerable cost savings.

Richard Ruitenburg
University of Twente
Session 1A

Asset Management as a Multidisciplinary Approach

Abstract

The discipline of Asset Management has changed profoundly over the last years. From the technical approach in Maintenance, to a more managerial perspective in Maintenance Management and recently into a multidisciplinary approach in Asset Management. Asset Management can be described by at least five important characteristics: Asset Management is 1. a multidisciplinary practice; 2. in which the whole life cycle of a physical asset is taken into account; 3. with the goal to achieve certain objectives; 4. within the limits of risk and relevant regimes; and 5. it should determine the allocation of resources. In the Maintenance Engineering group of the University of Twente, research focuses on these different aspects of maintenance. Different disciplines are covered, as diverse as logistics, sustainability, knowledge management and maintenance policy selection. The whole life cycle of the asset is covered: from design for maintenance, FMEA and Maintenance Feedback Analysis to long term Asset Life Cycle Management. One of our recent research efforts has been a study of Asset Management practices in the Dutch maintenance sector, in close collaboration with the Dutch maintenance association NVDO. Three main conclusions on the topic of performance management were:

1. maintenance execution often does not work according to the maintenance instructions, limiting the potential of performance management through maintenance concepts.
2. the influence on the performance of assets is very limited in the short term; real influence can only be exerted in the range of 5 years.
3. many maintenance professionals would like to be able to spend more time on tactical and strategic issues, showing that long term performance management may receive less attention than desired.

Andrea Sanchez Ramirez
University of Twente

Session 3A

Design Framework for Advanced Vibration Monitoring Systems

Abstract

Vibration monitoring aims at acquiring, analyzing and interpreting signals to distinguish abnormalities in the dynamic behavior of a monitored system aiming to ensure its current and future functionality. Despite the individual advances on these tasks, there is a lack of convergence that limits the effectiveness of vibration monitoring. The need for a converged approach is even more acute when considering the new possibilities provided by the Internet of Things (IoT). This means that, to achieve advanced vibration monitoring systems with superior capabilities for autonomous, distributed and in situ diagnostics, the agreement between acquisition, analysis and interpretation must be achieved.

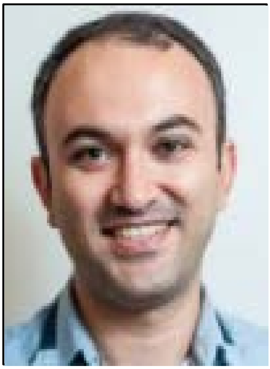
The problem lies in considering the monitoring activity with an *a posteriori* approach, i.e. the monitoring of the object is performed with little consideration to the characteristics of it. This paper therefore proposes an *a priori* strategy, using a framework for the design of advanced vibration monitoring systems. The design problem is formulated as *designing a system whose function is to monitor the divergence from the designed behavior of another system*. To tackle this problem a systems engineering approach based on the Function-Behavior-Structure (FBS) ontology is used.

The framework relates to the two fundamental issues in vibration monitoring: what to monitor and how to achieve the monitoring. The first question is approached as the definition of monitoring strategies based on the functionality (I) and maintenance requirements (II) of the monitored system. The second question is elaborated in relation to the methods (III) and elements (IV) that must be realized by the monitoring activity to take place. This yields a design guideline that considers the monitoring and monitored system in an integral way. As an example of the implementation of this framework the case of rail-wheel monitoring using a wireless sensor network is presented.

Loe Schlicher
Eindhoven University of Technology
Session 2A

Cost Operating Games

Abstract
We consider an environment in which several service providers face the problem of opening a facility-in order to provide a low utilized service within a certain radius- or to incur a specific penalty fee. Due to low utilization, service providers may benefit from jointly opening these facilities. We examine the allocation of the collective cost savings for such situation by studying an associated cooperative game, which we call a cost operating game. We analyze various properties of these cost operating games.



Engin Topan
Eindhoven University of Technology
Session 2B

A Combined Maintenance Policy with Condition Based Inspection Intervals and a Preventive Replacement Interval

Abstract

Motivated by a consumer electronics manufacturer, we consider optimal replacement of machine tools having critical functions in production lines. The condition of a tool is important to maintain the quality of the goods produced. A tool can be in three states: normal, defective and failed. Under a normal state, a tool works fine and defects do not exist. Under a defective state, a tool still works but a defect exists. Due to quality concerns a defective tool is replaced immediately by a new one. A defect is not self-announcing therefore it can be detected only by inspections. To maintain the quality of the goods, tools are inspected regularly. Under the failed state, a tool does not work, therefore, it is immediately replaced by a new one. Unlike a defective state, a failed state is self-announcing. In addition to inspection information, condition of a tool can be imperfectly estimated by indirect indicators such as quality and process measures collected by sensors continuously for mainly production and quality control reasons. In contrast to information collected during inspection the information collected in this way is continuous but imperfect.

A tool is inspected after every T units produced and it is replaced depending on the condition, or regardless of its condition it is replaced preventively after K (with $K>\tau$) units produced, whichever occurs first. Our objective is to use the indirect measures as condition indicators and implement condition based maintenance and also to find the optimal inspection interval T and the preventive replacement time K minimizing the total maintenance cost. To facilitate condition based maintenance we define the inspection interval dependent on condition indicators. We combine delay time model and random coefficient model to evaluate our policy. We apply our model to find the optimal state- dependent inspection intervals and the preventive replacement time of tools in use at electro chemical machining lines of the manufacturer.

Kim Verbert
Delft University of Technology
Session 3B

Early-Stage Maintenance Scheduling Based on Real-Time Condition Monitoring

Abstract

Last-minute maintenance scheduling is often undesired, as it may cause downtime during operational hours, may require rescheduling of other activities, and does not allow to optimize the management of spare parts, material, and personnel. Furthermore, it may be beneficial to combine or spread various maintenance activities, which is not possible when maintenance needs are known just in time.

We propose a two-step approach to early-stage maintenance scheduling.

The first step is to decide for each system component in need of maintenance independently on the optimal time and type of maintenance. As information regarding the system health is available in real time, it is not obvious when to settle on a decision regarding the time and type of maintenance. On the one hand, we want to determine the maintenance schedule sufficiently in advance. On the other hand, we want to schedule based on accurate predictions of the system health. Since the prediction accuracy increases over time, a trade-off between accuracy and timeliness has to be made. To handle this trade-off, we propose a sequential decision making approach. At each time, we first determine, based on the currently available information, the optimal maintenance policy (time and type of maintenance). Next, based on the expected costs (including risk) of this policy, the expected time to failure, and the expected improvements in future predictions, we decide whether to accept this maintenance policy or to postpone the decision to a later time. If the policy is accepted, it is forwarded to the system-level optimization.

In the second step, we optimize the system-level maintenance schedule for total costs. By taking account of dependencies between system components, costs can be reduced by spreading or combining maintenance. Hereby, a trade-off between economics of scales and loss of functionality is made.

The proposed approach is demonstrated based on a case involving maintenance planning for a railway network.

Gero Walter
Eindhoven University of Technology
Session 3A

Nonparametric System Reliability Combining Expert Knowledge and Data

Abstract

The estimation of the reliability curve for technical systems is an important building block in determining maintenance policies. For a complex technical system, reliability calculations are usually based on the reliability of its components. Data on component failures is however often scarce, and to obtain meaningful estimates for the reliability of a component, and in turn of the system, it is often necessary to include expert information in the analysis.

Such expert information could come, e.g., from the component manufacturer. However, this information should often be taken with a pinch of salt, as the manufacturer might over- or understate the component reliability (overstating to, e.g., outrival a competitor, or understating to, e.g., sell more replacements). Furthermore, components might just behave differently under the conditions of the present system.

We show how such uncertain information on components can be efficiently combined with test data using a flexible nonparametric approach imposing no restrictions on the failure time distributions. For each time point t in a grid of time points and each component type k, we count the number of components still functioning in the test data, and express expert information by an interval for the expected survival probability. This interval determines a corresponding set of Beta distributions, used as a set of prior distributions in a Bayesian setting.

This leads to a tractable imprecise probability model that produces a set of posterior predictive system reliability functions. It adequately reflects uncertainty in expert information, the amount of data, and furthermore provides prior-data conflict sensitivity: Observing data that are very surprising from the viewpoint of the expert leads to a larger set, mirroring the additional uncertainty due to this conflict. Making use of the survival signature, a recently developed alternative to the system signature, the method allows for arbitrary system layouts.

Sha Zhu
Erasmus University Rotterdam
Session 3A

Using Maintenance Plan in Spare Part Demand Forecasting and Inventory Control

Abstract

Lumpiness in spare parts demand is a nightmare for inventory managers since it increases the difficulty in demand forecasting. In the situation of preventive maintenance, the lumpiness in spare part demand is triggered by both of the lumpiness in component repairs and the uncertainty of individual probable defective component generating spare part demand. Since maintenance plan provides prior information about defective component arrival, it captures the lumpiness in component repairs and further explains the lumpiness in spare parts demand to some extent. Maintenance plan might prevent us from keeping redundant inventory in the period when there is no component replacement and allow us to estimate the spare part demand based on component arrivals. Therefore, we can make good use of maintenance plan to improve spare part demand forecasting and inventory management.

We propose an estimation of spare part demand distribution and build a dynamic model to obtain the order policy. We first propose a periodic review, lost sale inventory model which minimizes total inventory holding, shortage penalty and ordering cost under maintenance plan. Next, we explore the relationship between the component repairs and the spare part demand. Assuming the same spare part installed in the same type of component has a constant replacement probability in each time period, we can estimate the probability that a component repair needs a certain spare part. With the information of component arrivals by maintenance plan, the number of spare parts demand is then binomial distributed and we can obtain the order policy from the inventory model. We consider two solution concepts, one with and another without maintenance plan, in our inventory model to examine the value of information. A case study performed on real data provided by Fokker Service show that the total cost is reduced by 8.4% using maintenance plan.

List of participants

Name			Institution
Alp		*Akcay*	*Eindhoven University of Technology*
Henk		*Akkermans*	*WCM / Tilburg University*
Ahmad		*Al Hanbali*	*University of Twente*
Alireza		*Alemi*	*Delft University of Technology*
Filippos		*Amoiralis*	*University of Twente*
Joachim		*Arts*	*Eindhoven University of Technology*
Sarah	*van der*	*Auweraer*	*KU Leuven*
Mauro		*Barbieri*	*Philips*
Rob		*Basten*	*Eindhoven University of Technology*
Rinze		*Benedictus*	*Delft University of Technology*
Rob		*Bosman*	*University of Twente*
Robert		*Boute*	*KU Leuven*
Onno		*Boxma*	*Eindhoven University of Technology*
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