The IEEE PES Big Data Tutorial, Webinar July 2, 2020

Tutorial on Infrastructure Asset Management with Power System Applications Professor Lina Bertling Tjernberg linab@kth.se www.kth.se/profile/linab @linabertling

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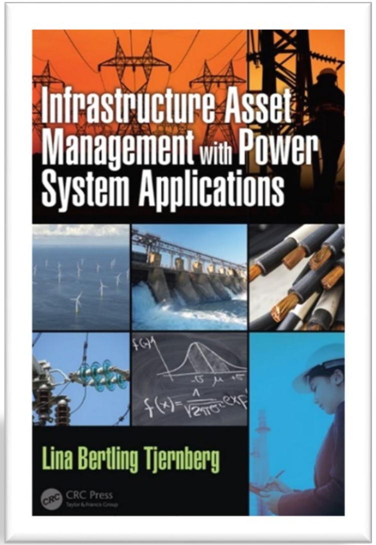
Sustainable Development Goals

www.un.org/sustainabledevelopment/sustainable-development-goals/

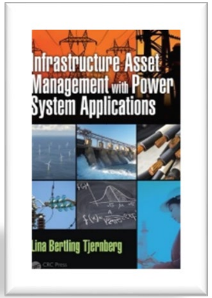
Three key messages

1. The value of making smart decisions gives the reason for adopting Asset Management (AM)
2. Standards needed for successful joint developments
3. Reliability analysis and applications to preventive maintenance (PM) provides efficient tools for AM
   - ✓ Novel methods with large volumes of data e.g. machine learning condition monitoring using Supervisory control and data acquisition (SCADA)



All figures in the presentation are from: Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018. Free shipping online from: https://www.crcpress.com/9781498708678

Acknowledgements



This book on AM is the result of just about 20 years of dedicated work in the field of applied reliability theory and numerous applications for the electric power system.

I would like to express my deep gratitude to the many people who have inspired me, who have supported me, and who have contributed to the work contained in this tutorial. It is not possible to name you all who have been with me over the course of the years but you are all thought of with true gratitude including academic mentors, industrial collaborators and mentors as well as students and researchers who have worked within my research groups.

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Outline of the Tutorial

- Different parts of the tutorial
  - Introductions
  - Maintenance as a strategic tool
  - Reliability Centered Asset Management Method
  - Case Study

Introduction

- Welcome to this tutorial! Who are you?
- What are the main drivers for AM in your view?
- What are the main challenges for the Electric Power system and AM in your view?

KTH in brief

- KTH Royal Institute of Technology was founded in 1827, and Electrical engineering in 1901.
- In numbers (2019) www.kth.se/en/om
  - 5 044 employees (317 professors)
  - 13 514 full time students
  - 1 665 research students

Hannes Alfvén receives the Nobel prize in physics (1970)

- QS ranking KTH 98 and Electrical & Electronic Engineering: 17
- The KTH Energy Platform connects more than 450 researchers in 30 research groups and five competence centres in 17 research areas related to energy issues. www.kth.se/energy

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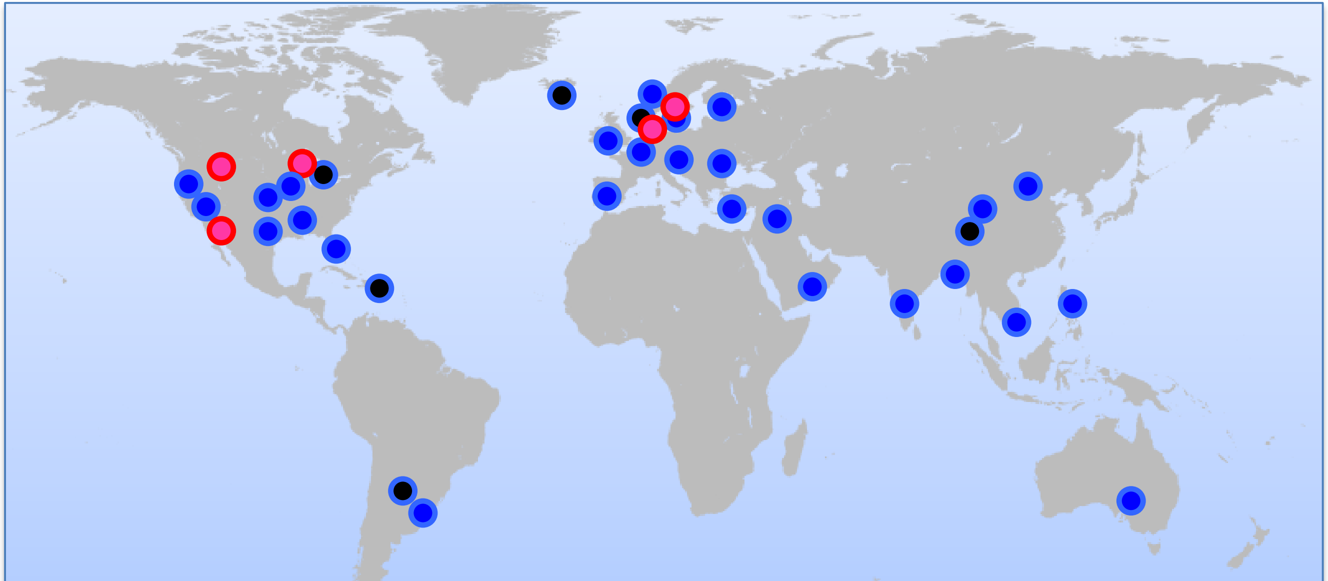
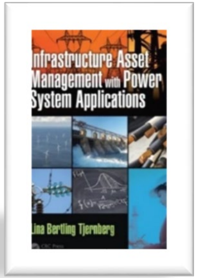
Lina Bertling Tjernberg - in brief



- Positions: Stockholm, Saskatoon, Toronto, Gothenburg, Palo Alto
- Top Visits: Iguazu, Niagara, Gullforss, Nordned, Three Gorges
- Key notes: Beijing, Jeju Island, Melbourne, Sarajevo, Gramado

Lina Bertling Tjernberg - in brief

- **Professor in Power Grid Technology**
- Director of the KTH Energy Platform
- *Education:* Docent 2008, PhD 2002 Electric Power Systems, MSc Vehicle Engineering/Systems engineering 1997, all at KTH Royal Institute of Technology.



- *Current:* Standing Committee Member of the World Energy Council, Member of the National Strategic Council for Wind Power, Chairman of SEK Svensk Elstandard, Vice chair of the Board of Parliament Members and Researchers.
- *Past:* Member of the advisory council of the Energy Markets Inspectorate , Member of the Swedish Government Coordination Council for smart grid (2012-2014), IEEE PES board (2012-2015), Sweden Chapter chair 2009-2019, Editor of the Smart Grid Transaction (2010-2015), the IEEE Reliability Risk and Probability Applications (RRPA) Subcommittee board (chair 2011-2013), Conference chair of the first IEEE ISGT Europe in 2010, 9th PMAPS in 2006.
- *Visits:* Stanford University (2014), University of Toronto (2002/2003), University of Saskatchewan (2000).
- *Author:* +100 papers, the book *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press, Taylor and Francis, April 2018* List of publication from here.

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Introduction - terminology and trends

- Energy – transformed and transported
- Electric power system - infrastructure for transporting energy
- Key trends
  - Electrification and storage
  - Circular economics
  - Digitalization

Introduction – need of AM

- For the coming years, there is an expected major need of investments in the electric power systems worldwide, either as a result of an aging infrastructure, from the need of expansions or/and a result from transition into a sustainable energy system.
- In the USA, the cumulative investment gap between 2016 and 2025 has been estimated to be 177 billion dollars.
- A 10-year strategy plan in Europe foresees around in total 150 billion euros of investments in electric power infrastructure.

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Outline of the Tutorial

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  - Maintenance as a strategic tool
  - Reliability Centered Asset Management Method
  - Case Study

Maintenance as a strategic tool

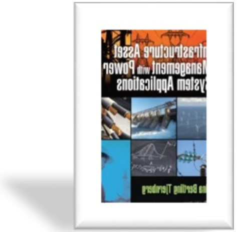
- The **aim** of asset management is to handle physical assets in an optimal way in order to fulfil an organization's goal whilst considering risk, where the *goal* could be maximum asset value, maximum benefit, or minimal life cycle cost (LCC), and the *risk* could be defined by the probability of failure occurrence and its consequence, for example, unavailability in power supply to customers.

Maintenance as a strategic tool

- There are different possible actions to handle these assets: acquire, maintain, replace, or redesign. AM implies consequently to make **right** decisions on:
  - What assets to apply actions for
  - What actions to apply
  - How to apply the actions
  - When to apply the actions

Maintenance as a strategic tool

- To make the right decisions, there is a need of:
  - Condition data
  - Failure statistics
  - Reliability modeling techniques
  - Reliability assessment tools
  - Maintenance planning tools
  - Systematic techniques for maintenance planning, e.g. reliability centered maintenance (RCM)



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Maintenance as a strategic tool

AM Standard

- The ISO 55000 family of standards is the first set of international standards for AM
- They are emerging from the Publicly Available Specification (PAS) 55
- The PAS55 was launched by the British Standards Institute (BSI), in 2004, resulting from an effort led by the Institute of Asset Management (IAM). It is considered as the first internationally recognized specification for AM
- A major difference is that the PAS55 is focused on the optimal management of physical assets, but the <u>ISO 55000 is a standard for any asset type</u>

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Maintenance as a strategic tool

AM standard

- The ISO 55000 family of standards aligns with other major management systems.
  - This includes ISO 9001 for quality management, ISO 14001 for environmental management, and ISO 31000 for risk management.
- The ISO 55000 family of standards provides the first management standard to implement the ISO Annex SL.
  - The Annex SL is a high-level structure to provide a universal structure, identical core text, and common terms and definitions for all management standards.

Maintenance as a strategic tool

AM standard - selected terminology from ISO 55000:

- *Asset*: Item, thing, or entity that has potential or actual value to an organization
- *Asset life*: Period from asset creation to asset end-of-life
- *Life cycle*: Stages involved in the management of an asset
- *Asset management*: Coordinated activity of an organization to realize value from assets
- *Preventive action*: Action to eliminate the cause of a potential nonconformity or other undesirable potential situation
- *Predictive action*: Action to monitor the condition of an asset and predict the nee for preventive action or corrective action
- *Corrective action*: Action to eliminate the cause of a nonconformity and to prever recurrence

Maintenance as a strategic tool

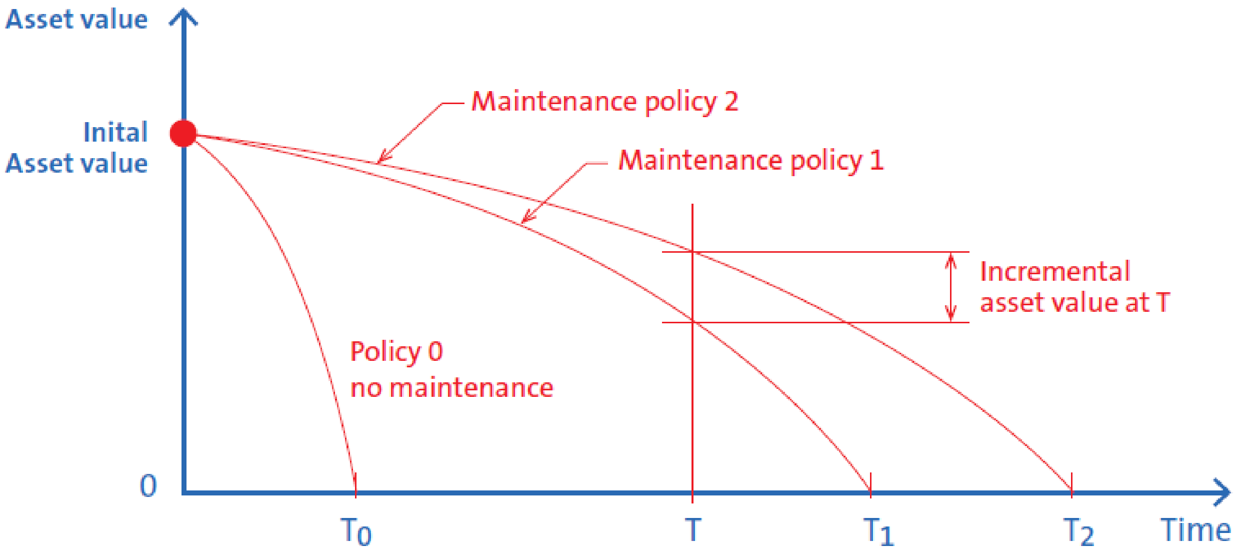

Illustration of the impact of maintenance policies on life curves

Figure 2.1 in *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018.* Adapted from: Endrenyi, J. , Anders, G., Bertling L., Kalinowski, B., *Comparison of Two Methods for Evaluating the Effects of Maintenance*, the 8th PMAPS, Ames, Iowa, 2004.

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Maintenance as a strategic tool

- Maintenance is one of the main tools of asset management.
- It can be defined as an activity of restoration where an unfailed device has its deterioration arrested, reduced, or eliminated.
- Its goal is to increase the duration of useful component life and postpone failures that typically would require expensive repairs. Consequently, the task of maintenance is to slow the deterioration process.
- This is shown in Figure 2.1 where increasing deterioration is expressed in terms of decreasing asset value. The asset value curves in the diagram are here referred as life curves.

Maintenance as a strategic tool

- If failure is identified with the condition of zero asset value and lifetime is defined as the mean time to failure, the life extensions $T0$ to T, when Policy 1 is applied instead of neglecting maintenance, and $T1$ to $T2$, when Policy 1 is replaced by Policy 2,
- In aspects of reliability Policy 2 is superior to Policy 1.
- Maintenance has its own costs which has to be taken into account when comparing policies and the most cost-effective policy chosen.
- The costs of maintenance should be balanced against the gains resulting from increased reliability. When costs are considered, Policy 2 may or may not be superior to Policy 1

Maintenance as a strategic tool

- Maintenance procedures are an integrated part of the planning, construction, and operation of a system. Moreover, they are of central and crucial importance to the effective use of available equipment.
- The aim of maintenance activities is to continuously meet performance, reliability, and economic requirements, while also adhering to the constraints set by system and customer requirements.

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Maintenance as a strategic tool

- Functions are what an asset is expected to perform and can also be anything an asset has to comply with, such as a color or shape. The function of an asset does not have to be exact. In some cases, it is sufficient if the performance of an asset lies within some interval, for example, for an oven to provide a temperature. It is possible to divide functions into two subcategories
  - Primary functions describe the main purpose of the asset
  - Secondary functions describe additional features the asset should meet such as color or safety aspects

Maintenance as a strategic tool

- *Functional failures* is the inability of an item of equipment to ful fill one or more of its functions.
- *Failure modes* are events that cause functional failures.
- *Failure effects* are what happen when a failure mode occurs. The effects include evidence of failures, safety, and environmental hazards or production effects.
- *Failure consequences* The consequences of all failures can be classified as being either Hidden, Safety, Environmental, Operational, or Non operational.
- *Potential failures* are a state of an asset which indicates that a function failure will occur.

Maintenance as a strategic tool

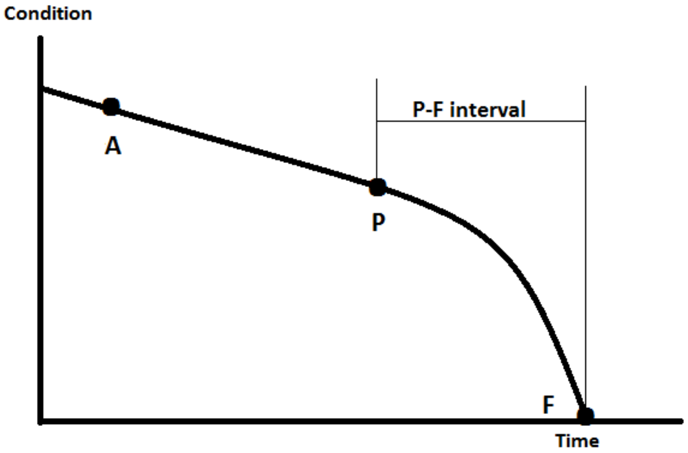

Figure 2.2 The P–F curve. The graph shows the events of: A, the failure starts to occur; P, the potential failure; and F, the functional failure.

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Maintenance as a strategic tool

- The P–F curve in Figure 2.2 shows the relationship between operation time and the condition of an asset.
- At point (A), a failure of the asset starts to occur. At the point (P), it is possible to detect that a failure will occur.
- This is called a potential failure. Point (F) corresponds to the time when a functional failure has occurred.
- The P–F interval is the time between it is possible to detect that a functional failure will take place and the time when it is expected to occ This interval is also referred to as the warning period.

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Maintenance as a strategic tool

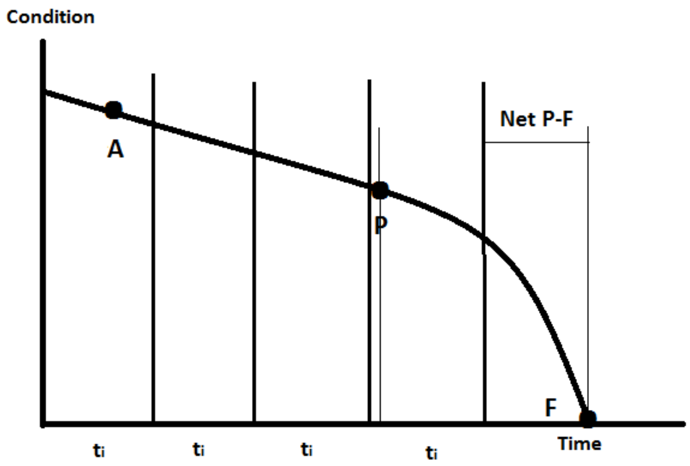

Figure 2.3 The net P–F interval. The graph shows the events of: A, the failure starts to occur; P, the potential failure; F, the functional failure; and the Inspection interval *ti*.

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Maintenance as a strategic tool

- If an asset is checked at regular intervals and a potential failure is found, the time left until a functional failure occurs is the net P–F interval (Figure 2.3).
- This is the worst-case time available to prevent the functional failure from occurring after detecting the potential failure.

Maintenance as a strategic tool

- Many failures can be classified as **age related**. These kinds of failures are often found on mechanical equipment and are, for example, due to fatigue, corrosion, oxidation, and evaporation.
- To be classified as an age-related failure, the probability of failure should increase at some point in time. The increase of failure probability can, for example, be constant in time or start at a specific age when the component usually wears out.

Maintenance as a strategic tool

- *Non-Age-Related Failures* Often failures are not due to age but rather to surrounding factors such as a nonuniform stress or handling errors which may occur at random. For these failures, there is no certain point in time when the likelihood of failure increases.
- *Hidden Failures* If a failure is not noticed under normal working conditions, then the failure is a hidden failure. These failures alone are often of minor issue but in case of multiple failures they can be disastrous. Failures of safety equipment are often classified as hidden failures and will not become evident until there is another failure.

Maintenance as a strategic tool

- Maintenance is a combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.
- Maintenance can be carried out in different ways. One way to illustrate the different types of maintenance is shown in Figure 2.4.

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Maintenance as a strategic tool

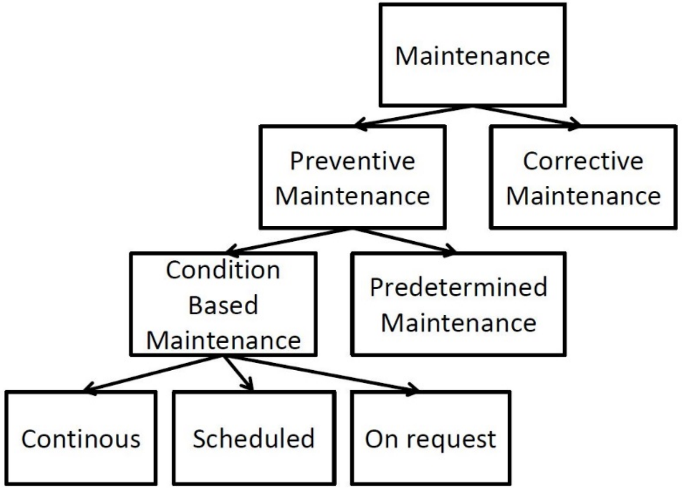

Figure 2.4 Overview of maintenance concepts. Outgoing from standard EN13306 *Maintenance Terminology*.

Maintenance as a strategic tool

- Preventive maintenance is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.
- Predetermined, or scheduled, maintenance is a PM carried out in accordance with established intervals of time or number of units of use but without previous condition investigation.

Maintenance as a strategic tool

- Predetermined maintenance is an option if a failure is age related and the probabilities of failure in time can be established. Depending on the consequences of a failure, different maintenance intervals can be chosen. If the consequences of a failure are not too severe and the cost for predetermined tasks are high, one might choose to allow the intervals between tasks to be longer than if the functional failure leads to a safety hazard which has consequences that cannot be tolerated.
- Examples of predetermined maintenance tasks are scheduled restoration and discard tasks.

Maintenance as a strategic tool

- Condition-based maintenance is a preventive maintenance based on performance and/or parameter monitoring and subsequent actions.
- When dealing with non-age-related failures, CBM tasks are often used.
- CBM or on-condition tasks are performed by inspecting assets to determine if any potential failures have occurred. Some common methods include using human senses such as listening for unusual noise or condition monitoring of the asset. These tasks do not help postpone a failure but can detect that a failure will occur and thereby make it possible to act in order to avoid the consequences of a failure.

Maintenance as a strategic tool

- CBM can be continuous, scheduled, or on request. If CBM is scheduled, intervals for conducting CBM tasks could be chosen with the P–F and net P–F intervals previously described.
- To make sure that a CBM task will detect a potential failure before a functional failure occurs, the interval between inspections must be shorter than the P–F interval. When a potential failure is detected, it is often desirable to have some additional time to correct the fault before a functional failure occurs. To accomplish this, the maintenance interval must be shortened further.

Maintenance as a strategic tool

- Corrective maintenance (CM) is carried out after fault recognition and intended to put an item into a state in which it can perform a required function.
- CM can be used if there is no way to detect or prevent a failure or it is not worth doing. It simply means that the asset is run till a failure occurs and then the system function is restored. This may of course not always be an option if the consequences of a breakdown are severe.

Maintenance as a strategic tool

- To find out whether a hidden failure has occurred, failure-finding tasks are used. This is done by checking if equipment is working in the way it should. These tasks can for example include switching on and checking if spare equipment is functioning properly.
- Redesign is used if there is no possibility to conduct maintenance on an asset and the probability and consequences of the failure are too high. Redesign might also be advantageous if maintenance is too expensive compared to redesigning. Redesign is not always considered to be part of maintenance but is included here.

Maintenance as a strategic tool

- The aim of PM is to extend the lifetime of the components. Component lifetimes can be prolonged when the causes of component failure and therefore component failure rates themselves reduce. This is of course dependent on the nature of the causes. One way of understanding the relationship between maintenance and reliability would be to study these causes.

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Maintenance as a strategic tool

- Moreover, the cost-effective planning of a system implies that the correct components are maintained, at the correct time and with the correct maintenance activity. In this context, this means focusing maintenance on the critical components that is those that have a significant impact on system reliability and to reduce the dominant causes.

Maintenance as a strategic tool

- Essentially, there are four tasks in a scheduled maintenance program:

  1. Inspection of an item to detect a potential failure
  2. Reworking an item before a maximum tolerable age is exceeded
  3. Discarding an item before a maximum tolerable age is exceeded
  4. Inspecting an item and finding failures that have occurred but were unknown

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Maintenance as a strategic tool

- For each failure type, an RCM program should be able to determine the type of maintenance task, if any, that should be applied and how frequently. Decision diagrams assist in this process. The following are some typical maintenance questions.
  - What efforts are required for this maintenance?
  - Is the maintenance performed too little or incorrect?
  - Is preventive maintenance done on the correct items?
  - What is the relationship between failure and maintenance costs?

Applying the RCM method would be one way of providing answers to these maintenance questions!

Maintenance as a strategic tool

Design for PM

- PM should be a prime consideration for any new equipment installation. Effective PM begins with good design with a conscious effort toward maintainability. Quality, installation, configuration, and application are fundamental prerequisites in attaining a satisfactory PM program. Installation cost without regard for performing efficient and economic maintenance influences system design.
- Experience shows that equipment lasts longer and performs better when covered under a PM program.

Maintenance as a strategic tool

Equipment Deterioration

- Equipment begins to deteriorate with installation. This is normal and if unchecked, the deterioration can progress and cause equipment malfunction or failure. Harsh environmental conditions and system stresses such as overload, severe duty cycle, load increases, circuit alterations, and changing voltage conditions can accelerate the deterioration process.
- An effective PM program can detect and mitigate these conditions. Equipment PM procedures should be developed to accomplish four basic functions:

Maintenance as a strategic tool

Equipment Deterioration

- Equipment PM procedures should be developed to accomplish four basic functions:

1. To keep the equipment clean
2. To keep the equipment dry
3. To keep the equipment sealed tight
4. To minimize the friction

Maintenance as a strategic tool

Data Analytics

- Statistics is a branch of mathematics including the collection, analysis, interpretation, presentation, and organization of data.
- Data is a set of values being either qualitative or *quantitative* variables. *Qualitative* properties are observed and can generally not be measured. Quantitative properties on the other hand have numerical values.
- The methods presented in this tutorial have its basis in the analysis of quantitative data. It is, however, believed that a sound maintenance management requires both qualitative and quantitative data since the experience of the specific component or system being analyzed not always can be expressed in numerical values.

Maintenance as a strategic tool

Data Analytics

- Two main statistical methods are used in data analysis: *descriptive* and *inferential* statistics.
- The further summarize data from a sample using indexes. The data analytics term for analysis of this data is exploratory data analytics (EDA). The EDA aims to find patterns and relationships in data.
- The latter draw conclusions from the data that are subject to random variation and are commonly referred to as probability theory. The data analytics term for the analysis of this data is confirmatory data analysis (CDA). The CDA applies statistical techniques to determine whether hypotheses about a data set are true or false.

Maintenance as a strategic tool

Data Analytics

- Data analytics (DA) is the process of examining data sets. Advanced types of DA include typically the different methods of:
- *Data mining* involving the sorting of large data, identifying trends, patterns, and relationships
- *Predictive analytics* seeking to predict customer behavior, equipment failure, future events
- *Machine learning and artificial intelligence technique* that uses automated algorithms, making possible to solve larger problems faster compared to traditional analytical models

Maintenance as a strategic tool

Data Analytics

- Big Data is a term for a data set that is so large or complex that traditional data analysis methods and tools are not possible to use to get results within a tolerable elapsed time.
- Challenges typically include capturing, storage, analysis, searching, sharing, visualizing, querying, and updating. These challenges might result in that, for example, data mining is not possible to apply.

Maintenance as a strategic tool

Data Analytics

- Below is a definition from the Gartner IT Glossary:

"Big Data is high-volume, high-velocity and/or high-variety information assets that demand cost-effective, innovative forms of information processing that enable enhanced insight, decision making, and process automation".

Outline of the Tutorial

- Different parts of the tutorial
  - Introduction and expectations
  - Maintenance as a strategic tool
  - Reliability Centered Asset Management Method
  - Case Study

RCM and RCAM

- This part presents the generic method of reliability-centered maintenance (RCM) and its extension into a quantitative approach, that is, Reliability-Centered Asset Management (RCAM) method.
- It presents the different stages of performing an RCM and RCAM analysis including performing a Failure Mode and Effect Analysis (FMEA) of critical components. Finally, it discusses the different needs of input data.

RCM and RCAM

RCM Concepts

- The term RCM identifies the role of focusing maintenance activities on reliability aspects.
- The RCM methodology provides a framework for developing optimally scheduled maintenance programs.
- The aim of RCM is to optimize the maintenance achievements (efforts, performance) in a systematic way.
- The aim is to achieve cost effectiveness by controlling the maintenance performance, which implies a trade-off between corrective and preventive maintenance and the use of optimal methods.

RCM and RCAM

The Emergence of RCM

- The RCM concept originated in the civil aircraft industry in the 1960s with the creation of the Boeing 747 series of aircraft (the Jumbo).
- One prerequisite for obtaining a license for this aircraft was having in place an approved plan of preventive maintenance (PM).
- However, this aircraft type was much larger and more complex than any previous aircraft type, thus PM was expected to be very expensive. Therefore, it was necessary to develop a new PM strategy. United Airlines led the developments and a new strategy was created.

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RCM and RCAM

The Emergence of RCM

- This was primarily concerned with identifying maintenance tasks that would eliminate the cost of unnecessary maintenance without decreasing safety or operating performance.
- The resulting method included an understanding of the time aspects of reliability (aging) and identifying critical maintenance actions for system functions. The maintenance program was a success. The good outcome raised interest and the program spread.
- It was further improved, and in 1975 the US Department of Commerce defined the concept as RCM and declared that all major military systems should apply RCM.

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RCM and RCAM

The Emergence of RCM

- The first full description was published in 1978
- in the 1980s the Electric Power Research Institute (EPRI) introduced RCM to the nuclear power industry.
- Today RCM is under consideration by or has already been implemented by many electrical power utilities for managing maintenance planning.

RCM and RCAM

Different versions of RCM

- In the 1980s, environmental questions became important issues, which led to a change in the RCM decision diagram, and a separate treatment of environmental aspects o failures was defined. This led to the adopting a new name that is RCM2.
- Attempts to develop the RCM methodology further have been made by EPRIGEN (a subsidiary of EPRI), with the adoption of an RCM process called streamlined RCM (SRCM), which is a simplified version of RCM aiming at lowering the cost of performing RCM. and resource capacity.

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RCM and RCAM

The RCM Method

- RCM provides a formal framework for handling the complexity of the maintenance issues but does not add anything new in a strictly technical sense.
- RCM principles and procedures can be expressed in different ways, however, the concept and fundamental principles of RCM remain the same.

RCM and RCAM

The RCM Method

- The following features originate from the first definition of RCM, and define and characterize the RCM method.
- The RCM method facilitates the:

1. Preservation of system function
2. Identification of failure modes
3. Prioritizing of function needs
4. Selection of applicable and effective maintenance tasks

RCM and RCAM

The RCM Method

- There are several different formulations of the process of creating an RCM program and achieving an optimally scheduled maintenance program found in the literature.
- Three formulations have been addressed in this section. The first two have both been derived from the original RCM definition, and the third is an approach based on a set of questions rather than steps.

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RCM and RCAM

The RCM Method

- *Smith* defined a systematic process for RCM by implementing the following features that have been defined earlier:

1. System selection and information collection
2. System boundary definition
3. System description and functional block diagrams
4. System functions and functional failures
5. Failure mode and effects analysis (FMEA)
6. Logic decision tree analysis (LTA)
7. Selection of maintenance tasks

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RCM and RCAM

The RCM Method

- *Moubray:* the first step is to identify the system items and which of these ought to be analyzed.
- RCM process into seven questions for each item:

1. What are the functions and performances required?
2. In what ways can each function fail?
3. What causes each functional failure?
4. What are the effects of each failure?
5. What are the consequences of each failure?
6. How can each failure be prevented?
7. How does one proceed if no preventive activity is possible?

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RCM and RCAM

The RCAM Method

- The RCAM has been formulated based on an understanding of RCM concepts and experience gained from RCM application studies.
- The RCAM identifies the central role of defining the relationship between component behavior and system reliability that is made through the evaluation of the causes of failures.
- The RCAM method was first published by *Bertling (2002)* and has since then been applied for several different power system applications.

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RCM and RCAM

The RCAM Method (Table 4.1)

Step	Procedure	Level	Data required	Results
1	Reliability analysis	S	Comp data	Reliability indices
2	Sensitivity analysis	C	Comp data	Critical components
3	Analysis of critical components	C	Failure modes	Critical components affected by maintenance
4	Analysis of failure modes	C	Failure modes, causes of failures etc.	Frequency of maintenance
5	Estimation of composite failure rate		Maintenance frequency	Composite failure rate
6	Sensitivity analysis	S	Frequency of maintenance	Relationship reliability and PM
7	Cost/benefit analysis	S	Costs	RCAM

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RCM and RCAM

The RCAM Method

- Table 4.1 presents the RCAM that includes the main procedures for developing RCM plans, and consequently is also the first result in the development process.
- Table 4.1 also identifies the following issues:
  1. the logical order of the different procedures required,
  2. the need for interaction between the system and the component levels, and
  3. an indication of the different input data needed.

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RCM and RCAM

The RCAM Method.

- *Stage 1 System reliability analysis* defines the system and evaluates critical components for system reliability (Steps 1 and 2).
- *Stage 2 Evaluation of PM and component behavior* analyzes the components in detail and with the support of necessary input data, a quantitative relation between reliability and PM measures can be defined (Steps 3–5).
- *Stage 3 System reliability and cost/benefit analysis* puts the understanding of the component behavior gained in a system perspective. The effect of PM on components is analyzed with respect to system reliability and benefit in cost for different PM strategies and methods (Steps 6 and 7).

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RCM and RCAM

The RCAM Method.

- The central part of the RCAM, and the greatest challenge, is the definition of a relationship between reliability and preventive maintenance, that is, Stage 2 in the RCAM analysis discussed previously.
- This could be done through a generic approach involving the steps to be processed or a generic theory involving mathematical relations to be solved.
- Below are two alternative approaches presented for Stage 2 in the analysis. The availability of data and recourses in time would be the main arguments for the selection of approach.

RCM and RCAM

***The RCAM Method*.**

- **Definition 4.1** Approach I implies that a PM activity results in a percentage reduction in the causes of failures for affected components. Furthermore, it assumes that the failure rate is also reduced by the equivalent percentage. The resulting model of the relationship between failure rate and PM is referred to as $\lambda(PM)$.

RCM and RCAM

***The RCAM Method*.**

- **Definition 4.2** Approach II implies that a functional relationship is established between failure rate and PM activities. This must be based on detailed knowledge and understanding of the condition of the components as well as the failure rate characteristics. The resulting model of the relationship between failure rate and PM is referred to as $\lambda(t,PM)$.

RCM and RCAM

The RCAM Method.

- The PM strategy provides a recommendation for performing an activity in the future. However, on the actual day for the PM measure, the decision would be based on whether it would be beneficial to do the same at that time, or would it be more profitable to postpone it, or even to do something else.
- The RCAM method implies the development of a policy based on predicted behavior that should be used to set a policy for determining when and how to use resources for maintenance.

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RCM and RCAM

Failure Mode and Effects Analysis (FMEA)

- FMEA is a useful tool when performing an RCM analysis.
- It is a way to evaluate potential failure modes and their effects and causes in a systematic and structured manner.
- *Failure modes* mean the ways in which something could fail.
- *Effects analysis* refers to studying the consequences of those failures.
- The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

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RCM and RCAM

Failure Mode and Effects Analysis (FMEA)

- By itself, an FMEA is not a problem solver, it should be used in combination with other problem-solving tools.
- The analysis can be done either in a qualitative or quantitative way. The basic steps in performing an FMEA could be:
  1. Define the system to be analyzed. Complete system definition includes defining of system boundaries, identification of internal and interface functions, expected performance, and failure definitions.

RCM and RCAM

Failure Mode and Effects Analysis (FMEA)

2. Identify failure modes associated with system failures. For each function, identify all the ways failure could happen. These are potential failure modes.
3. Identify potential effects of failure modes. For each failure mode, identify all the consequences on the system. “What happens when the failure occurs?”
4. Determine and rank how serious each effect is. The most critical pieces of equipment which affected the overall function of the system need to be identified and determined.

RCM and RCAM

Failure Mode and Effects Analysis (FMEA)

5. For each failure mode, determine all the potential root causes.
6. For each cause, identify available detection methods.
7. Identify recommended actions for each cause that can reduce the severity of each failure.

RCM and RCAM

Failure Mode and Effects Analysis (FMEA)

- The FMEA classifies each potential failure according to the severity of the mission success and personnel/equipment safety.
- The FMEA could be extended with a criticality analysis (CA). The CA will provide the estimates of system critical failure rates based on past history and current information.
- The resulting FMECA (failure mode, effects, and criticality analysis) is a reliability evaluation and design technique that examines the potential failure modes within a system in order to determine the effects of the overall system and the equipment within the system.

RCM and RCAM

Failure Mode and Effects Analysis (FMEA)

- The FMECA is a living document that is not only beneficial when used in the design phase but also during system use. As more information on the system is available, the analysis should be updated in order to provide the most benefit.
- Generic maintenance data is a valuable tool when historical information is not available or when the engineering is establishing a maintenance-based line for a new system. This type of data is extremely rare but important to the establishment of a good RCM program.

RCM and RCAM

Systematic AM process

- The overall goal is to reach a systematic AM process with RCM and RCAM.
- This does not only mean to implement the RCM and RCAM, but most important to find a process for updating the maintenance programs resulting from performing RCM-analysis. It is worth underlining that experience shows that it is challenging to reach this goal.
- The last chapter in this book gives an example from early adoption of RCM for Hydro Power Systems which give more insight in such an experience.

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RCM and RCAM

Systematic AM process

- The RCM process starts in the design phase and continues for the life of the system as shown in Figure 4.3. There are several major tasks required to implement the RCM concept.
- In order for the RCM or RCAM analysis to be possible, there is a need for comprehensive knowledge about the system, its components, and other suitable input data to support a quantitative analysis. In the following section, these needs are further discussed.

RCM and RCAM

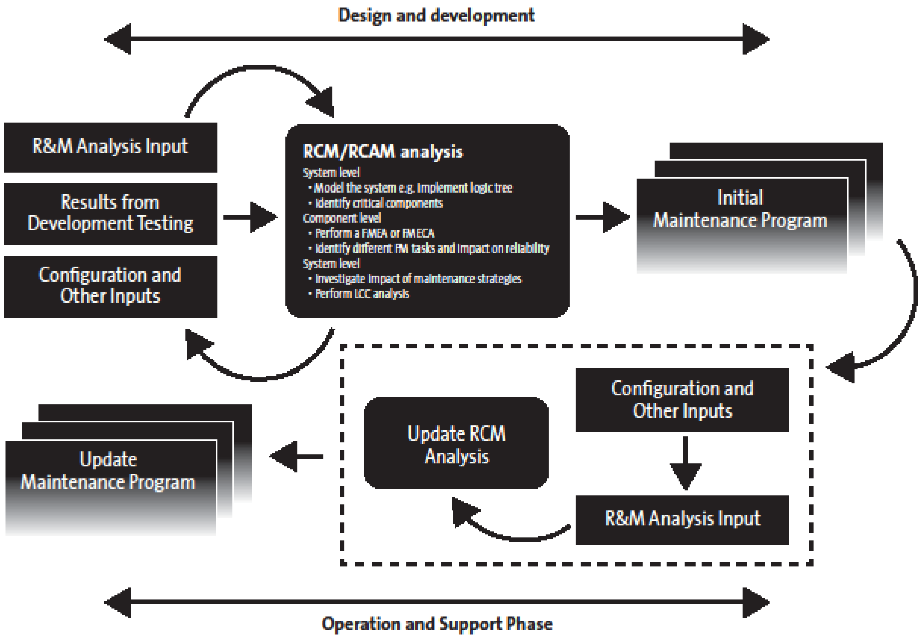
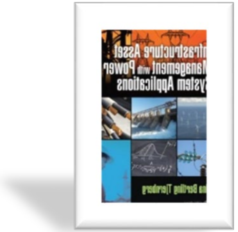


Figure 4.3. An overview of steps of the RCM and RCAM process.

Outgoing from the: IEEE, [39] *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, The Gold Book*. IEEE Std 493-2007, February 2007.

RCM and RCAM



Systematic AM process

- According to IEEE Goldbook [39], these tasks can be grouped into two main activities as follows.

1. *Conduct supporting analyses:* RCM is an information-intensive process. Supporting analyses providing these data include the FMEA, fault tree analysis, functional analysis, and others.
2. *Conduct the RCM analysis:* The RCM analysis consists of using a logic tree to identify effective, economical, and, when safety is concerned, required preventive maintenance.

RCM and RCAM

Systematic AM process IEEE Goldbook [39],

- A central part of RCM analysis is how to collect, select, and define these different input data needs.
- At the system level, the following data are required:
  1. System descriptions
  2. System drawings
  3. PM and control programs
  4. Commitments or requirements for existing programs
- At the component level, the following data are required:
  1. A list of components
  2. Component maintenance history data

RCM and RCAM

Systematic AM process IEEE Goldbook [39],

- For the cost/benefit analysis, the following data are required:
  - The cost of reliability, that is, investment cost and outage cost
  - The cost of undertaking maintenance, that is, the cost of manpower, materials, components, and so on
  - The cost of not undertaking maintenance, that is, outage costs for the utility and for the customers

RCM and RCAM

***Systematic AM process*,**

- The input data for performing the RCM and RCAM analysis also involves the experience from practice.
- At the system level, the main areas for input are from two areas [39].
  1. the understanding of the overall procedures involved in maintenance planning.
  2. a dialogue is needed with the utilities to get to know the relationship between maintenance and reliability.

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RCM and RCAM

Systematic AM process [39],

- At the component level, the following issues need to be discussed:
  1. Which modes can be affected by maintenance
  2. The relationships between failures and lifetimes
  3. Whether maintenance can affect "constant" failure rates or wearing out
- For the cost/benefit analysis, it is critical that the following issue is discussed:
  – What are the factors that need to be balanced

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RCM and RCAM

Input data requirements [39]

- The RCM analysis requires an extensive amount of information. Much of this information is not available early in the design phase and therefore the RCM analysis for a new product cannot be completed until just prior to production.
- The data needs fall into four categories:
  1. failure characteristics,
  2. failure effects,
  3. costs, and
  4. maintenance capabilities and procedures.

RCM and RCAM

Input data requirements [39]

- *Failure Characteristics:* Preventive maintenance is effective only for certain underlying probability distributions.
- Components and items, for example, for which a constant failure rate applies (e.g., the underlying probability distribution is the exponential), do not benefit from preventive maintenance. Only when there is an increasing probability of failure should preventive maintenance be considered. This is why RCM is performed on components in failure mode.

RCM and RCAM

Input data requirements [39]

- *Failure Effects:* The effects of failure of some items are minor or even insignificant.
- The decision whether or not to use preventive maintenance for such items is based purely on costs.
- If it is less expensive to allow the item to fail (and then perform corrective maintenance) than to perform preventive maintenance, the item is allowed to fail. As stated earlier, allowing an item to fail is called run to failure.

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RCM and RCAM

Input data requirements [39]

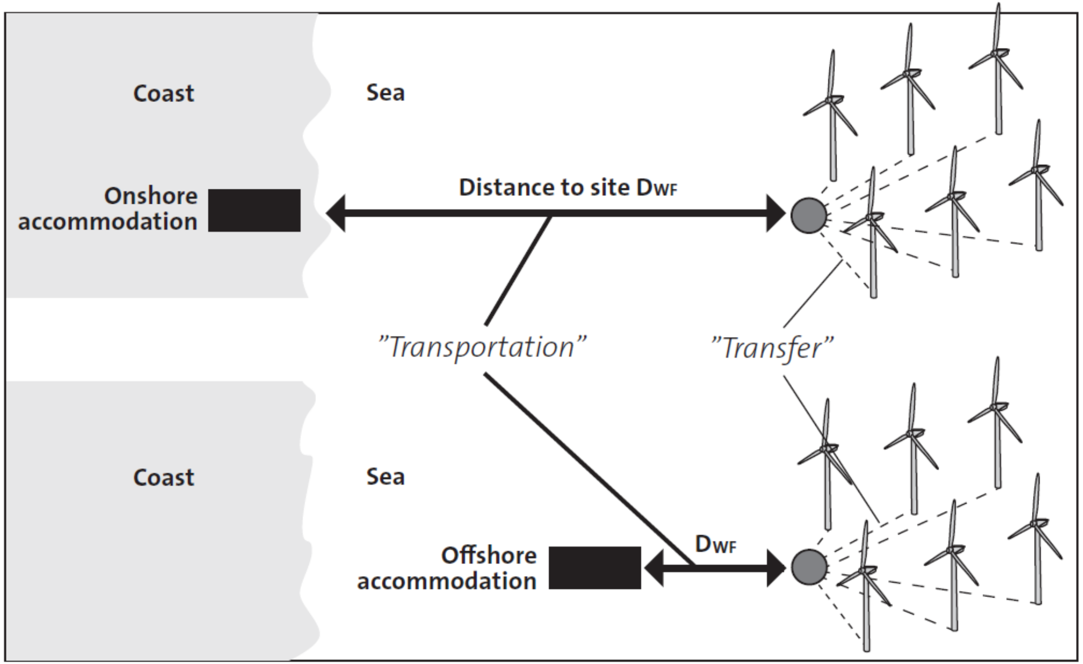
- *Costs:* The costs that must be considered are the costs of performing a preventive maintenance task(s) for a given item, the cost of performing corrective maintenance for that item, and the economic penalties, if any, when an operational failure occurs.
- *Maintenance Capabilities and Procedures:* Before selecting certain maintenance tasks, the analyst needs to understand what the capabilities are, or are planned, for the system. In other words, what is or will be the available skill levels, what maintenance tools are available or are planned, and what are the diagnostics being designed into or for the system.

Outline of the Tutorial

- Different parts of the tutorial
  - Introduction
  - Maintenance as a strategic tool
  - Reliability Centered Asset Management Method
  - Case Study

Case study

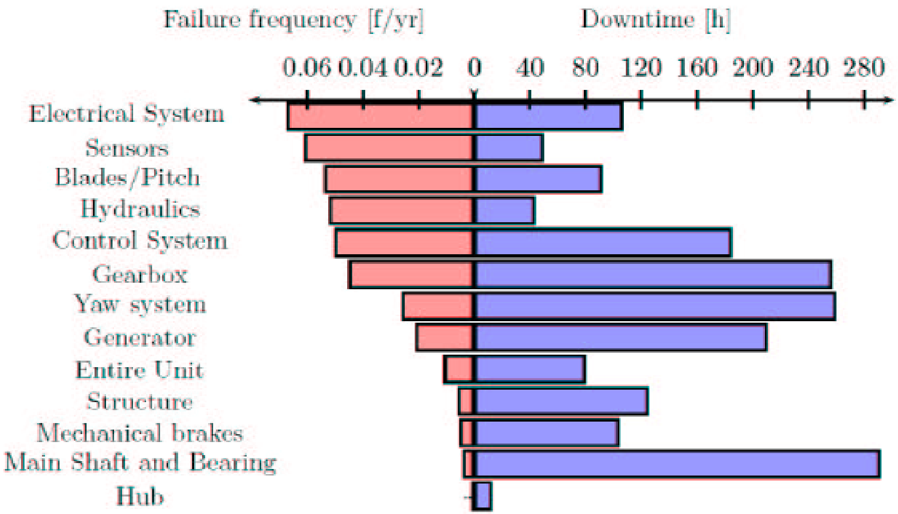
Case Study: RCAM offshore wind farm



- Goal is to reduce O&M costs for offshore wind farms
  - ✓ transportation costs are high
  - ✓ accessibility constrained by the weather

Illustration of the logistics of maintenance technicians and transportation. Figure 9.4 in *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018*

Case Study : RCAM – Stage 1 Critical components

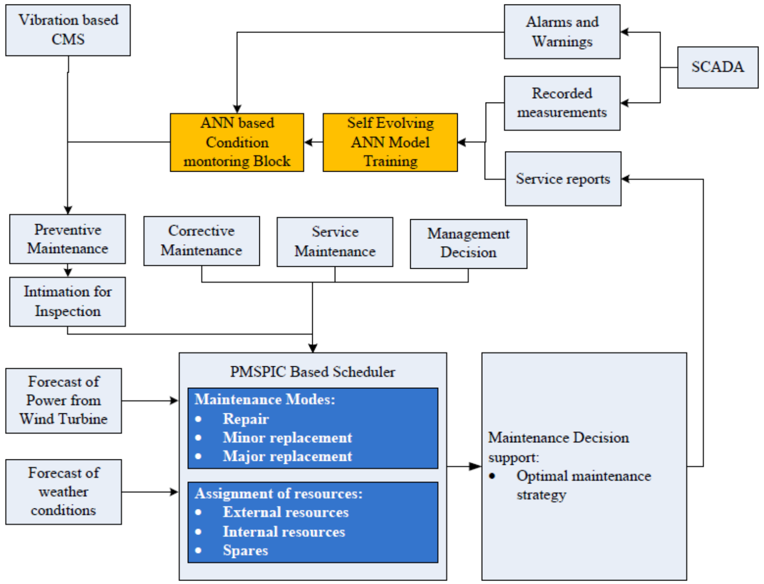


(Adapted from "Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005", J. Ribrant and L.M. Bertling, IEEE Transaction on Energy Conversion, vol.22, num.1, 2007)

- Outage data used to identify critical components in the system
  - Unavailability = failure frequency * outage time

Case Study: RCAM – Stage 2 Fault detection

- A framework is proposed for AM of wind turbines with ANN based CM approach using data from SCADA



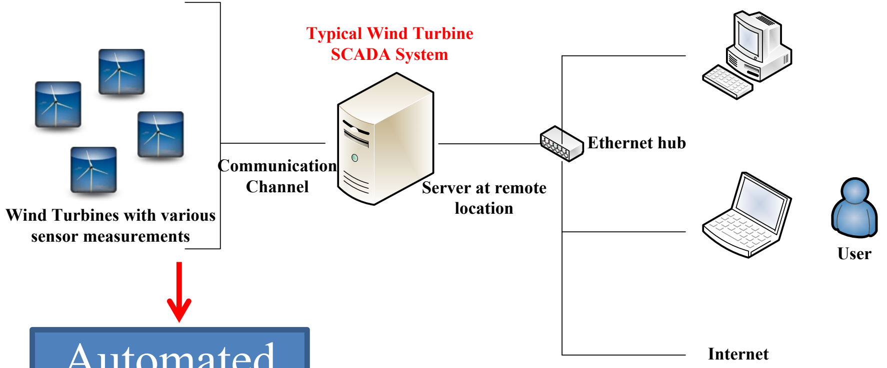
ANN: Artificial Neural Networks

PMSPIC: Preventive Maintenance Scheduling Problem with Interval Costs

SCADA: Supervisory Control And Data Acquisition system

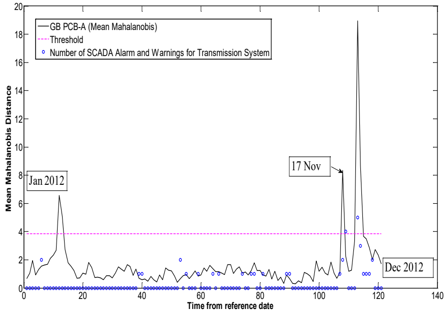
Bangalore P., Bertling Tjernberg L, An artificial neural network approach for early fault detection of gearbox bearings, IEEE Transactions on Smart Grid, Vol. 6, No. 2., March 2015.

Case Study: RCAM – Stage 2 Fault detection



Automated training of ANN

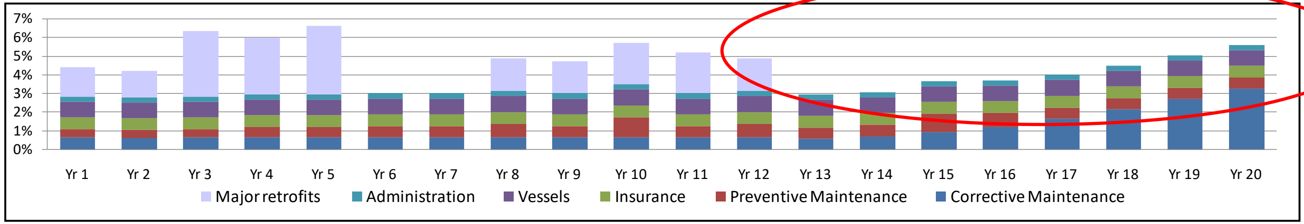
ANN based Anomaly Detection

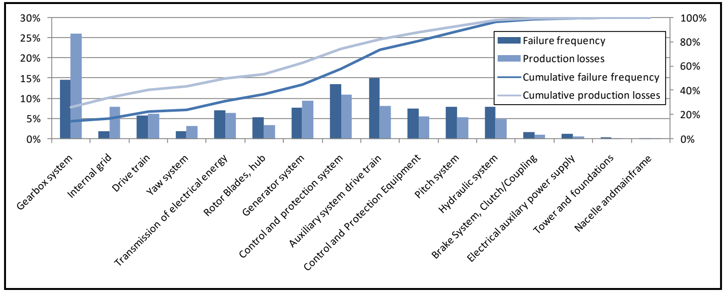


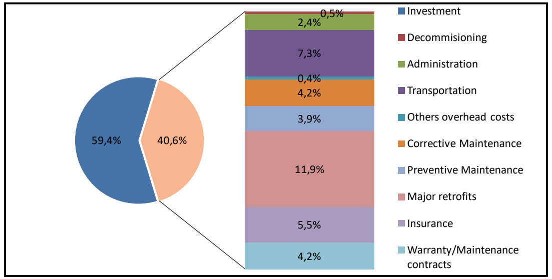
Bangalore P., Bertling Tjernberg L, [An artificial neural network approach for early fault detection of gearbox bearings,] IEEE Transactions on Smart Grid, Vol. 6, No. 2., March 2015.

Case Study: RCAM Stage 3 – LCC Analysis

- Case study based on Horns Rev (80 Vestas V80 2MW)







A Model for the Optimization of the Maintenance Support Organization for Offshore Wind Farms, Besnard F., Fischer K., Bertling Tjernberg L, IEEE Transactions on Sustainable Energy, April 2013.

Example CMS Wind

An Anomaly Detection Approach Based on Machine Learning and SCADA Data for Condition Monitoring of Wind Turbines

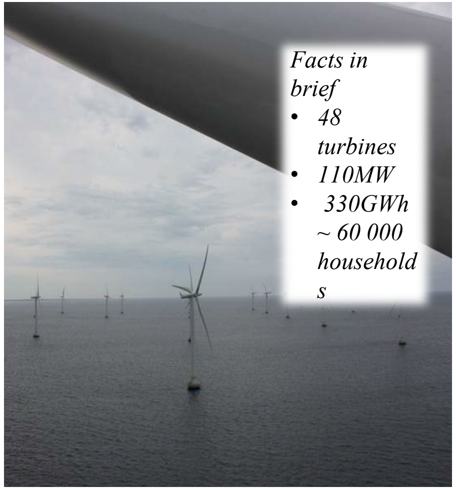
Results from publications

Y. Cui, P. Bangalore, and L. Bertling Tjernberg, An anomaly detection approach based on machine learning and SCADA data for condition monitoring of wind turbines, In proceedings of the International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Boise, Idaho, June 2018.

Y. Cui, P. Bangalore, and L. Bertling Tjernberg, An anomaly detection approach using wavelet transform and artificial neural networks for condition monitoring of wind turbines’ gearboxes , In proceedings of Power Systems Computation Conference (PSCC), Dublin, Ireland, June 2018.

Key messages

- Condition monitoring is a shown efficient tool for maintenance management of wind turbines with the target optimizing the maintenance effort.
- This work aims to propose an effective anomaly detection approach for critical components of the wind turbine
- Novel methods for condition monitoring with ANN handling large volumes of data from SCADA



Lillgrund Wind farm, the worlds largest offshore farm when put in operation, 2008. @linabertlingtjernberg

Contents

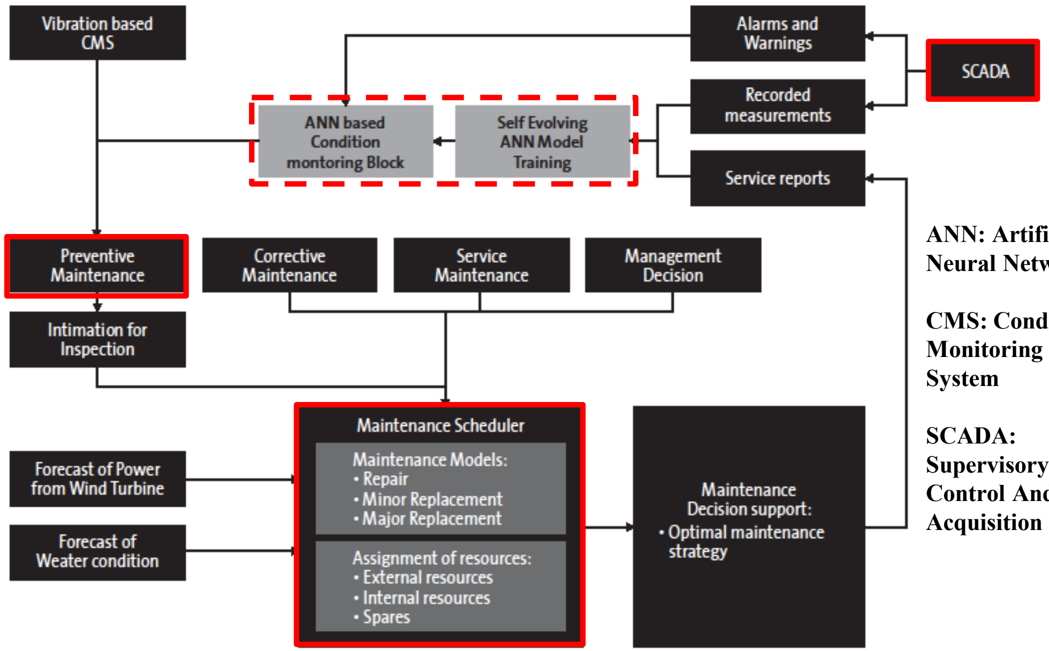
Motivation

- Wind power is a key solution developments for the sustainable energy systems
- High operation and maintenance cost (O&M) are main challenges for wind power developments
- Condition based preventive maintenance is a tool for efficient maintenance planning

Lillgrund Wind farm, @linabertlingtjernberg

Contents

Methods – SEMS Framework



ANN: Artificial Neural Networks

CMS: Condition Monitoring System

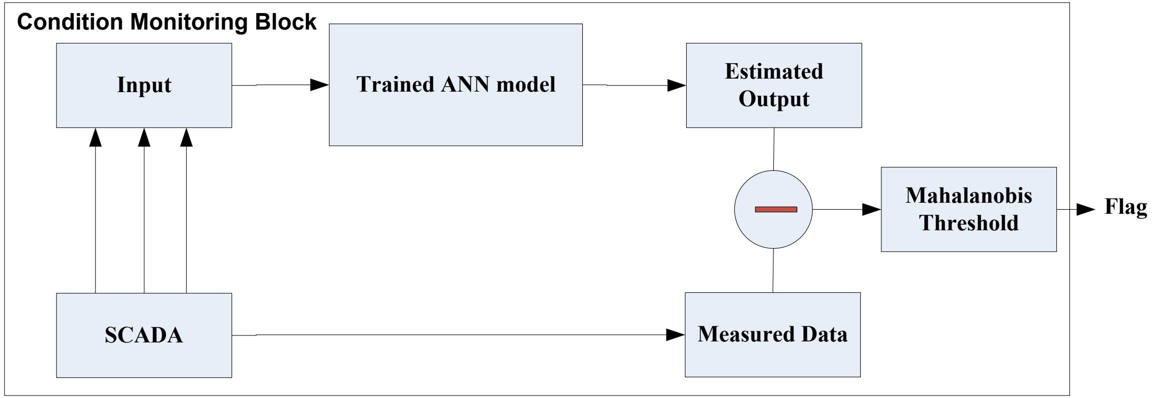
SCADA: Supervisory Control And Data Acquisition system

Self Evolving Maintenance Scheduler (SEMS) Framework.
Figure 8.21 in *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018.* Adapted from: Banglore, P. and Bertling, L., An artificial neural network approach for early fault detection of gearbox bearings, *IEEE Transactions on Smart Grid*, 2015.

Method - SEMS

- The SEMS framework considers a short window of time which exists between an indication of impending failure from the CMS and the eventual failure of the component.
- Any alarm from the vibration based CMS or the ANN-based condition monitoring approach will give intimation to the maintenance personnel to perform an onsite inspection of the specific component.

Method: ANN based condition monitoring



ANN-based condition monitoring block.
Figure 8.22 in *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018,* Adapted from: Banglore, P. and Bertling, L., An artificial neural network approach for early fault detection of gearbox bearings, *IEEE Transactions on Smart Grid*, 2015.

Method: NARX ANN Model

- Artificial neural network is based on the biological structure of the neural networks in living organisms. Connection of simple processing units together enables delivery of a complex process.
- The the non-linear auto-regressive neural network with exogenous input (NARX) is used in this work.
- The dynamic behavior of a NARX model can be described by the following equation.

$$y_t = F(y_{t-1},\ldots,y_{t-q+1};u_t,\ldots,u_{t-q+1})$$

- where *F* is the non-linear function, u(t) represents the input vector at time instant ‘t’, y(t) is the corresponding output, and ‘*q*’ is the delay line memory.

Method: NARX ANN Model

- The non-linear auto-regressive neural network with exogenous input (NARX) structure is used in this work

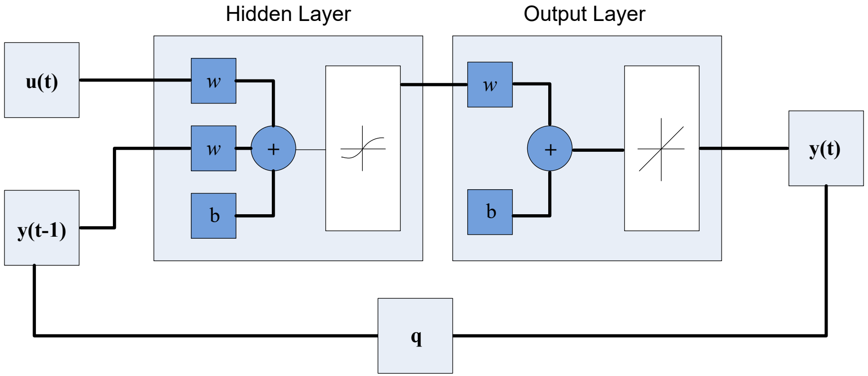


Figure 8.23 in *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018.* Adapted from: Bangalore, P. and Bertling, L., An artificial neural network approach for early fault detection of gearbox bearings, *IEEE Transactions on Smart Grid*, 2015.

Method: input data SCADA alarm

- Alarms from SCADA systems
  - trigger when key component signals exceed threshold limits
  - indicate the changes of operation state and component malfunctions
  - requires operators to take prompt actions e.g. to avoid severe damages.
- The *alarm logs* record the information of the alarms that happen during the operation process including:
  - detected and acknowledge time, error numbers and text, categories and subsystems, and severity indications.

✓ This study applies a common manual for the SCADA alarm logs for wind turbines of major manufacturers.

Method: input data SCADA alarm

- The approach applies the data of SCADA as primitive in-put. The data include two parts: operation data and alarm logs.
  1. The operation data are usually averaged every ten minutes and contain the values of main parameters of wind turbines.
     - Used to forecast the behaviors of wind turbines
  2. The alarm log records the reported operation errors, detected time and the corresponding subsystem information.
     - Used to make decisions.

Method: Pre-processing of data

- Pre-processing of the raw records sampled from SCADA to remove garbage data which are assumed to be error values.
  1. Missing data filter: records with missing attribute values are filtered out.
  2. Clustering filter: the operation data are analyzed to keep those parts under healthy operations. Those records with the errors reported in the alarm log are seen as malfunctions hence are deleted at this step. The data are classified into subgroups.
  3. If the records locate outside three standard deviations from their mean values in each subgroup, then they are assumed to be outliers and are deleted in the filter.
  4. Normalization: the operation data are normalized to the standard normal distribution to eliminate the scale effect.

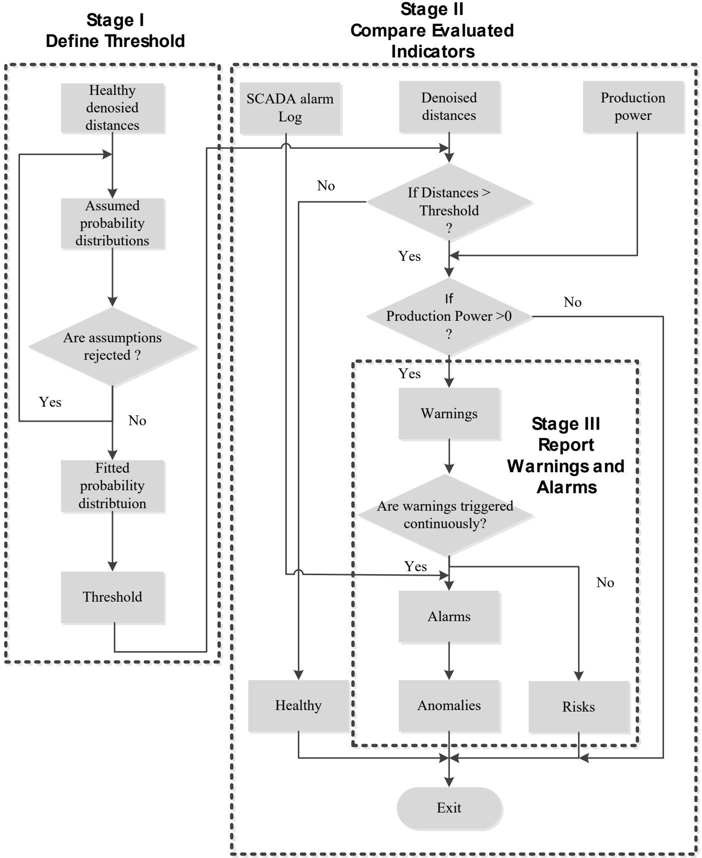
Method: ANN Model

- Nonlinear autoregressive neural networks with exogenous inputs (NARX) networks are employed to model the normal behaviors of wind turbines.
- In this paper, Levernberg-Marquardt back propagation is applied to train NARX networks and mean squared errors to evaluate their performances.
- The approach uses the Mahalanobis distance to measure the deviations between the healthy operations and possible malfunctions of wind turbines. The Mahalanobis distance measures the similarity between two independent sample sets.

Method: Anomaly analysis

- In the approach the absolute errors of the estimated values are calculated from the constructed neural networks and the real measurements in SCADA system of the temperature signals.
- Then Mahalanobis distances of the respective errors under the healthy operations and in the test period are calculated.
  - The approach applies these distances as evaluated indicators to assess the operation states of wind turbines.
- To attain accurate anomaly analysis, the discrete wavelet transform is applied to filter the obtained Mahalanobis distances to eliminate the interference of high frequency noises.
- The approach integrates alarm information with the evaluated indicators to perform the anomaly analysis.

Method: the anomaly analysis



Y. Cui, P. Bangalore, and L. Bertling Tjernberg, An anomaly detection approach based on machine learning and SCADA data for condition monitoring of wind turbines, In proceedings of the International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Boise, Idaho, June 2018.

Method: Stage I define thresholds

- The threshold determines the upper limit of the Mahalanobis distances under healthy operations.
- The approach calculates the denosied Mahalanobis distances when there are no malfunctions reported in the wind turbines.
- It is assumed that these distance values can be represented by a certain probability distribution. Since the samples are large enough, normal distributions are mainly considered in this paper.
- Kolmogorov-Smirnov statistics test is applied to test the assumptions that the available distance values come from the specific probability distributions. If the assumption cannot be rejected, then an optimal probability distribution can be calculated by curve fitting. Otherwise new probability distributions are tested until they cannot be rejected by the statistics test anymore. The threshold is defined at a high value that has a low probability in the fitted probability distribution, which is assumed to represent an extreme value under healthy operations.

Method: Stage II Compare evaluated indicators

- The denoised Mahalanobis distances are compared with the threshold which is calculated at the previous stage.
- If the distance does not cross the threshold, then the wind turbine is regraded to be healthy and no incipient anomalies exist at the moment.
- Otherwise there is deemed to be possible operational risks existing in the wind turbine and the analysis steps forward to the next stage. What is noted that the grid production power should also be checked to ensure the analyzed wind turbine is in the normal operation.

Method: Stage III Report warnings and alarms

- The approach defines warnings and alarms to measure the different risk degrees of the possible anomalies.
- If the evaluated indicators are beyond the threshold, then a warning is triggered.
- It indicates that there are possible operational risks in the wind turbines. An alarm is reported to warn operators of the potential incipient anomalies and further inspection activities should be arranged in time in case of severe damages of subassemblies.
- In this approach, alarms consist of two parts:
  - one part is based on the results of the neural networks;
    - this trigger only if warnings at Stage II last continuously, in case that the occasional warning may be triggered accidentally.
  - the other part is from the alarms recorded in the SCADA alarm logs.
    - these indicates the change of operation states and component malfunctions.

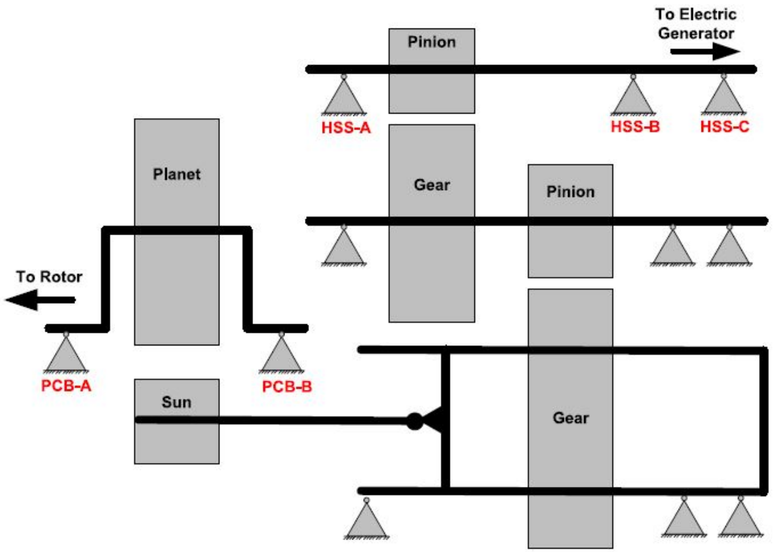
Contents

Results - Case study

- The SEMS Framework and the proposed ANN based condition monitoring approach are applied to real practice
- Continuous SCADA data and maintenance records are used for two different wind turbines, of the same manufacturer, rated 2MW and located onshore in southern part of Sweden
- The gearbox used in the wind turbines is a planetary gearbox combined with two-stage parallel shaft gearbox. This is a common configuration used in the wind industry due to its large ratio and power capacity.
- The gearbox has a flexible mounting and is connected to the generator shaft using composite coupling. The brake disc is mounted on the high speed shaft (HSS) of the gearbox coupled to the composite coupling. Several parameters of the gearbox such as bearing temperature, lubrication oil temperature and lubrication oil pressure are monitored and recorded in SCADA system.

Results - Case Study:

- Three stage planetary gearbox with different bearings.



✓ Measurements available in the SCADA system for the five bearings marked in red e.g.

- generated power
- temperature
- rotor rotations

Figure 8.24 in *Infrastructure Asset Management with Power System Examples, L. Bertling Tjernberg, CRC Press Taylor and Francis, April 2018.* Adapted from: Bangalore, P. and Bertling, L., An artificial neural network approach for early fault detection of gearbox bearings, *IEEE Transactions on Smart Grid*, 2015.

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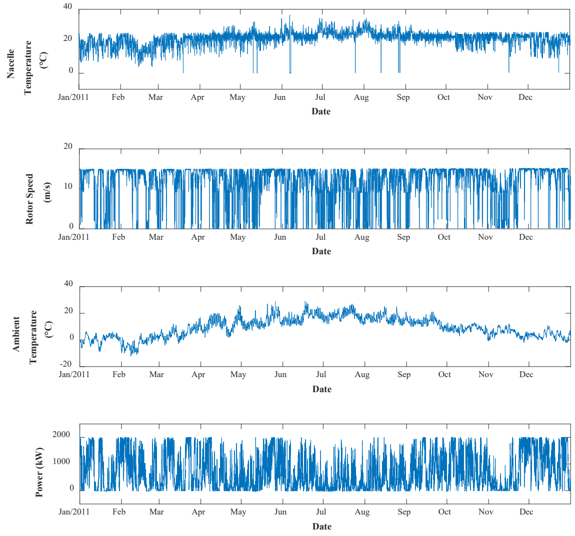
Case Study: Operating state of the gearbox

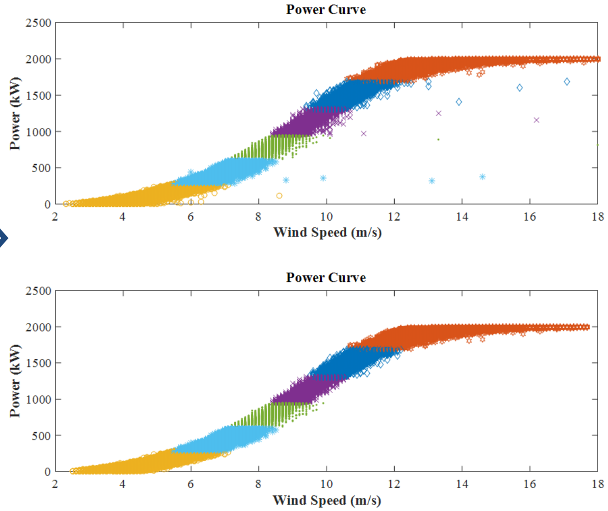
- The proposed approach is applied to the real data of a 2MW indirect driven onshore wind turbine. A fault in bearing of the gearbox was detected in a regular inspection on November 23, 2012. The replacement was performed until February 15, 2013.
- The study analyze the operation states of the gearbox:
  - two neural networks are constructed with the respective output of the bearing temperature and lubrication oil temperature.
  - four attributes were used as input for both the networks, which are the nacelle temperature, rotor speed, ambient temperature, and grid production power.
  - operation data of one year for the training and those of the other fourteen months for the test.
- This case study applies the temperature signals to explore the possibility to detect possible anomalies.

Results

Input data



Clustering filter results



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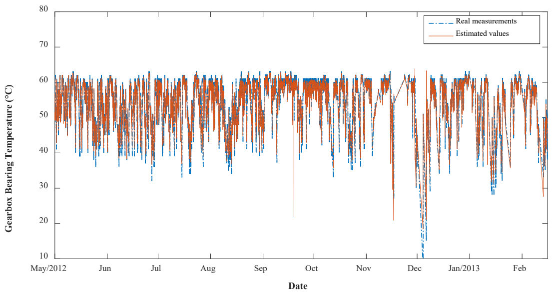
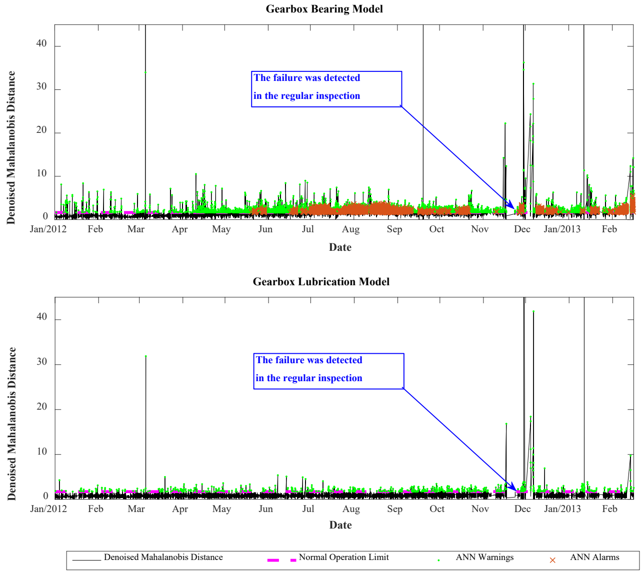
Results

Estimated temperature signals from neural networks



Anomaly analysis results



Results

- The anomaly analysis results of the bearing and lubrication models of the test wind turbine are shown in the figure the which are based on the calculation of Mahalanobis distances of the estimated temperature signals and the measured values and the wavelet denoising.
- It can be seen that the denoised Mahalanobis distance in both the networks increase sharply around the time that the failure was detected. In the bearing model, 8348 warnings and 1364 alarms are reported based on the results of the NARX models. The first alarm happens on May 19, 22:40, 2012, which is six months ahead of the failure was found. In the following months, more alarms are triggered continuously, indicating that the potential health changes probably happen in the gearbox bearing. In the lubrication model, 521 warnings are totally reported in the test period.
- However, none of these warnings last over two hours, hence no alarms are triggered in this model. It can be implyed that no severe changes happen in the gearbox lubrication system. The above analysis based on the results from NARX models can also be certified by the actual regular inspection.

Contents

Summary

- an anomaly detection approach is presented using machine learning and SCADA data for the condition monitoring of wind turbines.
- The approach applies NARX models to estimate the temperature signals of wind turbines, uses the Mahalanobis distance as evaluated indicators, and employs the wavelet transform to denoise the noisy signals.
- The main contribution of the approach is to consider the SCADA alarms with the condition monitoring based on machine learning techniques. The results show that the proposed approach can compensate the weakness of SCADA alarm logs to remind of the possible anomalies in wind turbines. It is also certified that the approach is capable of detecting anomalies at an early stage.

Further reading RCAM Wind

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Closure: summary remarks

- AM for smart decisions targeting sustainable development goals
- Standards provide the basis for implementation of AM
- Reliability analysis and maintenance efforts provide tools for AM
- It is beneficial to apply maintenance strategies based on the results of quantitative systematic techniques such as RCAM and LCC
- Performing RCM and RCAM are part of the design and development and also the operation and support phase
- Input data from condition monitoring could be used for AM

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