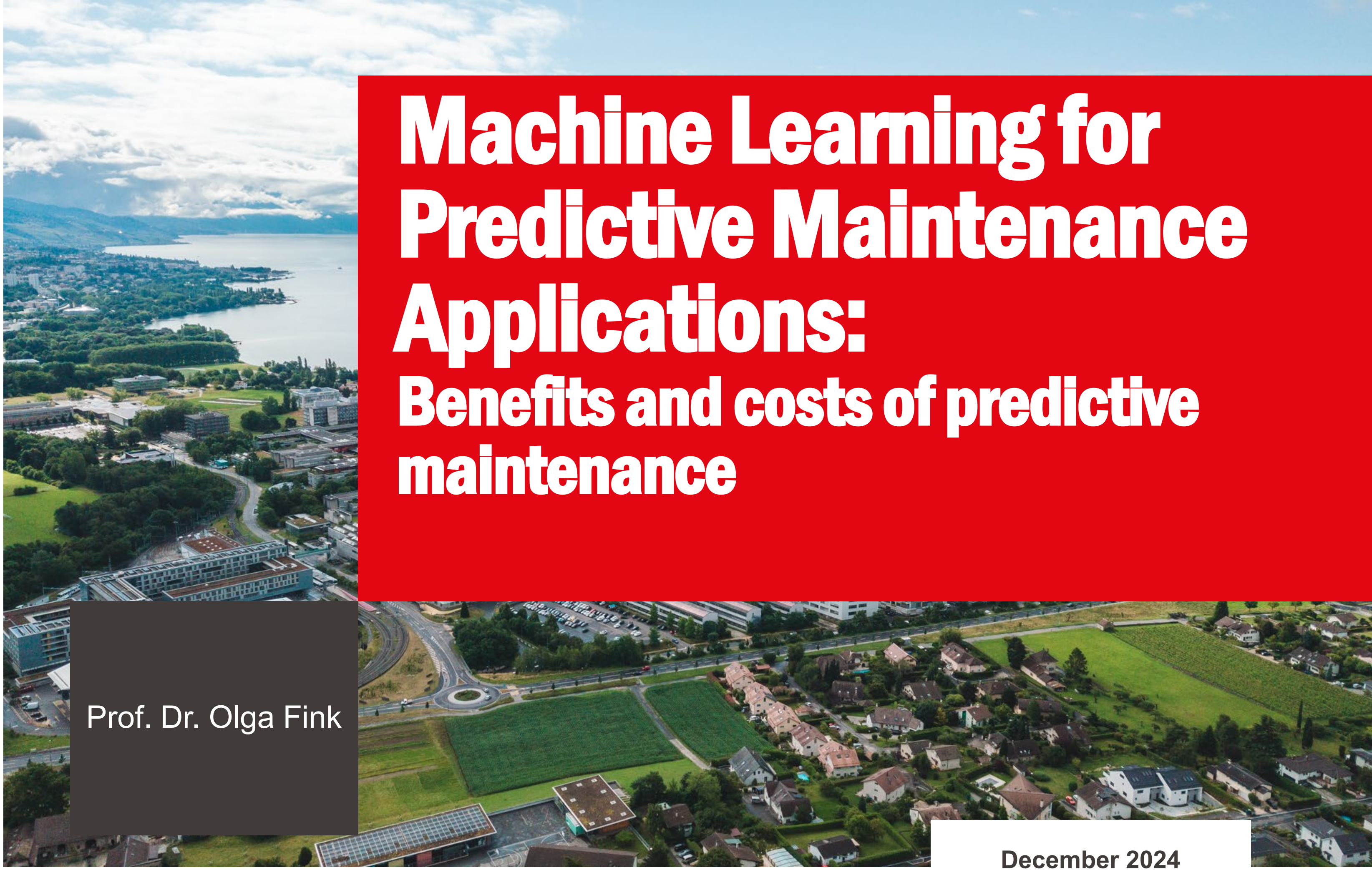

Machine Learning for Predictive Maintenance Applications:

Benefits and costs of predictive maintenance

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How to quantify the benefits of predictive maintenance

Evaluating the usefulness of a railway switch condition monitoring system

The Fundamental Maintenance/Value Trade-off

Goal (depending on application) is either to:

- Perform maintenance so that the remaining useful life (RUL) and the remaining useful performance (RUP) are maximized (use up as much of the life as possible), while simultaneously avoiding failures (unscheduled maintenance)

Or:

- Find the optimum mix of condition based / predictive, scheduled and unscheduled maintenance that minimizes the life-cycle cost

→Note that the goal is not to completely avoid failures, this is NOT a "safety" argument, it is an economic argument.

Source: Sandborn, 2015

Challenge to Implementing PHM

The economic challenge:

- Describe PHM costs/benefits in terms of standard economic measures, e.g. ROI

The logistics challenge:

- Determine impact of PHM on higher level system logistics support measures

The technical challenge:

- Match technology to needs, including data sources, sensors and weight, space, and bandwidth constraints

Source: Luna, 2013

Why is it so difficult?

- Quotes from an aerospace company
- “One (difficult) issue is how to calculate the benefits of PHM. […] This is because PHM avoids costs. So how do you prove that (non-existent) costs would have been there had the PHM not been in place”
- “We see real benefits in terms of cost savings because by using PHM, we avoided a number of cancelations, delays etc. But how you attribute those to PHM is open to debate.”
- “Business cases are very difficult and I think it was more of an appreciation on a senior level that you almost have to do this to mitigate the risks”

Source: Pomfret, 2014

Why is it so difficult? (cont)

- Quote from an equipment company
- “Because you can say to someone ‘this (technology) can pick up the (possible) failures and then at the end of the year, when you sum up all the (possible) failures you identified, you will have a certain amount of savings’. But the problem is how to prove it would happen and save them that money, because it never happened. It is all a little bit gray and that is a problem”

Source: Pomfret, 2014

Return on Investment (ROI)

- Return on Investment (ROI)
  - the ratio of money gained or lost (whether realized or unrealized) on an investment relative to the amount of money invested
- ROI = (Return – Investment)/Investment =Avoided Cost/Investment – 1
- ROI = NPV/Initial Investment

ROI < 0:	**NPV < 0, or, Avoided Costs < Investment**
ROI = 0:	**NPV = 0 , or, Avoided Costs = Investment**
ROI = 1:	**NPV = Initial Investment, or, Avoided Costs = 2*Investment**

Source: Luna, 2013

Deriving Value from PHM at the System and Enterprise Levels

- System-level PHM value means taking action based on prognostics to manage one specific instance of a system, e.g., one truck or one wind turbine. The actions tend to be "real-time" and consist of:
  - Modify how you sustain the system (e.g., call ahead to arrange for a maintenance action)
  - Modify the mission (e.g., reduce speed, take a different route)
  - Modify the system (e.g., adaptive re-configuration)
- Fleet-level PHM
  - Optimize the availability and life cycle costs at fleet level (may not be optimal at system level)
- Enterprise-level PHM value
  - taking action based on prognostics to manage an enterprise, e.g., a whole fleet of trucks or a farm of turbines. The actions are longer-term strategic planning things (usually not real-time):
  - Optimizing the logistics
  - Management via availability and other outcome-based contracts

Design, including Requirements Definition

- What Failure Modes are to be detected? (FMECA, Fault-Symptom Analysis)
- Do the sensors exist?
  - If not, cost of introduction/implementation
- How will the HM system be integrated with the platform?
  - Does this generate additional related costs
- Where will the data be collected?
  - On-board or downloaded (and how often)
  - How is the data transmitted (e.g. via LoRaWAN, satellite)
  - Is a secure system needed?
- Where/how will the data be stored/archived/accessed?
- Software creation for data analysis
- Development of dedicated algorithms
- System adaptability for future growth/platform changes

Investment Costs

- Also known as technology cost, implementation cost
- Costs necessary to "develop, install, and support PHM"
  - Non-recurring costs
    - Algorithm development
    - Hardware, software development (requirements, design, etc.)
    - Training, documentation, data
    - Integration into system, IT system
    - Test, qualification
  - Recurring costs (per unit)
    - Added hardware (sensors, connectors, etc.), assembly, test, installation
  - Annual costs (per unit time)
    - Data management (collection, analysis, reporting, archiving), PHM maintenance, decision support, retraining, adaptation of the algorithms

PHM Benefits Expected

- Increased availability
  - Early notification of degrading conditions and future failure
  - Fewer unplanned failures
  - Faster repair time associated with fixing minor problems
  - Reduced potential for loss of service or equipment
- Reduced cost of operations
  - Reduced costs of problem identification and repair
  - Reduced probability of catastrophic failure
  - Reduced spares inventory and redundant equipment
  - Accurate identification of problem
  - Reduced maintenance actions with no fault found
  - Identification of remaining useful life and recommended remedial action
  - Provides “condition” for support of condition-based maintenance

Source: Luna, 2013

Cost Savings and Avoided Costs

- Cost Savings
  - When a proposed action will clearly reduce costs
- Avoided Costs
  - When an action prevents a future cost, if it is reasonably certain that the cost would have appeared without the action. For example, preventive maintenance for machinery
- Lost Opportunity Costs
  - Foregoing a gain that would appear by choosing a different course of action

Cost Benefit

- For PHM, cost benefit is mainly from avoided costs
  - Measurable and Tangible
    - Maintenance costs (cost of repair)
      - Lower average cost of repair for convenient fix
      - Fewer man-hours (lower skill levels, lower manpower levels)
    - Consumable costs (fuel, material)
    - Supply costs (sparing, potentially transportation costs)
    - Loss of service
  - Measurable but Intangible (or can be difficult to quantify by cost)
    - Availability, Mission Effectiveness
  - Not measurable and Intangible (or difficult to measure and quantify by cost)
    - Public perception / Image, Leverage use of data, etc.
- How to relate PHM operational and support impacts to avoided costs?

Source: Luna, 2013

Prognostics Benefit Classes

- Reduce Lead Times
  - Advanced warning of failure allows for logistics planning and actions before failure occurs, reducing lead times for implementing repair/replacement
- Avoid Consequences of Failure
  - Advanced warning of failure allows for…
    - Repair/replacement before failure occurs, thus avoiding its potential consequences
    - Fix at convenient time, location, etc.
- Extend Life/Reduce Maintenance Frequency
  - Advanced warning of failure allows for transition from time-based to condition-based maintenance
- Optimize Resource Use
  - Advanced warning of failure allows for potential failures to be grouped to optimize use of scarce/costly resources

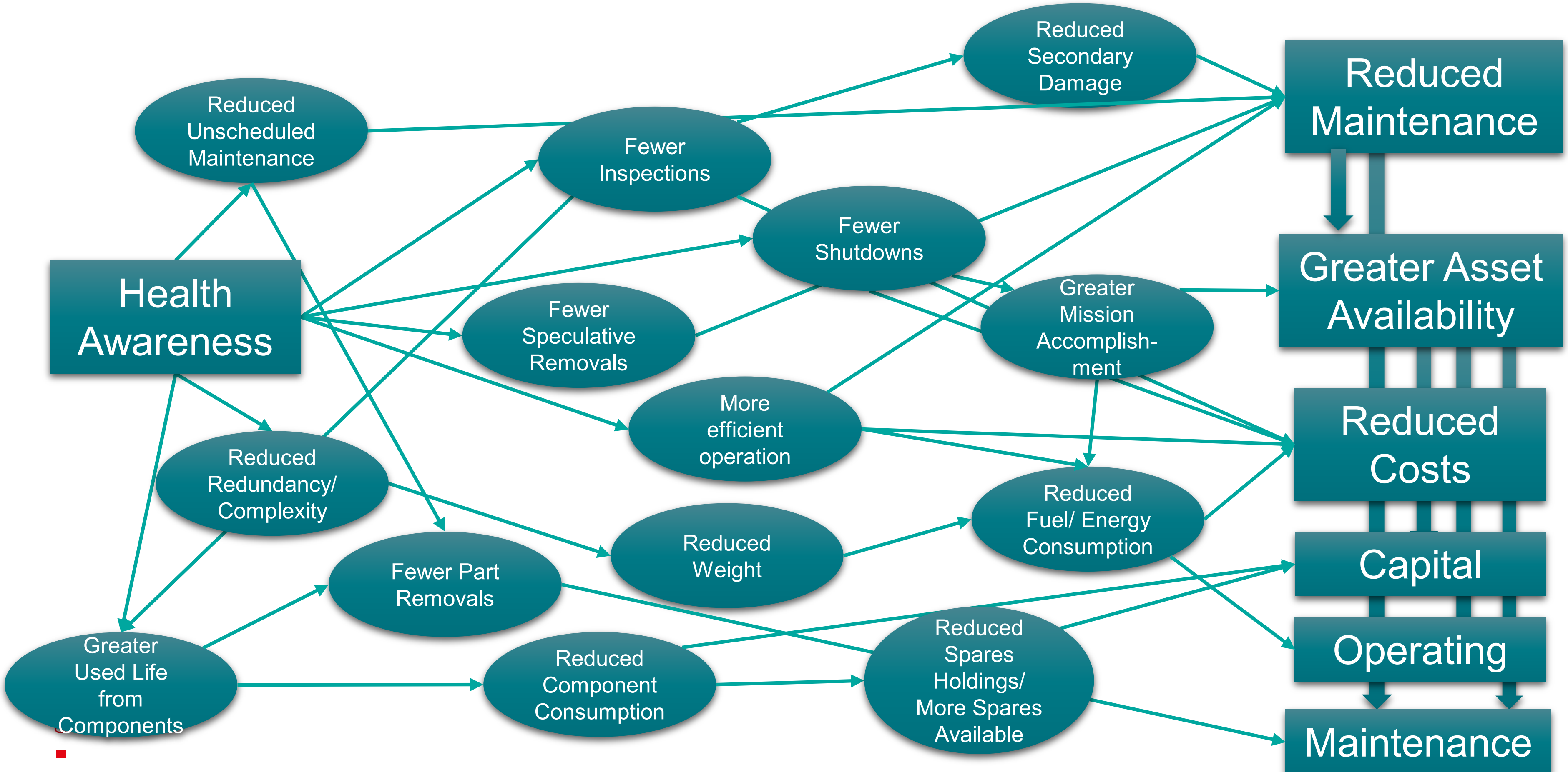
Source: Luna, 2013

Additional considerations

- Reduction in redundancy (long term)
  - Can redundancy be decreased for selected sub-systems?
- Reduced waste stream
  - Less to end-of-life (dispose of) – disposal avoidance
  - Reduction in take-back cost
- Reduced liability
- Warranty claim verification (resulting in warranty reserve fund reduction)
- Reduced time for taking systems into operation (particularly at fleet level)

Source: Luna, 2013

Different perspectives at the benefits



Source: Luna, 2013

Artificial Intelligence Act

Key elements of the EU AI Act (1/2)

- Risk-Based Approach:
  - The EU AI Act categorizes AI systems according to the risk they pose to safety and fundamental rights. The classifications range from minimal risk to unacceptable risk, with corresponding regulatory requirements.
- Prohibited Practices:
  - Certain uses of AI are completely banned under the act, such as AI systems that manipulate human behavior to circumvent users' free will (e.g., subliminal manipulation) and those that exploit vulnerable groups.
- High-Risk AI Systems:
  - High-risk AI applications, such as those used in critical infrastructure, employment, and essential private and public services, are subject to strict compliance requirements. These include transparency obligations, human oversight, and robustness.
- Data and Record Keeping:
  - High-risk AI systems must use high-quality data sets that are free of biases and errors to minimize risks. Providers must keep detailed records of the functioning of their AI systems throughout their lifecycle.

Key elements of the EU AI Act (2/2)

- Transparency:
  - AI providers must ensure a high degree of transparency, particularly for high-risk applications. This includes providing information to users about AI system capabilities, limitations, and the human oversight measures in place.
- Market Surveillance:
  - Member states are required to establish market surveillance frameworks to oversee the introduction of AI systems into the market. This includes checking AI systems for compliance before and after they enter the market.
- Governance:
  - The act proposes the creation of a European Artificial Intelligence Board, which would facilitate the implementation of the regulation across the EU and support the consistent application of rules.
- Compliance and Enforcement:
  - Penalties for non-compliance with the AI Act are substantial, ensuring that AI system providers and users adhere strictly to the regulations.

Definitions

- **AI system** means a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments;
- **Risk** means the combination of the probability of an occurrence of harm and the severity of that harm;
- **Provider** means a natural or legal person, public authority, agency or other body that develops an AI system or a general-purpose AI model or that has an AI system or a general-purpose AI model developed and **places it on the market or puts the AI system into service** under its own name or trademark, whether for payment **or free of charge**;

EU AI Act: Risk levels

Raphaël Déchaux: A Presentation of the AI Act

Unacceptable risk

- All AI systems considered a clear threat to the safety, livelihoods and rights of people
- will be banned,
- Examples: social scoring by governments, toys using voice assistance that encourages dangerous behavior…

High risk (1/2)

- AI systems identified as high-risk include AI technology used in:
  - critical infrastructures (e.g. transport), that could put the life and health of citizens at risk;
  - educational or vocational training, that may determine the access to education and professional course of someone’s life (e.g. scoring of exams);
  - safety components of products (e.g. AI application in robot-assisted surgery);
  - employment, management of workers and access to self-employment (e.g. CV-sorting software for recruitment procedures);
  - essential private and public services (e.g. credit scoring denying citizens opportunity to obtain a loan);
  - law enforcement that may interfere with people’s fundamental rights (e.g. evaluation of the reliability of evidence);
  - migration, asylum and border control management (e.g. verification of authenticity of travel documents);
  - administration of justice and democratic processes (e.g. applying the law to a concrete set of facts).

High risk (2/2)

- High-risk AI systems will be subject to strict obligations before they can be put on the market:
  - adequate risk assessment and mitigation systems;
  - high quality of the datasets feeding the system to minimise risks and discriminatory outcomes;
  - logging of activity to ensure traceability of results;
  - detailed documentation providing all information necessary on the system and its purpose for authorities to assess its compliance;
  - clear and adequate information to the user;
  - appropriate human oversight measures to minimise risk;
  - high level of robustness, security and accuracy.

What makes an AI system a high-risk system?

Criteria used to assess whether an AI system poses a risk of adverse impact on fundamental rights:

- Intended purpose of AI system
- Potential extent of the harm
- The extent to which harmed persons are in a vulnerable position
- The extent in which the outcome of the system is reversible
- The extent in which existing legislation provides for effective measures to address and minimize the risks

Limited risk

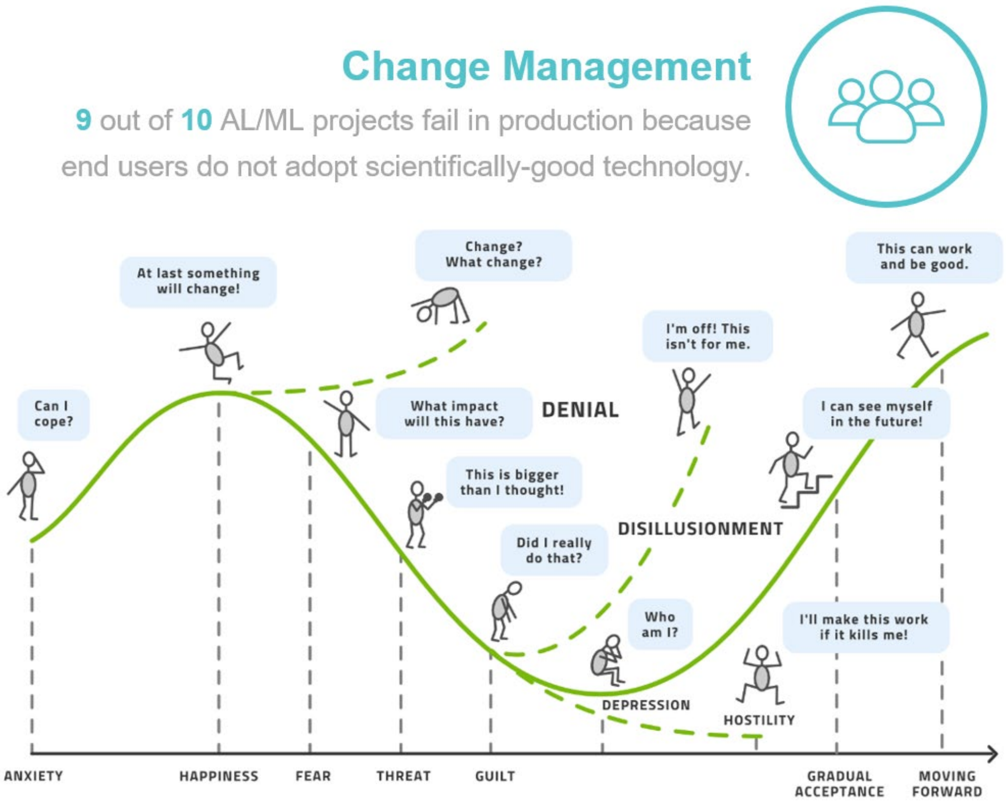
- Limited risk refers to AI systems with **specific transparency obligations**.
- When using AI systems such as chatbots, users should be aware that they are interacting with a machine so they can take an informed decision to continue or step back.

Minimal or no risk

- They neither use personal data nor make any predictions that influence human beings.

Change management

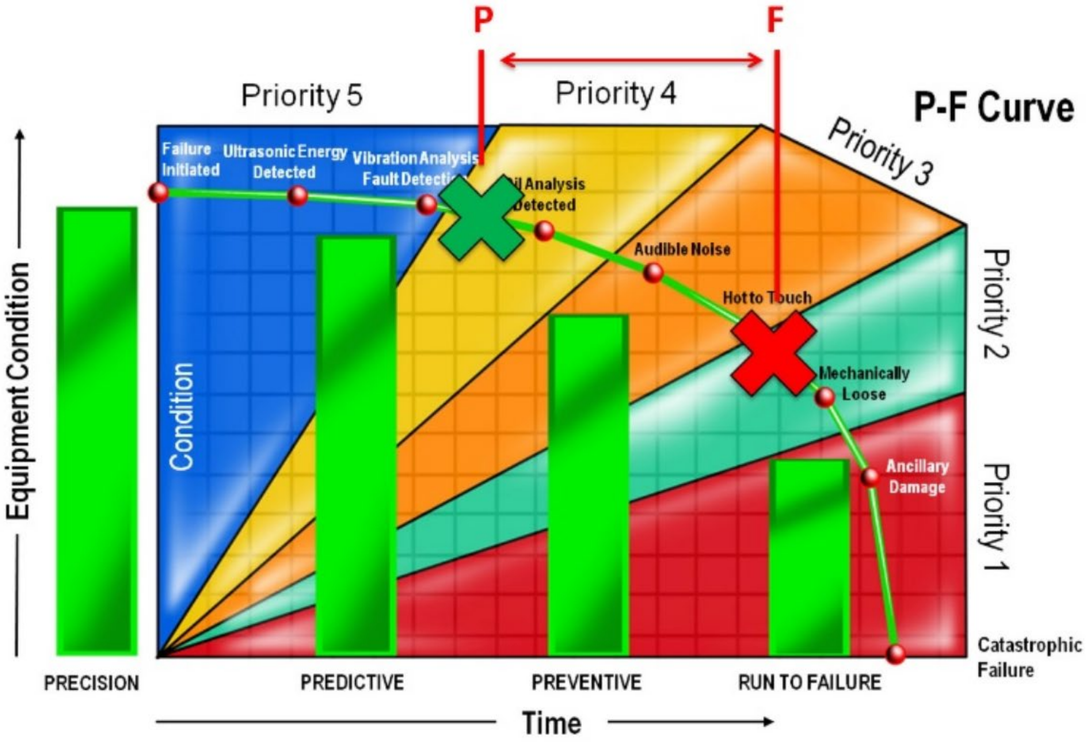
Quote (from Samsung)



Source: P. Bangert, Samsung

How to design effective condition monitoring and PHM systems?

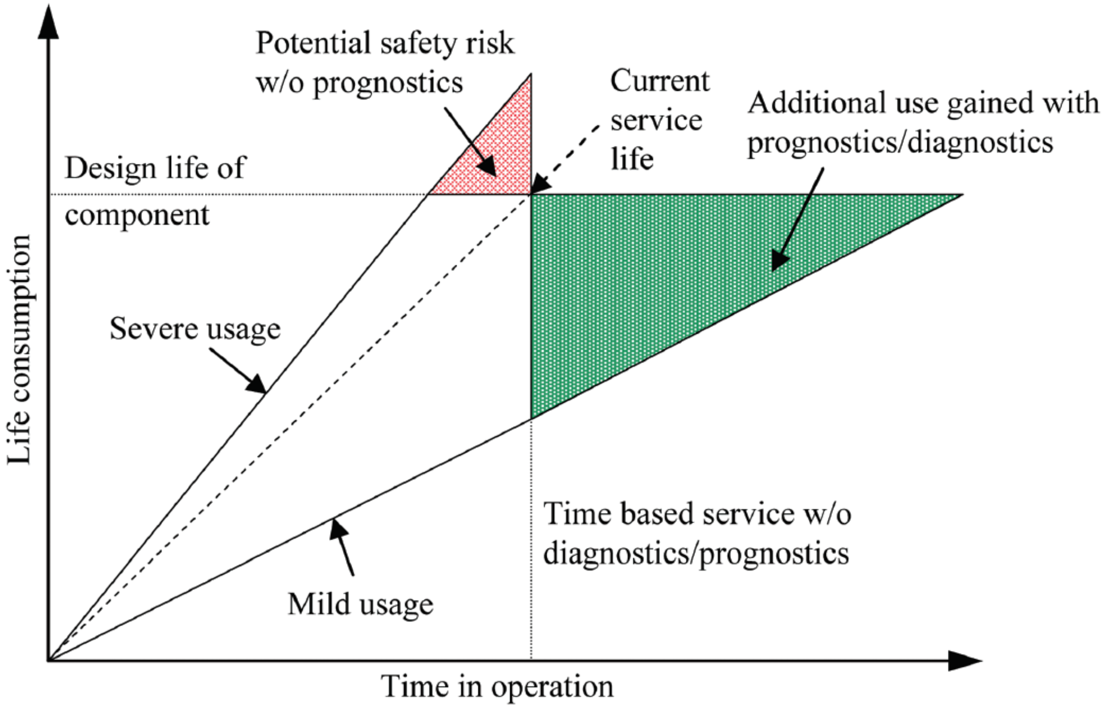
PF intervall



P= potential Failure
F=Failure

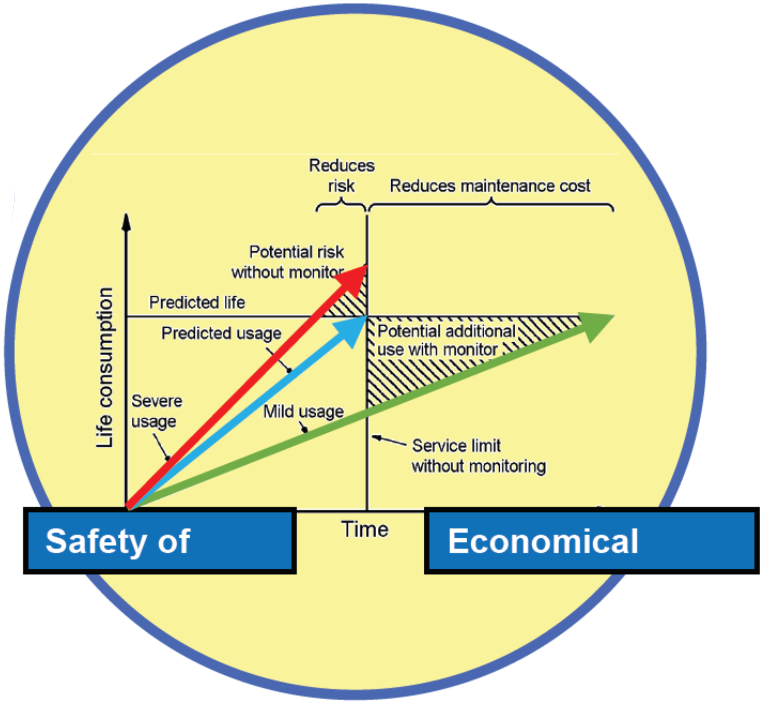
Source: GP Allied

Benefit Diagnostics / Prognostics



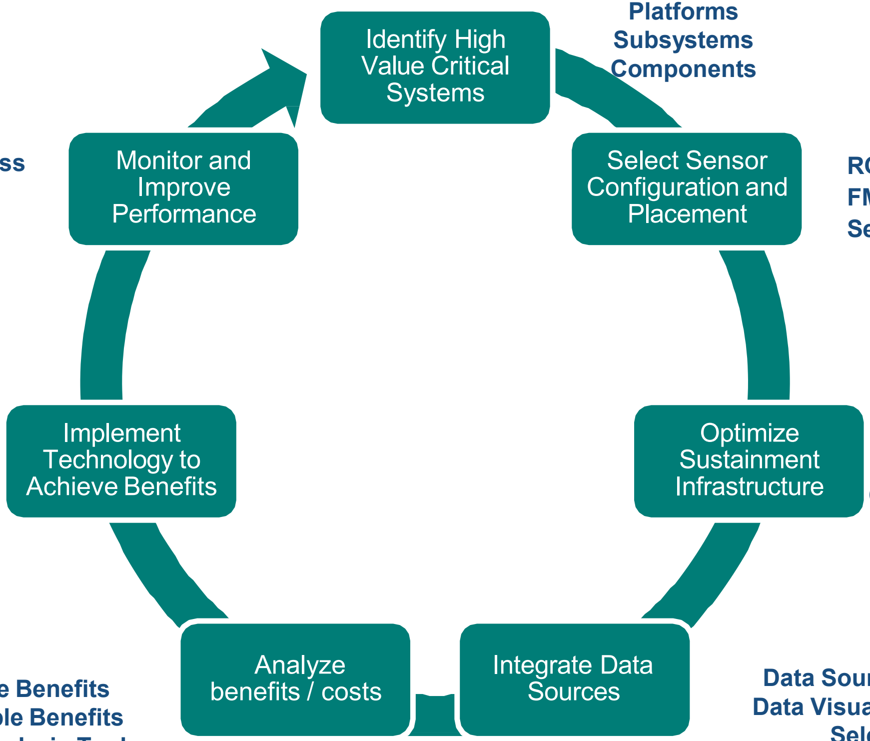
Source: Integrated Vehicle Health Management

Benefit Diagnostics / Prognostics



Source: Integrated Vehicle Health Management

Implementing and managing PHM



Platforms
Subsystems
Components

RCM (Reliability Centered Maintenance)
FMECA (Failure Modes Criticality and Affects Analysis)
Sensor Coverage

Review Infrastructure
Evaluate Supply Chain
Quantify Sustainment Impact

Data Source Analysis
Data Visualization Data Selection

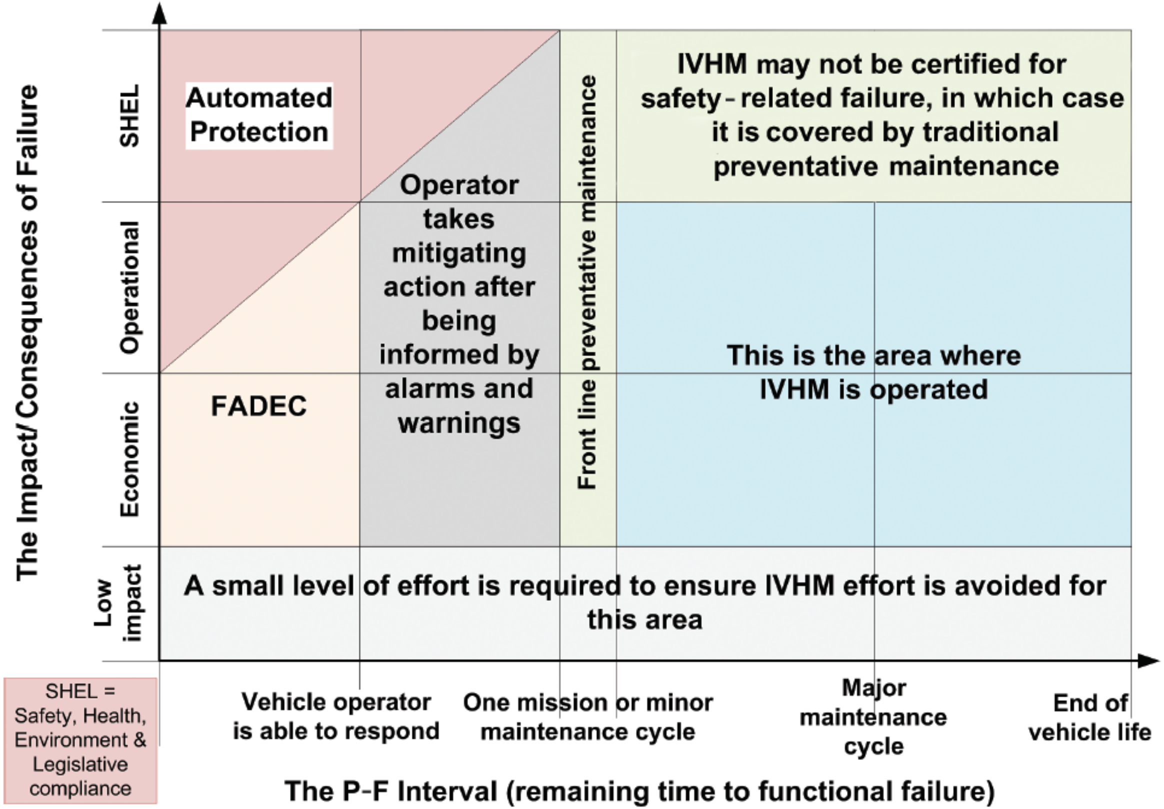
Quantifiable Benefits
Non-quantifiable Benefits
Metrics and Analysis Tools

Detection & Diagnosis
Predictive Analytics
Adaptive Reasoners

Measure progress
Analyze data
Define trends

Source: Luna, 2013

Impacts vs. PF-Intervall



FADEC=Full Authority Digital Engine Control

Source: Integrated Vehicle Health Management

Reliability Centered Maintenance (RCM) (1/2)

- Developed in the late 60s for the civil aviation industry
- now widely used in many industrial sectors
- Method for establishing a program for scheduled preventive maintenance
- Ensuring that the required level of safety and availability is achieved
- Possible improvement of safety, availability and economic efficiency of the overall system

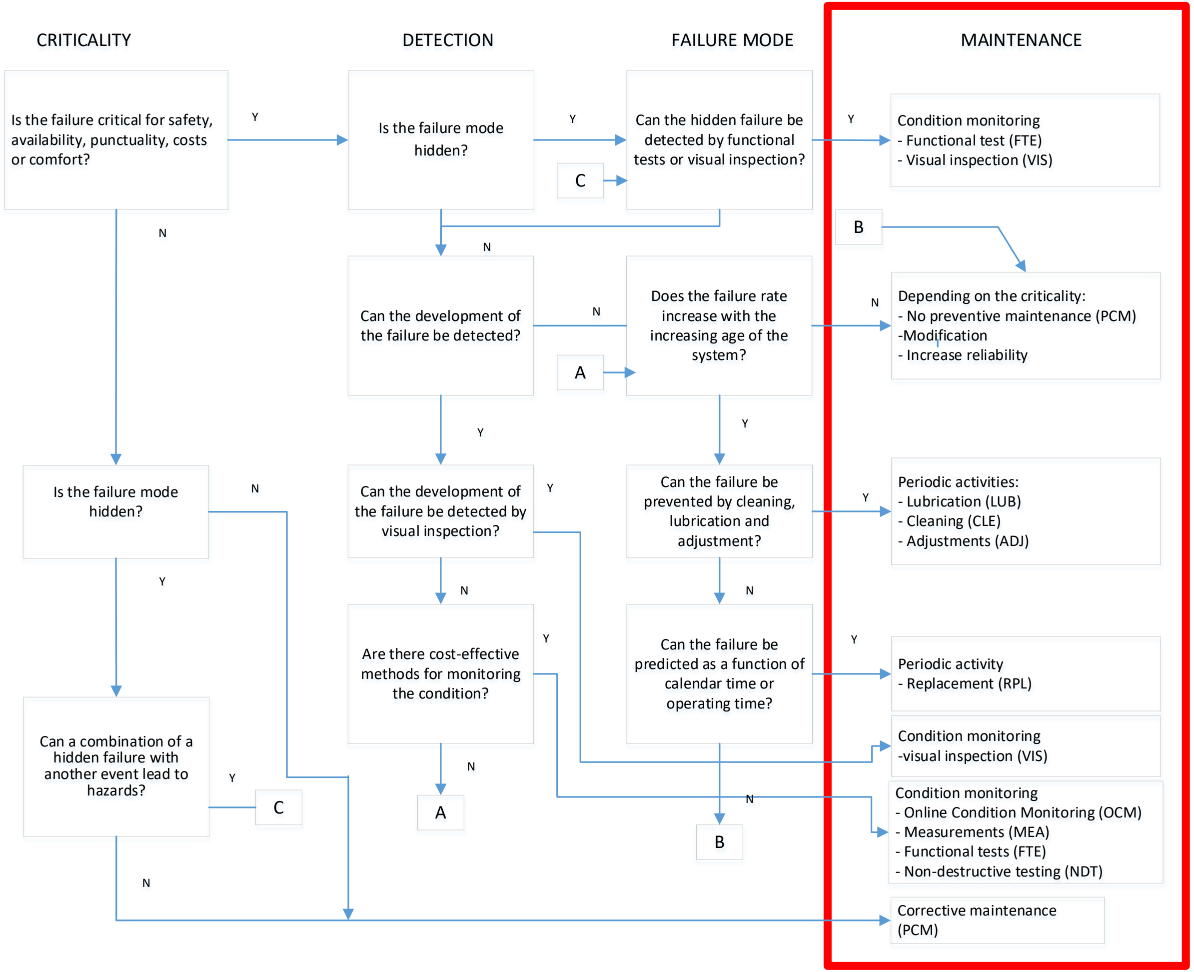
Reliability Centered Maintenance (RCM) (2/2)

- RCM is a systematic approach to the development of maintenance strategies.
- RCM aims to maintain a function, not to maintain a system
- RCM supports the search for the best maintenance strategy to reduce the probability of failure in relation to its severity
- According to the wear mechanisms and failure developments
- Statement about the necessity of the execution of a maintenance task (preventive/corrective)

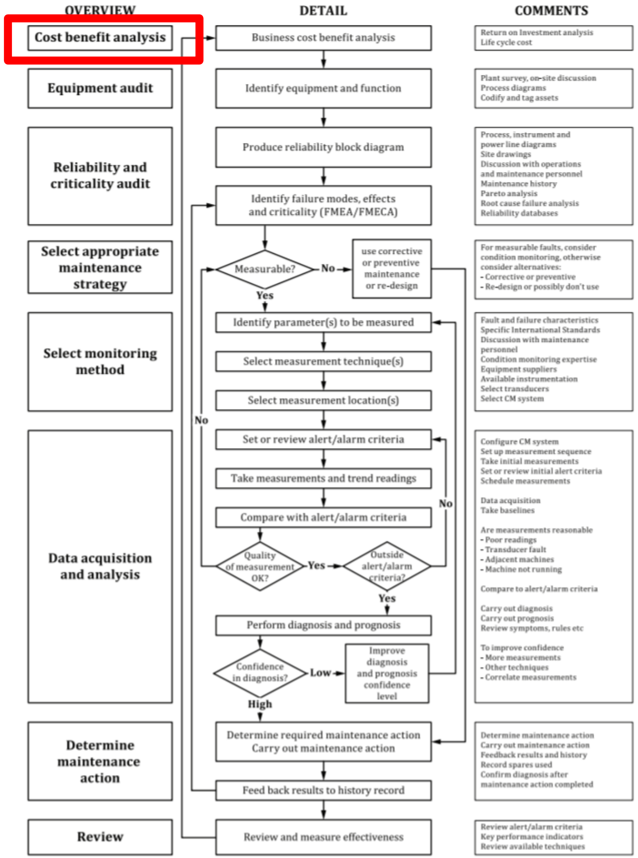
Questions about asset performance

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does it fail to fulfill its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?

RCM decision tree



Condition monitoring procedure



Source: ISO 17359

Cost-Benefit Analysis

- Life cycle costs
- Costs due to loss of production /unavailability costs
- Consequential damages
- Warranty and insurance

Condition monitoring methods

- Measurement technology
- Accuracy of the monitored parameters
- Feasibility of monitoring
- Operating conditions during measurement
- Measuring interval
- Data acquisition rate
- Registration of the monitored parameters
- Measuring points
- Preliminary warning and alarm criteria
- Reference values

Considerations in the selection of measuring points

- Safety,
- Selection of the transducers,
- Signal conditioning,
- High sensitivity to changes in system health,
- Low sensitivity to other influencing variables,
- Repeatability of the measurements,
- Attenuation or signal loss,
- Accessibility,
- Ambient conditions,
- Costs
- …

Data acquisition and analysis

- Measurement and trend analysis
- Quality of the measurement
- Comparison of the measurement results with the warning and alarm criteria
- Diagnostics and prognosis
- Improving the reliability of diagnoses and/or forecasts

Failure mechanisms / symptoms analysis

- physics-based analysis of the main failure mechanisms (the use of the term “mechanism”, and not “mode” is significant here) associated with the requirements and the symptom from which detection should have been made possible

Fault symptom analysis (potential fault types / symptoms to measure) → electric motor

	current	voltage	Resistance	partial discharge	Vibration	Temperature	Axial flow	Oil particle counting	…
Rotor winding	x				x	x	x		
Stator winding	x				x	x	x		
Extentric rotor	x				x				
Brushing fault	x	x				x			
Bearing failure	x				x			x	
Isolation deterioration	x	x	x	x					
Imbalance					x				
Misalignment					x				
…									

Examples of PHM requirements for a railway bogie system

- **Requirement 1:** The PHM system shall improve service reliability by predicting and avoiding the occurrence of hot axle box alarm at least one operation day before the event with at least 90% certainty of the event occurrence.
- **Requirement 2:** The PHM system shall reduce the maintenance cost by extending the periodicity for the motor and trailer wheels overhaul from 1 to 2 million kilometers by detecting 90% of the depart from the specified performances with at least 90% certainty
- **Requirement 3**: The PHM system shall improve the availability by reducing the duration of the visual check of frame and wheels at E12 by 90% by automating the detection of the relevant failure mechanisms.

Failure mechanism / Symptoms

- For requirement 1:
  - Failure mechanisms: Fatigue, wear, cracking, plastic deformation, corrosion, electrical erosion of the axle bearings, temperature ageing or contamination of the axle bearings grease, drift/offset of the phonic wheel
  - Symptoms: abnormal vibrations on the axlebox, increase of temperature, abnormal noise for the bearings, presence of particles/water, abnormal viscosity for grease, aberrant value of the phonic wheel measure
- For requirement 2:
  - Failure mechanisms: Shelling, spalling scaling, surface/sub-surface fatigue cracks propagation, wheel-rail contact wear
  - Symptoms: presence of cracks on the surface/under the surface of the wheel, abnormal wheel surface condition, abnormal vibrations on the wheels
- For requirement 3:
  - Failure mechanisms: fatigue cracks propagation on the frame/axle/wheels, impacts, atmospheric /chemical corrosion, material deformation
  - Symptoms: presence of cracks on the surface of the frame/axle/wheels, presence of impacts traces, abnormal surface condition, abnormal vibration on the bogie and/or carbody (dynamic characteristics)