Asset maintenance management
“plant and equipment, however well designed, will not remain safe or reliable if not maintained”
• 1369: first citation of the French word ‘maintinir’ with the meaning of “bearing”
• 1389: maintenance = “action of providing a person with the necessity of life”
• 1413: maintenance = “action of upholding or keeping in being”

TODAY:
• IEC60300: Maintenance = set of actions that ensure the ability to maintain equipment or structures in, or restore them to, the functional state required by the purpose for which they were conceived.

Not only the labor of the maintenance operator, but also administration, supervision, planning, scheduling,…
Group of technical, administrative and managerial actions during one component’s life cycle, intended to keep or re-establish it into a state which allows it to carry out the required functions [EN13306]
• Maintenance Management Process

Strategy Definition
conditions the success of maintenance in an organization,
determines the effectiveness of the subsequent implementation

Strategy Implementation
allow us to minimize the maintenance direct cost,
determines the efficiency of our management
• Maintenance Management Process

Strategy Definition
conditions the success of maintenance in an organization, determines the effectiveness of the subsequent implementation

Strategy Implementation
allow us to minimize the maintenance direct cost, determines the efficiency of our management

“…doing the right thing”
• Maintenance Management Process

Strategy Definition
conditions the success of maintenance in an organization, determines the effectiveness of the subsequent implementation

Strategy Implementation
allow us to minimize the maintenance direct cost, determines the efficiency of our management

“…doing the right thing”

“…doing the (right) thing right”
Industrial systems are made up of various components, equipment and structures characterized by:

- different reliability
- different failure mechanisms
- different impacts on the cost of operation
- different impacts on the safety of the equipment, operators and public

Each equipment needs to have a maintenance approach that is appropriate to its characteristics and to the consequences of its failure.

A decision must be taken on the maintenance strategy, which defines the components of a system that will have a corrective, scheduled or condition-based maintenance and will further specify the details of each of this type of approaches.
What to take into account, for every component?

- Legislation
- Company’s quality policy
- Manufacturer indications
- Maintenance experience
- Job priority analysis
- ... Criticality analysis

**Component**

**Maintenance plan definition**
- Work instruction description
- Required disciplines
- Required working hours and spare list
- Eventual priorities

**Maintenance Strategy**
- Unplanned
- Periodic
- Condition-based
- Predictive

**Mathematical models**
Two common approaches for defining a maintenance strategy

- **Risk-Based Maintenance (RBM)**
- **Reliability-Centred Maintenance (RCM)**
• BASIC IDEA: **Risk** is the criterion for the basis of maintenance planning.

• OBJECTIVE: reduce the overall **risk** that may result as the consequence of unexpected failures of operating facilities.

• METHOD:
  – Identify all the failure scenarios
  – Determine the associated **risk**
  – Prioritize the failure scenarios according to the associated **risk**
  – Develop a maintenance strategy that minimizes the occurrence of the high-**risk** failure scenarios:

• EXPECTED RESULTS: high-**risk** components will be inspected with greater frequency and maintained in a more thorough manner, so that the overall operation of the system achieves tolerable **risk** criteria.
The Concept of Risk

Hazard

Environment

People
The Concept of Risk

- **Safeguards**
- **Hazard**
- **Environment**
- **People**
The Concept of Risk

UNCERTAINTY

Safeguards

Hazard

Environment

People
1. What undesired conditions may occur?

Accident Scenario, S
1. What undesired conditions may occur?  
   Accident Scenario, \( S \)

2. With what probability do they occur?  
   Probability, \( p \)
1. What undesired conditions may occur?  
   Accident Scenario, $S$

2. With what probability do they occur?  
   Probability, $p$

3. What damage do they cause?  
   Consequence, $x$
Risk Analysis: evaluation

Uncertainty Representation: (probabilistic & non-probabilistic frameworks)
Uncertainty Propagation (advanced and hybrid MC methods)
Multi-state degradation models
Dynamic behaviors
Influencing Factors

Hazard Analysis
- Hazop
- FMEA

Qualitative RAM analyses
- FTA
- ETA
- Markov Models
- Petri Net
- Bayesian Networks

Quantitative RAM analyses

Failure Probability Assessment

International Standards
- Transport Model
- Fire & Explosion models
- ABM for Emergent phenomena
- Best Practices & Lessons Learnt
- Resilience and Vulnerability analysis

Evaluation of the consequences

Risk Evaluation

RISK = \{S_i, p_i, x_i\}
Uncertainty Representation: (probabilistic & non-probabilistic frameworks)

Uncertainty Propagation (advanced and hybrid MC methods)

Multi-state degradation models

Dynamic behaviors

Influencing Factors

Risk Analysis: evaluation

Hazard Analysis
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- Petri Net

Bayesian Networks

Quantitative RAM analyses

International Standards
- Transport Model
- Fire & Explosion models

ABM for Emergent phenomena

Best Practices & Lessons Learnt

Resilience and Vulnerability analysis

Evaluation of the consequences

Risk mitigation
- PHM
- Inspections
- FRACAS/RCA

Redundancies
- Reliable components

Maintenance

Design
Risk Analysis: evaluation

Uncertainty Representation:
(probabilistic & non-probabilistic frameworks)

Uncertainty Propagation
(advanced and hybrid MC methods)

Multi-state degradation models
Dynamic behaviors
Influencing Factors

How to cost-effectively reduce the asset risk?

Failure Probability Assessment

Evaluation of the consequences

Risk mitigation

Risk Evaluation

Design
- Redundancies
- Reliable components

Maintenance
- PHM
- Inspections
- FRACAS/RCA

Hazard Analysis
- Hazop
- FMEA

Qualitative RAM analyses

Quantitative RAM analyses

FTA
ETA

Markov Models
Petri Net
Bayesian Networks

International Standards
Transport Model
Fire & Explosion models
ABM for Emergent phenomena
Best Practices & Lessons Learnt
Resilience and Vulnerability analysis
1. Risk Assessment

2. Maintenance planning based on risk:
   • Maintenance should be planned so as to lower the risk to meet the acceptable criterion by reducing the probability of failures and their consequences
   • Approaches for decision-making used are:
     - the **Reverse Fault Tree Analysis (RFTA)**: assign the desired probability of the top event (failure scenario) such to satisfy the acceptable risk criterion; compute the corresponding new probabilities of the basic events (failure modes) and from these infer the corresponding maintenance intervals;
     - the **Analytic Hierarchy Process (AHP)**: identify the risk factors affecting the failure scenario; pairwise compare their importance in contributing to the failure scenario; derive the risk factors importance; prioritize components and plan maintenance interventions based on this importance.
     - the **Multi Attribute Value Theory (MAVT)**: identify the risk factors affecting the failure scenario; compare their importance values in contributing to the failure scenario; apply Portfoolio Decision Analysis to allocate budget
Reverse Fault Tree Analysis
The Airlock System (AS) prevents the dispersion of contaminants by keeping the pressure of the inside of the reactor vault lower than the outside pressure.

<table>
<thead>
<tr>
<th>Basic Failure Events</th>
<th>ID Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pressure equalizer valve failure</td>
<td>V1</td>
</tr>
<tr>
<td>2 Doors failure</td>
<td>D1</td>
</tr>
<tr>
<td>3 Seal failure</td>
<td>S1</td>
</tr>
<tr>
<td>4 Gearbox failure</td>
<td>G1</td>
</tr>
<tr>
<td>5 Minor pipe leakages</td>
<td>P1</td>
</tr>
<tr>
<td>6 Major pipe leakages</td>
<td>P2</td>
</tr>
<tr>
<td>7 Exhaust pipe failure</td>
<td>E1</td>
</tr>
<tr>
<td>8 Empty tank</td>
<td>T1</td>
</tr>
<tr>
<td>9 Tank failure</td>
<td>T2</td>
</tr>
</tbody>
</table>
Fault Tree Model

**Objective**: Reduce the Top Event probability to make the risk acceptable

**Decision Problem**: how?

Top event = “AS fails to maintain the pressure boundary”.

FT developed for analyzing a scenario of a Design Basis Accident occurred in the AS of a CANDU Nuclear Power Plant in 2011.
Application of Risk Importance Measures (RIMs), which aim at quantifying the contribution of components or basic events to the system risk.

Example: Risk Reduction Worth (RRW) is the maximum decrease in risk consequent to an improvement of the component associated with the basic failure event considered.

\[
RRW_{\text{Door}} = \frac{P(\text{Air Lock Failure})}{P(\text{Air Lock failure|Door working})}
\]
Application of Risk Importance Measures (RIMs), which aim at quantifying the contribution of components or basic events to the system risk.

Example: Risk Reduction Worth (RRW) is the maximum decrease in risk consequent to an improvement of the component associated with the basic failure event considered.

Approach (Iterative):

1. Calculate component RRW values
2. Rank component importance values
3. Apply one of the possible actions on the most important basic event
‘Traditional’ RFTA Approach

Application of Risk Importance Measures (RIMs), which aim at quantifying the contribution of components or basic events to the system risk.

Example: Risk Reduction Worth (RRW) is the maximum decrease in risk consequent to an improvement of the component associated with the basic failure event considered.

Approach (Iterative):

1. Calculate component RRW values
2. Rank component importance values
3. Apply one of the possible actions on the most important basic event

Drawback: the procedure does not necessarily lead to the global optimal solution.
• **Objectives**
  – Develop methods for identifying combinations (portfolios) of risk management actions to minimize residual risks at different cost levels of risk management cost
  – Account for risk, cost of risk management and resource constraints simultaneously
  – Apply and evaluate methods to nuclear and other safety critical systems

• **Challenges**
  – Develop computationally tractable approaches for large systems
  – Using incomplete information when reliable parameter estimates are not available
Methodology steps:
1. Failure scenario modeling
2. Definition of failure probabilities
3. Specification of actions
4. Optimization model
To analyze the failure scenarios, the Fault Tree is mapped into a Bayesian Belief Network.

Step 1: Airlock system failure modeling

Advantages of BBN

- Multi-state modeling

Multi-state description of pipe leakage event
Step 1: Airlock system failure modeling

Advantages of BBN

- Multi-state modeling
- Extension of concepts of AND/OR gates

Example: AND gate

\[ P_{X|C} \]

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>( \overline{C} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( \overline{B} )</td>
<td>0</td>
</tr>
<tr>
<td>( \overline{A} )</td>
<td>B</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>( \overline{B} )</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ P_{X|C} \]

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>( \overline{C} )</th>
</tr>
</thead>
<tbody>
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<td>( \overline{B} )</td>
<td>0.97</td>
</tr>
</tbody>
</table>

\[ P_{X|C} \]

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<th></th>
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<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>0.03</td>
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<tr>
<td></td>
<td>( \overline{B} )</td>
<td>0.97</td>
</tr>
<tr>
<td>( \overline{A} )</td>
<td>B</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>( \overline{B} )</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Information sources

• Information provided by AND/OR gates in FT
• Statistical analyses
• Expert elicitation

The probability of occurrence of the events is defined according to their role in the failure scenarios. Specifically:

• Initiating events $\rightarrow$ failure probabilities of system components;
• Intermediate and top events $\rightarrow$ conditional probability tables.
Action characteristics:

- Impact on the prior and conditional probabilities;

Action $a$ modify the probability of occurrence of the states $s$ of event $i$. 
Step 2 and 3: Definition of failure probabilities

Valve failure

<table>
<thead>
<tr>
<th>Action</th>
<th>$R_{a_i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration test</td>
<td>$a_1$ $10^{-1}$</td>
</tr>
<tr>
<td>Sensor</td>
<td>$a_2$ $10^{-2}$</td>
</tr>
</tbody>
</table>

$P_{a_1}^2(s = 1) = 10^{-4} \cdot 10^{-1}$

$P_{a_2}^2(s = 1) = 10^{-4} \cdot 10^{-2}$

Risk Reduction Rate (RRR)
Action characteristics:

• **Impact on the prior and conditional probabilities**;

• **Entail a cost** (capital investment costs and ordinary periodic expenses over the life-time). To consider this, we relay on the annualized cost at year Λ (time horizon):

\[
c_\alpha = \sum_{\lambda=0}^{\Lambda} \frac{c_\alpha^\lambda}{(1 + r)^\lambda}
\]

• \(r\) = discounted rate, \(\lambda\) = year number
### Action Parameters

<table>
<thead>
<tr>
<th>Node</th>
<th>Index</th>
<th>Action</th>
<th>$c_a [\text{k€}]$</th>
<th>$R_{c_a}(1)$</th>
<th>$R_{c_a}(2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked seals</td>
<td>$a^1_1$</td>
<td>Inspection plan</td>
<td>60</td>
<td>$10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$a^1_2$</td>
<td>Duplicating</td>
<td>80</td>
<td>$10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>Valve failure</td>
<td>$a^2_1$</td>
<td>Calibration test</td>
<td>30</td>
<td>$10^{-1}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$a^2_2$</td>
<td>Sensor</td>
<td>40</td>
<td>$10^{-2}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$a^2_3$</td>
<td>Joined actions</td>
<td>60</td>
<td>$10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>Pipe leakage</td>
<td>$a^3_1$</td>
<td>Outer inspection</td>
<td>30</td>
<td>$10^{-1}$</td>
<td>$10^{-1.5}$</td>
</tr>
<tr>
<td></td>
<td>$a^3_2$</td>
<td>Inner and outer inspection</td>
<td>45</td>
<td>$10^{-2}$</td>
<td>$10^{-2.5}$</td>
</tr>
<tr>
<td></td>
<td>$a^3_3$</td>
<td>Protection coating</td>
<td>70</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
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<tr>
<td>Tank failure</td>
<td>$a^4_1$</td>
<td>Improving reliability</td>
<td>80</td>
<td>$10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>Empty tank</td>
<td>$a^5_1$</td>
<td>Level sensor</td>
<td>60</td>
<td>$10^{-3}$</td>
<td>-</td>
</tr>
<tr>
<td>Gearbox failure</td>
<td>$a^6_1$</td>
<td>Periodic test</td>
<td>40</td>
<td>$10^{-2}$</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$a^6_2$</td>
<td>Condition monitoring</td>
<td>100</td>
<td>$10^{-5}$</td>
<td>-</td>
</tr>
<tr>
<td>Exhaust pipe failure</td>
<td>$a^7_1$</td>
<td>Inspection plan</td>
<td>40</td>
<td>$10^{-2}$</td>
<td>-</td>
</tr>
<tr>
<td>Door failure</td>
<td>$a^8_1$</td>
<td>Periodic test</td>
<td>60</td>
<td>$10^{-4}$</td>
<td>-</td>
</tr>
<tr>
<td>Pressure equalizer failure</td>
<td>$a^{13}_1$</td>
<td>Synergy</td>
<td>-30</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

**Synergic effect:** selection of both actions $\rightarrow$ cost saving and risk reduction extra-benefit
<table>
<thead>
<tr>
<th>Node</th>
<th>Index</th>
<th>Action</th>
<th>$c_o \text{[k€]}$</th>
<th>$R_o(1)$</th>
<th>$R_o(2)$</th>
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<td>$a_{13}^1$</td>
<td>Synergy</td>
<td>-30</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

Synergic effect: if we act on both seal and pipe, we gain a cost saving.
Implicit enumeration algorithm to identify the optimal portfolios of safety actions.

The resulting portfolios are globally optimal in the sense that minimize the failure risk of critical events, instead of selecting actions that target the riskiness of the single events.
Step 4: Optimization model results

Airlock failure probability for the optimal portfolio of actions for different budget levels.

Greater budget $\rightarrow$ more effective actions $\rightarrow$ lower residual risk of failure of the airlock system.
Step 4: Optimization model results

- Cracked seals
- Valve failure
- Pipe leakage
- Tank failure
- Empty tank
- Gearbox failure
- Exhaust pipe failure
- Pressure equalizer failure
- Door failure

Duplicate, Inspection, No action, Cost

Coating, Inspection I/O, Inspection O, Cost

Sensor, Test, Cost

Sensor, PHM, Test, Cost

Synergy, Test, Cost

No action, 0 to 500

No action, 0 to 500

No action, 0 to 500

No action, 0 to 500

No action, 0 to 500

No action, 0 to 500
Step 4: Optimization model results

- Cracked seals
- Valve failure
- Pipe leakage
- Tank failure
- Empty tank
- Gearbox failure
- Exhaust pipe failure
- Pressure equalizer failure
- Door failure
Step 4: Optimization model results
Step 4: Optimization model results
The application of this approach leads to the following issues

<table>
<thead>
<tr>
<th>Iteration</th>
<th>Most risky event</th>
<th>Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>Valve failure</td>
<td>There are two possible actions, so which one should the experts select?</td>
</tr>
<tr>
<td>$t = 2$</td>
<td>Tank failure</td>
<td>The only applicable action is very expensive, could it be that many inexpensive actions have a higher impact on risk reduction?</td>
</tr>
<tr>
<td>$t = 3$</td>
<td>Valve failure Door failure</td>
<td>In case of a limited budget, which component should be improved first?</td>
</tr>
<tr>
<td>$t = 4$</td>
<td>Valve failure</td>
<td>If the experts apply a second action, do the joined actions have the same characteristics as two separate actions?</td>
</tr>
</tbody>
</table>
• If we are given Budget B=350K€, then we get the following results:

<table>
<thead>
<tr>
<th>Node</th>
<th>RRW approach</th>
<th>Portfolio optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracked seals</td>
<td>Duplicating</td>
<td>-</td>
</tr>
<tr>
<td>Valve failure</td>
<td>Sensor Calibration test</td>
<td>Sensor Calibration test</td>
</tr>
<tr>
<td>Pipe leakage</td>
<td>Protection coating</td>
<td>Protection coating</td>
</tr>
<tr>
<td>Tank failure</td>
<td>Improving reliability</td>
<td>Improving reliability</td>
</tr>
<tr>
<td>Empty tank</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gearbox failure</td>
<td>-</td>
<td>Periodic test</td>
</tr>
<tr>
<td>Exhaust pipe failure</td>
<td>-</td>
<td>Inspection plan</td>
</tr>
<tr>
<td>Door failure</td>
<td>Periodic test</td>
<td>Periodic test</td>
</tr>
</tbody>
</table>

$Q_{X_14}(1) = 1.4173 \cdot 10^{-8}$

$Q_{X_14}(1) = 1.1201 \cdot 10^{-8}$
Limitations of using RIM for RFTA in RBM:

• Actions can be applied to initiating events only → not accounting for synergies of joined actions.
• They do not account for feasibility and budget constraints.
• They do not necessarily lead to the global optimal portfolio of actions because the procedure implies assumptions and expert opinions which strongly affect the decisions at the following iterations.
• They cannot be applied in case of multi-state and multi-objective failure scenarios → they account for a unique critical event.
Consider interval-valued probabilities (e.g., probability of major pipe leakage is within $[10^{-4}, 10^{-3}]$)

Consider Evidential Networks instead of Bayesian network to propagate the uncertainty $\Rightarrow$ Interval-valued portfolios

Extend the optimization algorithm to treat uncertainty
Risk Model

Barries

<table>
<thead>
<tr>
<th>Action</th>
<th>Index</th>
<th>Cost [€]</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticorrosion paint</td>
<td>$\alpha_1$</td>
<td>1000</td>
<td>0.8</td>
</tr>
<tr>
<td>Pipe coating</td>
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<td>0.3</td>
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<td>Catalytic</td>
<td>$\alpha_3$</td>
<td>500</td>
<td>0.8</td>
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<td>Infrared</td>
<td>$\alpha_4$</td>
<td>800</td>
<td>0.5</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>$\alpha_5$</td>
<td>1500</td>
<td>0.2</td>
</tr>
<tr>
<td>Gas odour</td>
<td>$\alpha_6$</td>
<td>400</td>
<td>0.7</td>
</tr>
<tr>
<td>Fire sprinkler system</td>
<td>$\alpha_7$</td>
<td>2000</td>
<td>0.4</td>
</tr>
<tr>
<td>Hypoxic air technology</td>
<td>$\alpha_8$</td>
<td>4000</td>
<td>0.1</td>
</tr>
<tr>
<td>Fire protection synergy</td>
<td>$\alpha_9$</td>
<td>6000</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Barrier effects

$$x^1$$

$$P_{X^1, \alpha_1} = \begin{bmatrix} [0.9824; 0.9858] \\ [0.0144; 0.0178] \end{bmatrix}$$

$$P_{X^1, \alpha_5} = \begin{bmatrix} [0.9934; 0.9946] \\ [0.0054; 0.0066] \end{bmatrix}$$

Action portfolios are associated to Interval-valued probabilities
Optimization results

E.g. Portfolio 2: anticorrosion paint, Ultrasonic and fire protection synergies
Future research

– A method to facilitate the elicitation needs to be developed, to avoid asking experts to answer many and complex questions with possible introduction of biases

– Extend the proposed methodology to time-dependent systems

– Apply the developed model to fire safety issues
AHP for RBM
• A multiple criteria decision-making technique, which allows to reduce complex decisions to a series of simple comparisons and rankings
• It is used in RBM applications to prioritize components and plan maintenance interventions based on the risk factors likelihood and consequence contributions, and related insights
• Phase 1: formulate the decision problem in the form of a hierarchical structure. The decomposition of the decision criteria proceeds until further refinements are not needed.
  – Top level: overall objective of the decision problem
  – Intermediate levels: elements affecting the decision
  – Lowest level: decision options
• Crude oil pipeline (1500 km) in the western part of India.
• The entire pipeline is classified into a few (in this case 5) stretches (i.e., pipeline sections in between two stations).
• A risk structure model is built in the Analytic Hierarchy Process (AHP) framework.

• Phase 1: formulate the decision problem in the form of a hierarchical structure. The decomposition of the decision criteria proceeds until further refinements are not needed.

• Phase 2: determine the relative importance of the elements in each level of the hierarchy through a pair-wise comparison. Each element in an upper level of the hierarchical tree is used as criterion to compare the elements in the level immediately below.

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal Importance</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>Experience and judgment slightly favor one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td>Experience and judgment strongly favor one activity over another</td>
</tr>
<tr>
<td>7</td>
<td>Very strong or demonstrated importance</td>
<td>An activity is favored very strongly over another; its dominance demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>The evidence favoring one activity over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>2,4,6,8</td>
<td>For compromise between the above values</td>
<td>Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it.</td>
</tr>
</tbody>
</table>
• Pairwise comparisons of risk factors
• Each number represents the expert’s view about the dominance of the element in the column on the left over the element in the row on top.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Corrosion</th>
<th>External Interference</th>
<th>Construction and materials defect</th>
<th>Acts of God</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>External interference</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Construction and materials defect</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Acts of God</td>
<td>1/7</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
<td>1/4</td>
</tr>
<tr>
<td>Others</td>
<td>1/3</td>
<td>1/3</td>
<td>1/2</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Slightly favours of Corrosion over external interference

Dominance of corrosion over Acts of God demonstrated in practice
• Phase 1: formulate the decision problem in the form of a hierarchical structure. The decomposition of the decision criteria proceeds until further refinements are not needed.

• Phase 2: determine the relative importance of the elements in each level of the hierarchy through a pair-wise comparison. Each element in an upper level of the hierarchical tree is used as criterion to compare the elements in the level immediately below.

• Phase 3: compute the relative weights of the factors (mathematical procedure based on eigenvectors computation)
matrix entry $a_{ij}$ indicates the relative importance of the element $A_i$ over $A_j$

the ratio of the weight $w_i$ assigned to $A_i$ over $w_j$ assigned to $A_j$

$$
A = \begin{bmatrix}
  a_{11} & \cdots & a_{1K} \\
  \vdots & \ddots & \vdots \\
  a_{K1} & \cdots & a_{KK}
\end{bmatrix}
= \begin{bmatrix}
  w_1 & \cdots & w_1 \\
  \vdots & \ddots & \vdots \\
  w_K & \cdots & w_K
\end{bmatrix}
$$

A linear system of equations.
Is $K$ an eigenvalue of $A$?

Matrix $A$ is of rank 1 $\rightarrow$ the eigenvalues of $A$ are all zero, except one
Theorem: sum of the eigenvalues = matrix trace = $K$
The corresponding (normalized) eigenvector gives the priorities
The distance between $\lambda_{\text{max}}$ and $K$ can be considered as a measure of the deviation from consistency.

**Criticality Index (CI):**

$$CI = \frac{\lambda_{\text{max}} - K}{K - 1}$$

**Random Index (RI):** average value of $CI$, (computed for many randomly generated matrices from the scale 1 to 9, with reciprocals forced)

<table>
<thead>
<tr>
<th>Order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$RI$</td>
<td>0</td>
<td>0</td>
<td>0.52</td>
<td>0.89</td>
<td>1.11</td>
<td>1.25</td>
<td>1.35</td>
</tr>
</tbody>
</table>

**Consistency Ratio (CR)**

$$CR = CI / RI$$

**Rule of Thumb:** If $CR < 0.10$, then there is positive evidence for informed judgment.

**Example:** $CR = \frac{0.2}{0.89} = 0.22$ (the expert must reconsider his/her judgments)
<table>
<thead>
<tr>
<th>Factors</th>
<th>Corrosion</th>
<th>External Interference</th>
<th>Construction and materials defect</th>
<th>Acts of God</th>
<th>Others</th>
<th>Preference Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>0.40</td>
</tr>
<tr>
<td>External interference</td>
<td>1/2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>0.29</td>
</tr>
<tr>
<td>Construction and materials defect</td>
<td>1/3</td>
<td>1/3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>0.14</td>
</tr>
<tr>
<td>Acts of God</td>
<td>1/7</td>
<td>1/5</td>
<td>1/3</td>
<td>1</td>
<td>1/4</td>
<td>0.05</td>
</tr>
<tr>
<td>Others</td>
<td>1/3</td>
<td>1/3</td>
<td>1/2</td>
<td>4</td>
<td>1</td>
<td>0.12</td>
</tr>
</tbody>
</table>
• Phase 1: formulate the decision problem in the form of a hierarchical structure. The decomposition of the decision criteria proceeds until further refinements are not needed.

• Phase 2: determine the relative importance of the elements in each level of the hierarchy through a pair-wise comparison. Each element in an upper level of the hierarchical tree is used as criterion to compare the elements in the level immediately below.

• Phase 3: compute the relative weights of the factors (mathematical procedure based on eigenvectors computation)

• Phase 4: compute the relative weights of the alternatives with respect to the leaves of the tree

• Phase 5: find the composite weights of the decision alternatives by aggregating the weights through hierarchy.
Determining the probability of failure of pipeline stretches

Factors
- Corrosion
- External interference
- Construction and materials defect
- Acts of God
- Others

Sub-factors
- External corrosion
- Internal corrosion
- Third party activities
- Pifferage
- Construction defect
- Poor materials
- Human error
- Operational error

Alternatives
- Pipeline stretch 1
- Pipeline stretch 2
- Pipeline stretch 3
- Pipeline stretch 4
- Pipeline stretch 5

<table>
<thead>
<tr>
<th>Factors</th>
<th>Likelihood</th>
<th>Sub-factors</th>
<th>Likelihood</th>
<th>PLS₁</th>
<th>PLS₂</th>
<th>PLS₃</th>
<th>PLS₄</th>
<th>PLS₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>0.40</td>
<td>External</td>
<td>0.221</td>
<td>0.108</td>
<td>0.064</td>
<td>0.007</td>
<td>0.011</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Internal</td>
<td>0.181</td>
<td>0.038</td>
<td>0.022</td>
<td>0.020</td>
<td>0.042</td>
<td>0.060</td>
</tr>
<tr>
<td>External interference</td>
<td>0.29</td>
<td>3rd party</td>
<td>0.186</td>
<td>0.030</td>
<td>0.078</td>
<td>0.011</td>
<td>0.061</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Malicious</td>
<td>0.100</td>
<td>0.033</td>
<td>0.039</td>
<td>0.005</td>
<td>0.018</td>
<td>0.005</td>
</tr>
<tr>
<td>Construction and mat. defect</td>
<td>0.14</td>
<td>Construction</td>
<td>0.072</td>
<td>0.012</td>
<td>0.007</td>
<td>0.028</td>
<td>0.007</td>
<td>0.018</td>
</tr>
<tr>
<td></td>
<td></td>
<td>defects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor mats.</td>
<td>0.072</td>
<td>0.006</td>
<td>0.007</td>
<td>0.027</td>
<td>0.016</td>
<td>0.017</td>
</tr>
<tr>
<td>Acts of God</td>
<td>0.05</td>
<td>Human error</td>
<td>0.05</td>
<td>0.006</td>
<td>0.001</td>
<td>0.014</td>
<td>0.006</td>
<td>0.020</td>
</tr>
<tr>
<td>Others</td>
<td>0.12</td>
<td>Operational</td>
<td>0.048</td>
<td>0.001</td>
<td>0.005</td>
<td>0.003</td>
<td>0.008</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>error</td>
<td>0.072</td>
<td>0.001</td>
<td>0.003</td>
<td>0.009</td>
<td>0.003</td>
<td>0.056</td>
</tr>
</tbody>
</table>

Final weights

<table>
<thead>
<tr>
<th></th>
<th>PLS₁</th>
<th>PLS₂</th>
<th>PLS₃</th>
<th>PLS₄</th>
<th>PLS₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final ranking</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PL₁</th>
<th>PL₂</th>
<th>PL₃</th>
<th>PL₄</th>
<th>PL₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.236</td>
<td>0.227</td>
<td>0.123</td>
<td>0.172</td>
<td>0.242</td>
</tr>
</tbody>
</table>
On the basis of the prioritization obtained, specific inspection/maintenance requirements are determined for specific segments, to mitigate risk.

<table>
<thead>
<tr>
<th>Inspection and maintenance strategy</th>
<th>Problems</th>
<th>PLS1</th>
<th>PLS2</th>
<th>PLS3</th>
<th>PLS4</th>
<th>PLS5</th>
<th>PLS1</th>
<th>PLS2</th>
<th>PLS3</th>
<th>PLS4</th>
<th>PLS5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument pig survey</td>
<td>Internal corrosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>5</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Cathodic protection survey</td>
<td>External corrosion</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>More patrolling</td>
<td>Malicious</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Contingency plans</td>
<td>3rd party activities</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Contingency plans</td>
<td>Acts of God</td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Improved instrumentation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe coating</td>
<td>External corrosion</td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe replacement</td>
<td>Construction defect and poor pipe materials</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total cost (rupees 61 million for five years)</td>
<td>9</td>
<td>9</td>
<td>6</td>
<td>26</td>
<td>11</td>
<td></td>
<td>36</td>
<td>35</td>
<td>36</td>
<td>33</td>
<td>13</td>
</tr>
</tbody>
</table>

Note: *The cost figures are estimated from the budgetary offers of the vendors.
• AHP limitations:
  – the rank reversal phenomenon (i.e., the relative ranking of two alternatives may change when a new alternative is introduced)
  – Shortcomings of the 1-9 ratio scale
  – Pitfalls in quantification of qualitatively stated pairwise comparisons
  – Not applicable in case of a large number of alternatives
  – Uncertainty is not accounted

• The AHP-based RBM methodology does not tackle the problem of how to optimize the inspection campaign
• Develop a methodology to select portfolios of maintenance inspections to optimally allocate resources to minimize costs and maximize the benefit of maintenance on risk reduction

Accommodate imprecision of expert judgments
MAVT and PDA for RBM
Proposed method

- Failure likelihood and severity assessment
  - criticality ranking of items

- Item-specific maintenance optimization
  - item’s condition-specific rule to select maintenance option

- Maintenance portfolio optimization
  - proposal for maintenance resources allocation
Proposed method

Failure likelihood and severity assessment
- criticality ranking of items

Item-specific maintenance optimization
- item’s condition-specific rule to select maintenance option

Maintenance portfolio optimization
- proposal for maintenance resources allocation
Multi Attribute Value Theory

Likelihood

Pipe Features
- Material
- Pipe Age
- Diameter
Past Events
- Blockages
- Flushing
Local Circumstances
- Soil
- Traffic Load

Operational losses

Severity

Item repair cost

Cost to externals

Step 1: Value tree
Multi Attribute Value Theory

**Step 1:** Value tree

**Step 2:** Score elicitation for leaf attributes (SWING Method)

\[ v_i(x_i^j) = [v_i(x_i^j); \overline{v}_i(x_i^j)] \]

\( i = \) leaf attribute

\( x_i^j = \) value of pipe \( j \) with respect to attribute \( i \)
Elicited Expert Preferences

«The installation year before 1955 has the maximum influence on Pipe features»

«If the installation year is 1985, its influence on Pipe Features is between 40 and 80% of that of 1955»
Multi Attribute Value Theory

**Likelihood**

- **Pipe Features**
  - Material
  - Pipe Age
  - Diameter
- **Past Events**
  - Blockages
  - Flushing
- **Local Circumstances**
  - Soil
  - Traffic Load

**Step 1:** Value tree
**Step 2:** Score elicitation for leaf attributes (SWING Method)
**Step 3:** Criteria relative importance (PAIRS Method)
«With respect to pipe feature, attribute Material is more important than attribute Age which in turn is more important than attribute Diameter».

\[ w_{\text{Material}} \geq w_{\text{Age}} \geq w_{\text{Diameter}} \]
\[ w_{\text{Material}} + w_{\text{Age}} + w_{\text{Diameter}} = 1 \]

\[ v_{\text{pipe feature}}(x^j) = \min \left[ \sum_i w_i v_i(x^j_i) \right] \]

\[ \bar{v}_{\text{pipe feature}}(x^j) = \max \left[ \sum_i w_i \bar{v}_i(x^j_i) \right] \]

Under mild assumptions, the maximum and minimum values are attained at the extreme points of the weight feasible region (i.e.,

\((1\ 0\ 0); \left(\frac{1}{2}\ \frac{1}{2}\ 0\right); \left(\frac{1}{3}\ \frac{1}{3}\ \frac{1}{3}\right)\))

\[ v_{\text{pipe feature}}(x^j) = \min \left[ \begin{array}{c}
\frac{1}{3} v_{\text{Material}}(x^j_{\text{Material}}) \\
\frac{1}{2} v_{\text{Material}}(x^j_{\text{Material}}) + \frac{1}{2} v_{\text{Diameter}}(x^j_{\text{Diameter}}) \\
\frac{1}{3} v_{\text{Material}}(x^j_{\text{Material}}) + \frac{1}{3} v_{\text{Diameter}}(x^j_{\text{Diameter}}) + \frac{1}{3} v_{\text{Age}}(x^j_{\text{Age}})
\end{array} \right] \]
Example: Elicited Expert Preferences
«Local circumstances is the least important criterion in defining pipe failure likelihood»

\[ w_{\text{pipe features}} \geq w_{\text{local circumstances}} \]
\[ w_{\text{past events}} \geq w_{\text{local circumstances}} \]

- \( v_L(x^j) = \min[\sum_l w_l v_l(x^j)] \)
- \( \bar{v}_L(x^j) = \max[\sum_l w_l \bar{v}_l(x^j)] \)

\( l= \text{first level attribute} \)
Multi Attribute Value Theory

Step 1: Value tree
Step 2: Criteria relative importance
Step 3: Score elicitation for leaf attributes
Step 4: Value computation

Feasible criteria weights
### Item $x^t$
- **Material:** concrete
- **Pipe Age:** 10 years
- **Likelihood score:** $[20, 40]$
- **Severity score:** $[30, 60]$

### Item $x^j$
- **Material:** PVC
- **Pipe Age:** 40 years
- **Likelihood score:** $[60, 90]$
- **Severity score:** $[80, 100]$

### Item $x^k$
- **Material:** cast iron
- **Pipe Age:** 30 years
- **Likelihood score:** $[40, 70]$
- **Severity score:** $[30, 60]$

#### Dominance

![Risk Assessment Graph](image1)

#### Non Dominance

![Risk Assessment Graph](image2)
Pareto front of most critical maintenance items

- Item 3
- Item 56
- Item 72
- Item 101
- ...
- ...
- ...
- ...
Proposed method

Failure likelihood and severity assessment
  • criticality ranking of items

Item-specific maintenance optimization
  • item’s condition-specific rule to select maintenance option

Maintenance portfolio optimization
  • proposal for maintenance resources allocation
The benefit of performing maintenance depends on the item degradation state

These can be uncertain
The benefit of performing maintenance depends on the item degradation state. The probability of being in state $s$ depends on the pipe likelihood and is uncertain.

<table>
<thead>
<tr>
<th>Degradation State</th>
<th>$p_s^d$</th>
<th>$\bar{p}_s^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s = 1$</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>$s = 2$</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>$s = 3$</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>$s = 4$</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>$s = 5$</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>$s = 6$</td>
<td>0.7</td>
<td>0.9</td>
</tr>
</tbody>
</table>
We estimate the interval-valued costs of inspection, renovation and disruption.

\[ c_j^t = [c_j^t; \bar{c}_j^t] \]
Lower bound cost of renovation $C_{\text{ren}}^j(s) = c_j^d \cdot p_1^d + c_j^s$

Upper bound cost of renovation $\bar{C}_{\text{ren}}^j(s) = \bar{c}_j^d \cdot \bar{p}_1^d + \bar{c}_j^s$

$c_j^t = [c_j^t; \bar{c}_j^t]$
Lower bound cost of no renovation $C_{NOren}^j(s) = c_j^d \cdot p_s^d$

Upper bound cost of no renovation $\overline{C}_{NOren}^j(s) = \overline{c}_j^d \cdot \overline{p}_s^d$

$c_j^t = [c_j^t; \overline{c}_j^t]$
We will decide to renovate pipe $j$ only if $\overline{c}_{\text{ren}}(s) < \overline{c}_{\text{NOren}}(s)$.
The benefit of inspection is related to the reduction of expected disruption cost:

\[ B_j^s = \begin{cases} 
0 & \text{if optimal decision is NO ren} \\
\bar{c}_{\text{NOren}}^j(s) - \bar{c}_\text{ren}^j(s) & \text{otherwise}
\end{cases} \]

\[ c_j^t = [c_j^t; \bar{c}_j^t] \]
The benefit of inspection is related to the reduction of expected disruption cost

\[ \bar{B}_j^s = \begin{cases} 0 & \text{if optimal decision is NO ren} \\ \bar{c}_{\text{NOren}}^j(s) - c_{\text{ren}}^j(s) & \text{otherwise} \end{cases} \]

\[ c_j^t = [c_j^c; \bar{c}_j^d] \]

Decision Tree Analysis

Disruption
No Disruption
Renovation
No Renovation
Renovation
No Renovation
No Disruption
Disruption
[\(c_j^d; \bar{c}_j^d\)]
No Disruption
Disruption
[\(c_j^d; \bar{c}_j^d\)]
No Disruption
Expected Benefit

\[ B_j = \sum_{s \in S} p_j^s \cdot B_j^s \]
\[ \bar{B}_j = \sum_{s \in S} p_j^s \cdot \bar{B}_j^s \]

\[ c_j^t = [c_j^t; \overline{c_j^t}] \]
The decision for every pipe has to pursue two objectives:

Maximize benefit $[B_j, \bar{B}_j]$ 
Minimize cost $[c_j^t; \bar{c}_j^t]$ 

$$c_j^t = [c_j^t; \bar{c}_j^t]$$

Decision Tree Analysis
Proposed method

- Failure likelihood and severity assessment
  - criticality ranking of items

- Item-specific maintenance optimization
  - item’s condition-specific rule to select maintenance option

- Maintenance portfolio optimization
  - proposal for maintenance resources allocation
### Pareto front of most critical maintenance items

<table>
<thead>
<tr>
<th>Item 3</th>
<th>Benefit</th>
<th>Cost</th>
<th>Benefit</th>
<th>Cost</th>
<th>Benefit</th>
<th>Cost</th>
<th>Benefit</th>
<th>Cost</th>
<th>Benefit</th>
<th>Cost</th>
<th>Benefit</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item 56</td>
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<tr>
<td>Item 72</td>
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<tr>
<td>Item 101</td>
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</tr>
</tbody>
</table>

**How to select maintenance portfolios?**

- Yes
- No
- Yes
- Yes
- No
- No
- Yes
- ...
Objective: Identification of efficient inspection portfolios, i.e. a portfolio is efficient if no other feasible portfolio gives a higher overall benefit at a lower cost.

RPM: linear programming optimization technique, handling interval-valued objective functions and alternative interdependencies
• Large sewerage network in Espoo, Finland

• More than 33000 sewer pipes, for a total length of about 900 km.

• Analysis of a subset of 6103 selected pipes, whose past inspection outcomes are recorded.
Results: Step 1

First Pareto frontier: 2079 pipes

<table>
<thead>
<tr>
<th>Failure Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
</tr>
<tr>
<td>Class 2</td>
</tr>
<tr>
<td>Class 3</td>
</tr>
</tbody>
</table>

Pipe 3
Pipe 56
Pipe 72
Pipe 101
Pipe 235
Pipe 367
Pipe 461
...
### Results: Step 2

<table>
<thead>
<tr>
<th>NUMBER OF PORTFOLIOS</th>
<th>RUNNING TIME (MINUTES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM 2000</td>
<td>30</td>
</tr>
</tbody>
</table>

Need for reducing the uncertainty in expert estimations
A risk-based approach has been developed to optimize pipe inspection campaigns on large underground networks in the presence of imprecise knowledge.

The division of the methodology into three steps allows reducing the computational effort to select efficient inspection portfolios.

The integrated methodologies allow rigorously accommodating imprecise expert statements.

Espoo water system case study shows the feasibility of the approach.
Two common approaches for defining a maintenance strategy

- Risk-Based Maintenance (RBM)
- Reliability-Centred Maintenance (RCM)
• What is it?
  • A systematic approach for establishing maintenance programs

• Maintenance intervention approaches:
  • Corrective maintenance
  • Preventive maintenance (i.e., scheduled, condition-based, etc.)

• Primary objective
  • Determine the combination of maintenance tasks which will significantly reduce the major contributors to unreliability and maintenance cost in light of the consequences of failures
Since the 1930’s, the evolution of maintenance can be traced through three generations. RCM is a cornerstone of the Third Generation.

**Expectation from maintenance evolution**

**First Generation:**
- Fix it when it broke

**Second Generation:**
- Higher plant availability
- Longer equipment life
- Lower costs

**Third Generation:**
- Higher plant availability and reliability
- Greater safety
- Better product quality
- No damage to the environment
- Longer equipment life
- Greater cost effectiveness

**Fourth Generation:**
- PHM - driven maintenance

**Maintenance techniques evolution**

**First Generation:**
- Fix it when it broke

**Second Generation:**
- Scheduled overhauls
- Systems for planning and controlling work
- Big, slow computers

**Third Generation:**
- Condition monitoring
- Design for reliability and maintainability
- Hazard studies
- Small, fast computers
- Failure modes and effects analyses
- Expert Systems
- Multiskilling and teamwork
RCM report and additional textbook represent results obtained by commercial airlines and the US Navy in the 1960s and 70s to improve the reliability of their jets, especially the new one - Boeing 747.

<table>
<thead>
<tr>
<th>RCM implementation benefits</th>
<th>1950 - 1960</th>
<th>1980 -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain crashes per one million take-offs</td>
<td>More then 60</td>
<td>3</td>
</tr>
<tr>
<td>Plain crashes caused by component failure</td>
<td>40</td>
<td>0,3</td>
</tr>
</tbody>
</table>
Main Objective: apply the maintenance effort at the best location in the plant, with the most effective maintenance approach
Traditional Approach

1. Definition of Systems requiring Maintenance
   - Functional FMEA on Team Concept
   - Determination of systems to be maintained
   - Define HAMG Requirements on Systems

2. Definition of Maintenance Candidates
   - Detailed requirements for failure reports
   - Based on System FMEA
   - Determine maintenance tasks and frequency
   - Validate Maintainability requirements
   - Define Diagnosis Requirements

3. Analyze Maintenance Candidates based on Detailed Design
   - Analyze maintenance tasks
   - Validate maintainability design
   - Prepare input for documentation
   - Validate Diagnosis design

4. System Integration and System Qualification
   - Verification of Maintainability Requirements
   - Verification of Diagnosis requirements
   - Verify reliability requirements
   - Prepare Documentation and LOC

5. Product Delivery

RCM Approach

Traditional Approach Lower Product Investment Cost

Traditional Approach Higher Product Support Cost

RCM Approach Lower Product Support Cost

EN 60330 Approach Slightly Higher Product Investment Cost

EN 60330 Approach Lower Product Support Cost
System Selection and Definition

- **Qualitative methods** based on past history, expert judgement, best practices. General check–list:
  - Units that have undergone changes in the operational context, maintenance techniques and/or equipment design/technological advancements.
  - Units of inadequate reliability/availability performance.
  - Safety critical units, environmental critical, system entailing partial or total loss of production, delays, material loss or equipment/infrastructure damage, excessive maintenance costs, etc.
  - Units for which the preventive and/or corrective maintenance man hours currently allocated are unacceptably high.
  - Units of unacceptably high corrective to preventive maintenance ratio.

- **Quantitative methods**: impact of system degradation/failure on the techno–economic, operational, safety and/or environmental performances (e.g., Importance Measures, sensitivity analyses).
• Define operating context

• Make visible the requirements, policies, and acceptance criteria with respect to safety and environmental protection, as boundary conditions for the RCM analysis

• Acquire the available material in support of the analysis (e.g., drawings and descriptions of the system, process diagrams, existing studies, technical specifications, etc.)
Functional Failure Analysis (FFA)

- Identify the functions that are important for safety, availability or maintenance, and the performance criteria
- Identify the system boundaries and interfaces
- Define the indenture level at which the analysis is to be conducted

System break down: units at level ‘n’ are decomposed into units of level ‘n+1’

System: a unit performing a set of main functions
Sub-system: a set of equipment performing a certain set of functions
Equipment (Analysis Item): item that is able to perform at least one significant function as a stand alone item
Critical Item Selection (CSI)

- Identify the equipment that are potentially critical with respect to the functional failures (Functional Significant Items, FSI) or the maintenance costs (Maintenance Cost Significant Items, MCSI)

- Providing a critical function generally involves a number of equipment, even pertaining to different subsystems

- A formal approach (e.g., Fault Tree, Reliability Block Diagram) may be needed to identify the FSIs in case of complex systems (many redundancies, buffers, etc.)
Every function $F$ can be thought of as a more or less complex mapping between the system characteristics and an output variable which indicates, even qualitatively, the level of performance of the system function.

- Function is demanded at $t_0$
- Transient period $T_i = [t_0, t_1]$ to reach the required performance (even $T_i \to 0$)
- Function is delivered at the required performance ($T_c = [t_1, t_2]$)
- Shutdown phase ($T_s = [t_2, t_{\text{end}}]$)
Example: pump functions

- $F_1$: to deliver the required flow water (e.g., $400 \pm 30$ l/min), (main function);
- $F_2$: to contain the fluid (secondary function).
- $F_3$: to connect the pump to the upstream and downstream pipes (interface function).
- $F_4$: to connect the pump motor to the electric power supply (interface function).

- $F_1$: mapping from pump physical characteristics, the fluid inlet pressure and flow rate, the electrical power supplied, the fluid viscosity and density, etc., onto the delivered flow, which is represented by the performance variable $P_1$='quantity of flow'.
- $F_2$ and $F_3$: mapping from the pump structural characteristics, loads, maintenance actions, into the variables $P_2$='structural integrity' (i.e., the absence of cracks) and $P_3$='level of connection' (i.e., the tightness of the connections).
  - No transient period (i.e., $t_0=t_1$), functions remain constant up to the end of the mission ($t_2=t_{end}=\infty$)
- $F_4$ establishes a link between the electrical power supplier (e.g., voltage, amperage, etc.) and the pump motor, which is summarized by the variable $P_4$='level of electrical connection'.
  - No transient period (i.e., $t_0=t_1$), functions remain constant up to the end of the mission ($t_2=t_{end}=\infty$)
Functional Failure: insights

- Over-performance
- Erratic Performance
- Sudden stop
- Under-performance
- Slow start-up
- Untimely triggering
- No performance
- Slow shut-down
- Fail to stop

---

**Lower bound**  **Actual performance**  **Upper bound**
Example: mapping of functional deviations relevant to function $F_1$ of a pump into the deviations that are typically identified by an expert.

<table>
<thead>
<tr>
<th>Generic Functional Failure</th>
<th>Corresponding functional failure for the pump function $F_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over-Performance</td>
<td>Over-pumping</td>
</tr>
<tr>
<td>Under-Performance</td>
<td>Under-pumping</td>
</tr>
<tr>
<td>No-Performance</td>
<td>pump jammed</td>
</tr>
<tr>
<td>Erratic Performance</td>
<td>Erratic Output</td>
</tr>
<tr>
<td>Slow Start-up</td>
<td>Slow Start-up</td>
</tr>
<tr>
<td>Slow Shut-down</td>
<td>Slow Shut-down</td>
</tr>
<tr>
<td>Untimely Stop</td>
<td>Spurious stop</td>
</tr>
<tr>
<td>Untimely triggering</td>
<td>Spurious start</td>
</tr>
<tr>
<td>Fail to stop</td>
<td>Fail to stop</td>
</tr>
</tbody>
</table>
Failure Modes and Effect Criticality Analysis

1. Decompose the system in functionally independent subsystems
2. Define the mission phases (e.g., start-up, shut-down, maintenance, etc.) and their expected durations
3. For every mission phase, define each of the independent units in terms of:
   - required functions and outputs
   - internal and interface functions
   - expected equipment utilization and performance
   - Internal and external restraints
4. Construct block diagrams (highlights the relationships between the items)
5. Compile the FMECA table
**Failure mode**: The manner by which a failure is observed. Generally, it describes the observable effect of the mechanism through which the failure occurs (e.g., short-circuit, open-circuit, fracture, excessive wear)

<table>
<thead>
<tr>
<th>component</th>
<th>Failure mode</th>
<th>Effects on other components</th>
<th>Effects on subsystem</th>
<th>Effects on plant</th>
<th>Probability*</th>
<th>Severity +</th>
<th>Criticality</th>
<th>Detection methods</th>
<th>Protection and mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Failure modes relevant for the operational mode indicated</td>
<td>Effects of failure mode on adjacent components and surrounding environment</td>
<td>Effects on the functionality of the subsystem</td>
<td>Effects on the functionality and availability of the entire plant</td>
<td>Probability of failure occurrence (sometimes qualitative)</td>
<td>Worst potential consequences (qualitative)</td>
<td>Criticality rank of the failure mode on the basis of its effects and probability (qualitative estimation of risk)</td>
<td>Methods of detection of the occurrence of the failure event</td>
<td>Protections and measures to avoid the failure occurrence</td>
</tr>
</tbody>
</table>
### FMECA: Procedure steps

<table>
<thead>
<tr>
<th>Description</th>
<th>Failure modes relevant for the operational mode indicated</th>
<th>Effects of failure mode on adjacent components and surrounding environment</th>
<th>Effects on the functionality of the subsystem</th>
<th>Effects on the functionality and availability of the entire plant</th>
<th>Probability*</th>
<th>Severity +</th>
<th>Criticality</th>
<th>Detection methods</th>
<th>Protection and mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure effect: the consequence(s) a failure mode has on the Operation, Function or Status (OFS) of an item</td>
<td></td>
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</tr>
</tbody>
</table>

In some contexts, the effects are distinguished in:

- **Local effects**: on the OFS of the specific item being analyzed
- **Next higher level**: on the OFS of the next higher indenture level
- **End effects**: on the OFS of the highest indenture level
<table>
<thead>
<tr>
<th>component</th>
<th>Failure mode</th>
<th>Effects on other components</th>
<th>Effects on subsystem</th>
<th>Effects on plant</th>
<th>Probability*</th>
<th>Severity +</th>
<th>Criticality</th>
<th>Detection methods</th>
<th>Protection and mitigation</th>
</tr>
</thead>
</table>

Criticality Analysis (CA): a procedure by which each potential failure mode is ranked according to the considered criticality index.

The objective of CA is to identify the most important components from the safety/performance point of view

There are different approaches to CA, which depend on the type of FMECA.
• There are three main reasons for doing a Preventive Maintenance task:
  1. To prevent a failure
  2. To detect the onset of a failure
  3. To discover a hidden failure

• The following basic maintenance tasks are considered:
  1. Scheduled on-condition task
  2. Scheduled overhaul
  3. Scheduled replacement
  4. Scheduled function test
  5. Run to failure
Technical decisions: based on the structure of the system, failure criticality, failure causes, degradation mechanisms, etc.

Technical decision flow chart

- Will the loss of function caused by this failure mode on its own become evident to the operation crew under normal circumstance?
  - YES: Is a task to detect whether the failure is occurring or about to occur technically feasible?
    - YES: On condition maintenance
    - NO: Is a scheduled restoration/discard task to reduce the failure rate technically feasible?
      - YES: Scheduled restoration / replacement
      - NO: Is a failure-finding task to detect the failure technically feasible?
        - YES: Functional test
        - NO: Could the multiple failures affect safety?
          - YES: Redesign
          - NO: Corrective maintenance

- Does the failure mode cause a loss of function or other damage that could injure/kill someone or have a direct adverse effect on operational capability?
  - NO: S/O
  - YES: Is a task to detect whether the failure is occurring or about to occur technically feasible?
    - YES: Scheduled restoration / replacement
    - NO: Is a scheduled restoration/discard task to avoid the failures technically feasible?
      - YES: Functional test
      - NO: Redesign

FMECA
The theoretical justification

- Memory-less property of the exponential distribution: the probability that an equipment which has been working for time $s$ will survive an additional time $t$ depends only on $t$ (not on $s$), and is identical to the probability of survival for time $t$ of a new piece of equipment.
Memoryless property in practice

Maintenance policy 1: periodic replacement every $dt$ units of time.

![Graph showing periodic replacement]

$$\text{Probability of surviving } n \cdot dt \text{ units of time}$$

$$e^{-\lambda dt} \cdot e^{-\lambda dt} \ldots \cdot e^{-\lambda dt} = e^{-\lambda \cdot n \cdot dt} = e^{-\lambda \cdot \Delta t}$$

Maintenance policy 2: replacement every $\Delta t = n \cdot dt$ units of time.

![Graph showing replacement every $\Delta t$]

$$\text{Probability of surviving } \Delta t = n \cdot dt \text{ units of time}$$

$$e^{-\lambda \cdot \Delta t}$$
Non memoryless systems

\[ F(t) = 1 - e^{-\left(\frac{t}{0.8}\right)^2} \]

- Maintenance policy 1: periodic replacement every Year
  - Reliability at t=1 year 0.2096

- Maintenance policy 2: periodic replacement every Year
  - Reliability at t= 2 years 0.2096*0.2096=0.04

- Maintenance policy 3: periodic replacement every 2 Years
  - Reliability at t=2 years 0.0019

- Justification: periodic inspection every Year
  - Reliability at 2 years (conditioned!)

\[
R(2 \mid 1) = P(t > 2 \mid t > 1) = \frac{P(t > 2)}{P(t > 1)} = e^{-\left(\frac{2}{0.8}\right)^2} = e^{-\left(\frac{1}{0.8}\right)^2} - \left(\frac{2}{0.8}\right)^2 = 0.0092
\]
Weibull distribution is widely used in industrial practice due to its flexibility and capability of representing different reliability behaviours.

\[ F(t) = 1 - e\left(-\frac{t}{\alpha}\right)^\beta \]

\( \alpha = \text{const} \)

\( \beta = \text{const} \)
Type A; failure at the beginning followed by a constant or rate of failure and then a wear-out (Bathtub)

Type B; Classic wear-out, shows constant or increasing conditional probability of failure then a wear-out

Type C; Gradual aging wear out age is not identifiable

Type D; Best new, low conditional probability of failure

Type E; Totally random, constant conditional probability of failure at all ages

Type F; High rate of failure probability at the beginning but decreasing and getting constant after coming into service (Infant mortality)
### Basic Failure Patterns

<table>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>4%</td>
<td>3%</td>
<td>3%</td>
<td>6%</td>
<td>2%</td>
</tr>
<tr>
<td>B</td>
<td>2%</td>
<td>1%</td>
<td>17%</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>C</td>
<td>5%</td>
<td>4%</td>
<td>3%</td>
<td></td>
<td>17%</td>
</tr>
<tr>
<td>D</td>
<td>7%</td>
<td>11%</td>
<td>6%</td>
<td></td>
<td>9%</td>
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<tr>
<td>E</td>
<td>14%</td>
<td>15%</td>
<td>42%</td>
<td>60%</td>
<td>56%</td>
</tr>
<tr>
<td>F</td>
<td>68%</td>
<td>66%</td>
<td>29%</td>
<td>33%</td>
<td>6%</td>
</tr>
<tr>
<td>Failure profiles</td>
<td>Characteristics</td>
<td>Examples</td>
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</tr>
<tr>
<td>A</td>
<td>Associable to mechanical devices with low quality manufacturing process or mechanical devices with a necessary initial settling period.</td>
<td>Machines from late 18th to early 19th century.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Mechanical devices</td>
<td>Reciprocating-engine cylinders, turbine-engine compressor blades, all parts of the airplane structures.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Mechanical devices installed in adverse environmental conditions, devices installed out of the design work conditions.</td>
<td>Air filters or Salvage Air Valves in submarines.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Structures and wearout elements</td>
<td>Automobile bodies, tires, brakes, airplane structures, ship vessels, pressure vessels, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>complex devices with high stress work conditions.</td>
<td>High pressure relief valves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>Complex devices or machinery within a well balanced design.</td>
<td>Gyro compass, multiple sealing high pressure centrifugal pump.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Electronic components, complex components after corrective maintenance.</td>
<td>Computers, notebooks, PLCs, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Complex industrial machinery and industrial installations.</td>
<td>Whatever industrial plants taken into account the commission stage.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The failure pattern behavior heavily influences maintenance decision-making.

Reliability-Centered Maintenance (RCM) is a widely used approach for maintenance management in complex assets, which selects the best maintenance strategy for every component based on its failure pattern.
Maintenance strategy: definition based on two main aspects:

1. Technical ➔ availability, safety constraints, etc.

2. Economic ➔ direct and indirect costs of maintenance
Economical decisions: based on trade off between maintenance effectiveness (i.e., avoid failure) and efficiency (i.e., avoid useless interventions)
LCC (Life Cycle Cost) model is used to evaluate the total cost of the system during its life. The LCC usually includes:

- Cost of spare parts
- Time necessary to replace/repair the component
- Cost and time to perform preventive maintenance action

**Example:**

<table>
<thead>
<tr>
<th>Component</th>
<th>Spare Parts</th>
<th>Time to repair</th>
<th>Preventive maintenance</th>
<th>Material cost</th>
<th>Time to perform the activity</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan Motor</td>
<td>100 €</td>
<td>2 h</td>
<td>Change bearings</td>
<td>5 €</td>
<td>0,5 h</td>
<td>10 years</td>
</tr>
</tbody>
</table>
Main limitations of RCM

1. RCM analysis strongly relies on field data, which may be not available or incomplete:
   - New technology: data collected on the old technology are not applicable to the new technology
   - Different suppliers for the same subsystem
   - Data provided by the suppliers are inaccurate
   - Test campaigns are expensive → field data are used to estimate component reliability behaviours. However, field data are collected in very different operating conditions

2. RCM analysis focuses on the Failure Modes (FM)s, whereas maintenance is performed at component/subsystem level

3. In the train industry, LCC models usually do not take into account indirect costs (i.e. unavailability costs, penalty cost etc.)

Need for developing RCM approaches addressing these issues
1. Reliability behaviour: only failure rate $\lambda$ is provided $\rightarrow$ underlying assumption: failure time obeys the exponential distribution
   - Issue 1: what is the actual distribution of the failure time?
   - Issue 2: how accurate is the failure rate value?

2. FMECA: focus is on FMs, although maintenance looks at components

3. LCC does not take into account indirect costs and the actual reliability behaviour of the component
1. Reliability behaviour: only failure rate $\lambda$ is provided $\rightarrow$ underlying assumption: failure time obeys the exponential distribution

**Issue 1: what is the actual distribution of the failure time?**

We assume that the failure time obeys a Weibull distribution, due to its flexibility and capability of representing different reliability behaviours

$$F(t) = 1 - e^{-\frac{t}{\alpha}^\beta}$$
1. Reliability behaviour: only failure rate $\lambda$ is provided $\rightarrow$ underlying assumption: failure time obeys the exponential distribution

**Issue 1: what is the actual distribution of the failure time?**

We assume that the failure time obeys a Weibull distribution, due to its flexibility and capability of representing different reliability behaviours.

To fairly compare the Weibull distribution with the exponential distribution, we assume they must have the same number of expected failures in the time preventive maintenance interval $T$.

Which are the Weibull parameter $\alpha$ and $\beta$?
Constraint on the same expected number of failures in the same interval

\[ h(t) = \text{hazard rate} \]

\[ \frac{1}{T} \int_0^T \lambda \, dt = \frac{1}{T} \int_0^T h(t) \, dt = \frac{1}{T} \int_0^T \frac{\beta}{\alpha^\beta} t^{(\beta-1)} \, dt \]

\( h(t) \) for the exponential distribution

\( h(t) \) for the Weibull distribution

\[ \lambda = \frac{1}{T} \left( \frac{T}{\alpha} \right)^\beta \]
We need to set two parameters to obtain a Weibull distribution: $T$ and $\beta$

$\beta$: indicates the degradation behaviour of the component
- $\beta < 1 \Rightarrow$ Infant mortality, decreasing hazard rate. Example: defective components
- $\beta = 1 \Rightarrow$ Random failures (exponential distribution). Example: electronic components
- $\beta > 1 \Rightarrow$ Wear out, increasing hazard. Example: mechanical components

$T$: This parameter represents the time interval of observation: We assume $IT$ corresponds to the period of the scheduled replacement/restoration provided by the supplier.
Example:
Change the compressor motor every 15 years $\Rightarrow T = 15\ years$
1. Reliability behaviour: only failure rate $\lambda$ is provided $\rightarrow$ underlying assumption: failure time obeys the exponential distribution

   • Issue 2: how accurate is the failure rate value?

Suppliers can give inaccurate values of the failure rates:
1. The single value failure rate does not take into account the possible wear out of the component
2. Suppliers sell spare parts for maintenance: larger failure rates $\rightarrow$ larger incomes
3. Suppliers have to guarantee that the failure rate of the system is above a certain value: they could adjust its value to achieve this requirement
4. Often suppliers do not have access to field data, and cannot estimate the failure rate in real working conditions
Families of Weibull distributions

\[ \lambda_{\text{min}} \leq \lambda \leq \lambda_{\text{max}} \quad \beta_{\text{min}} \leq \beta \leq \beta_{\text{max}} \]

\( \beta_{\text{min}} \) and \( \beta_{\text{max}} \) are chosen according to the nature of the FM

Examples:

- Electronic components \( \Rightarrow \beta_{\text{min}} = 0.9 \) and \( \beta_{\text{max}} = 1.1 \) (close to exponential distribution)
- Mechanical components \( \Rightarrow \beta_{\text{min}} = 0.5 \) and \( \beta_{\text{max}} = 3 \) in order to simulate infant mortality and wear out
- High degradable component \( \Rightarrow \beta_{\text{min}} = 1 \) and \( \beta_{\text{max}} \geq 4 \) component with high dependence from the working time
1. Reliability behaviour: only failure rate $\lambda$ is provided $\rightarrow$ underlying assumption: failure time obeys the exponential distribution
   - Issue 1: what is the actual distribution of the failure time?
   - Issue 2: how accurate is the failure rate value?

2. FMECA: focus is on FMs, although maintenance looks at components

3. LCC does not take into account indirect costs and the actual reliability behaviour of the component
Failure model assumptions

- **FM1** (Failure Modes) are independent from each other.

- **PM1** (Preventive maintenance) acts on different failure modes of the component.

- **Scheduled replacement/restoration** restores the component to its *as-good-as-new* condition for the associated failure modes.

- **Corrective maintenance** → Component replacement (i.e., it acts on all failure modes).

- **Tests** (scheduled or continuous with sensor) detect hidden failures: the effects of misdetection are component-dependent.
• Scheduled PM (replacement/restoration and tests) are performed at fixed $\Delta T$
• The wear out of the failure modes associated to the PM are restored (replacement/restoration) or detected if hidden failure occurs before the test

Example:
• $PM1 = \text{Restoration of } FM1 \text{ and } FM2$
• $PM2 = \text{Test of } FM3 \text{ (hidden)}$
• When an evident failure occurs or an hidden failure is detected, the component is changed and all the FMs are restored

Example:
• \( PM1 = \text{Restoration of } FM1 \text{ and } FM2 \)
• \( PM2 = \text{Test of } FM3 \) (hidden)
1. Reliability behaviour: only failure rate $\lambda$ is provided $\rightarrow$ underlying assumption: failure time obeys the exponential distribution
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3. LCC must take into account indirect costs and the actual reliability behaviour of the component
The Life Cycle Cost (LCC) of the component: direct costs

\[
LCC = N_F \cdot C_F + \sum_{PMs} N_{PM,i} \cdot C_{PM,i} + \sum_{Tests} N_{Test,i} \cdot C_{Test,i} + C_{und} \cdot \Delta T_{und} \cdot N_{und}
\]

- \(N_F\) is the number of failures and corrective/indirect costs.
- \(N_{PM,i}\) is the number of preventive maintenance \(i\) and its cost.
- \(N_{Test,i}\) is the number of test \(i\) and its cost.
- \(C_{und}\) is the cost of an undetected failure.
- \(\Delta T_{und}\) is the time interval between an hidden failure and its detection.

\[
C_{j,i} = Time \ for \ execution \cdot Cost \ of \ labor + Material \ Cost
\]
Hvac Condenser Motor

Supplier FMECA data
\[ \lambda^s = 1,18 \cdot 10^{-6} \frac{f}{h} \]
Time Horizon=30 years

From RCM procedure

<table>
<thead>
<tr>
<th>FM</th>
<th>Status</th>
<th>Description</th>
<th>FM Frequency:</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM1</td>
<td>Operational</td>
<td>Internal mechanical breakage. This entails the HVAC out of service. The RCM analysis has shown that a scheduled maintenance is doable to prevent this FM.</td>
<td>25%</td>
</tr>
<tr>
<td>FM2</td>
<td>Hidden</td>
<td>Bearings degradation. This hidden FM causes an over-vibration, which increases the frequency of the other two FMs.</td>
<td>30%</td>
</tr>
<tr>
<td>FM3</td>
<td>Operational</td>
<td>Coil in short-circuit. This leads to the HVAC out of service. A corrective approach has been indicated for this FM.</td>
<td>45%</td>
</tr>
</tbody>
</table>
**Hvac Condenser Motor**

Supplier FMECA data

$$\lambda^s = 1,18 \cdot 10^{-6} \frac{f}{h}$$

Time Horizon=30 years

**From RCM Decision Tree**

<table>
<thead>
<tr>
<th>Task</th>
<th>Material Cost</th>
<th>Time for execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM1</td>
<td>75 €</td>
<td>1 h</td>
</tr>
<tr>
<td>PM2 (joint with PM1)</td>
<td>0 €</td>
<td>0.2 h</td>
</tr>
<tr>
<td>Corrective maintenance</td>
<td>105 €</td>
<td>1 h</td>
</tr>
</tbody>
</table>

**Supplier LCC data**
Consider a grid of values of $\tau$

For every value of vector $\tau$, consider a grid of values of $\beta$ and $\lambda$ and calculate the corresponding $\alpha$;

Apply Monte Carlo simulation to estimate $LCC(\tau, \beta, \lambda)$

Use the pairwise dominance criteria to eliminate the scheduled maintenance times $\tau$ yielding dominated $LCC$ values:

$\tau^x$ is pairwise dominated by $\tau^y$, $\tau^x \prec_p \tau^y$, iff $LCC(\tau^x, \beta, \lambda) > LCC(\tau^y, \beta, \lambda)$ $\forall \beta, \forall \lambda$

The pairwise dominance is a sufficient condition for the absolute dominance:

$\tau^x$ is absolutely dominated by $\tau^y$, $\tau^x \prec \tau^y$, iff $\min_{\beta, \lambda} LCC(\tau^x, \beta, \lambda) > \max_{\beta, \lambda} LCC(\tau^y, \beta, \lambda)$
Portfolio of non dominated solutions contains more than one element $\rightarrow$ decision on $\tau$ is based on the Decision Maker (DM) preferences.

For example, a risk averse DM wants to select the policy that minimizes the LCC of the worst combination of parameters (i.e., maximin regret policy):

- $LCC(\tau) = \max_{\beta, \lambda} LCC(\tau, \beta, \lambda)$

- Optimal $\tau$ is $\tau^* = \arg\min_{\tau} LCC(\tau)$
Simulation parameters
\[ \beta_1 \in [1.1, 1.5] \]
\[ \beta_2 \in [1.5, 3.5] \]
\[ \beta_3 \in [1.1, 1.5] \]
\[ \lambda = \{1,2\} \cdot \lambda^s \]

**Cost vs. \( \lambda^s \)**

- Absolute dominance
- No dominance
Simulation parameters

\( \beta_1 \in [1.1, 1.5] \)
\( \beta_2 \in [1.5, 3.5] \)
\( \beta_3 \in [1.1, 1.5] \)
\( \lambda = \{1,2\} \cdot \lambda^s \)

maximin regret \(\rightarrow\) corrective maintenance
What to take into account, for every component?

Component

- Legislation
- Company’s quality policy
- Manufacturer indications
- Maintenance experience
- Job priority analysis
- Criticality analysis

Maintenance plan definition
- Work instruction description
- Required disciplines
- Required working hours and spare list
- Eventual priorities

Maintenance Strategy
- Unplanned
- Periodic
- Condition-based
- Predictive

RCM
What to take into account, for every component?

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Component

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Maintenance Strategy

- Unplanned
- Periodic
- Condition-based
- Predictive

Mathematical models

How to optimize?
Maintenance strategy implementation: Issues

Issues:
- How to group the maintenance tasks?
- When to perform maintenance on a group?
- What to do upon failure?
- How to handle dynamic information for grouping?
- ….
Grouping strategies:

Off-line: for preventive maintenance, only.
- Direct: groups are a-priori-defined and remain always the same (e.g., block replacement)
- Indirect: Standard Indirect Grouping (SIG) and Joint Overhaul Problem (JOP)
Grouping strategies:

**Off-line:** for preventive maintenance, only.
- **Direct:** groups are a-priori-defined and remain always the same (e.g., block replacement)
- **Indirect:** Standard Indirect Grouping (SIG) and Joint Overhaul Problem (JOP)

SIG strategy: preventive maintenance intervention can be performed every T time
Optimization issue: Identify the best T and the corresponding portfolio of actions for every maintenance time
Grouping strategies:

Off-line: for preventive maintenance, only.
- Direct: Groups are a-priori-defined and remain always the same (e.g., block replacement)
- Indirect: Standard Indirect Grouping (SIG) and **Joint Overhaul Problem (JOP)**

**JOP strategy:**
- every $T$ time there is a global overhaul
- every $T/k$ time there is a minor maintenance (e.g., lubrication, strengthening, etc.)

Optimization issue: identify the optimal $T$ and the optimal times for minor events
Grouping strategies can be:

Off-line: for preventive maintenance, only.
- Direct: groups are a-priori-defined and remain always the same (e.g., block replacement)
- Indirect: Standard Indirect Grouping (SIG) and Joint Overhaul Problem (JOP)

Dynamic: for systems with diverse maintenance approaches, also to respond to failures
- Opportunistic
- Dynamic grouping
- Modular
Main Idea: every failure gives the opportunity to perform preventive maintenance on some working components.

The decision about the components to be repaired is taken based on their conditions:

- Monitored component: health indicator
- Non-monitored component: age, time to next preventive action
Main Idea: every failure gives the opportunity to perform preventive maintenance on some working components
The decision about the components to be repaired is taken based on their conditions:
- Monitored component: health indicator
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<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons/issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saving of the set-up costs</td>
<td>This approach is viable only when preventive maintenance can be performed upon failure (it usually needs to be timely arranged).</td>
</tr>
<tr>
<td>System more reliable than in the off-line grouping policies</td>
<td>Availability of an advanced CMMS to have the complete picture of the conditions of all the components</td>
</tr>
</tbody>
</table>

- Optimization issue: identify the components to be repaired in order to minimize the maintenance expenditures in the long run
Main Idea: information about component future behaviors can be factored into the decision on how to stop the system and which component has to undergo preventive maintenance. Information can be:

- Monitored component: component remaining useful life (RUL)
- Non-monitored component: time to next maintenance.
- Possible synergies (e.g., physical or logical proximity of the components (e.g., pipes close to each other))
- Varying use of component

- Optimization issue: at every time instant $t$, identify the optimal policy from $t$ on
Main Idea: at every corrective or preventive maintenance intervention, the entire system (module) is removed from operation and replaced by an overhauled or new module. The removed module is then repaired off-line.

- Optimization issue: find the optimal time for modular replacement, the optimal size of consignment stock
- Additional issue: how to encode the efforts and operability limitations of the maintenance crews?
This problem can be framed as a Joint Scheduling/Assignment Problem, where the optimal sequence and times of activities must be determined, as well as the assignment of limited resources to them.

Many algorithms developed to address this issue

As any optimization problem, we need to define:

**Constraints** -- a formal description of the requirements that must be satisfied by a candidate solution to the problem -- for example, that a particular task can't start until some other task finishes.

**Objective functions** -- a mathematical characterization of the quality of a solution e.g., minimize the makespan.
Main Idea: at every corrective or preventive maintenance intervention, the entire system (module) is removed from operation and replaced by an overhauled or new module. The removed module is then repaired off-line.

- Optimization issue: find the optimal time for modular replacement, the optimal size of consignment stock
- Additional issue: how to encode the requirements/limitations of the maintenance crews
- Additional issue: part flow management
• GT producers offer maintenance service contracts to Oil&Gas plant owners, which require managing the scheduled Maintenance Shutdowns (MSs) and the plant warehouse.

• Every new module can undergo a number R of cycles, provided that it is repaired after each cycle.

• At each MS, 2 decisions must be made for the module:

  1. **Removed Module**: send it to the workshop for repair it or scrap it?

  2. **Installed Part**: purchase a new module or take one from those available at warehouse?
Aramis experience on part flow management

**Decision on removal:**
- NMRC = 0 → scrap
- NMRC = r > 0 repair $C^{rep}(r)$ or scrap?

**Decision on replacement:**
Buy? $C^{pur}$

- Part from Warehouse?

WAREHOUSE

| MNRC = 1 | $w_{1,\theta} = 3$ |
| MNRC = 2 | $w_{2,\theta} = 1$ |
| MNRC = $R$ | $w_{R,\theta} = 2$ |

$g = 1$
$g = 2$
$\ldots$
$g = G$

$\bullet = MS$
$\times = FO$

$t_{\theta_k}$
$t_{\theta_k+2}$
$t_{\theta_k+4}$
$t_{\theta_k+5}$
$t_{\theta_k+6}$

$H$
$\Delta t$

$= MS$
$= FO$
The decision taken at every MS modifies the decisions at the next MSs affecting:

1. Warehouse composition
2. Parts installed on the GTs

Part flow management can be framed as **Sequential Decision Process (SDP)**.
Reinforcement Learning (RL) to solve the Part Flow problem

Environment: GT plant behavior
10% of savings with RL, because:

- Performing 2 early purchase completely modifies the part flow
  - 2 inspect actions can be performed on the new parts
  - 2 purchase actions (RL) instead of 3 purchase actions (MR)
  - 2 repair actions (RL) instead of 3 repair actions (MR)