Reliability-centered maintenance of the Electrically Insulated Joint
via Fault Tree Analysis:
A practical experience report

Enno Ruijters, Dennis Guck, Martijn van Noort, Mariëlle Stoelinga

July 1, 2016
Importance of maintenance

- Even very reliable systems need maintenance
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Maintenance

- **Crucial**: Large impact on reliability, availability, life span.
- **Costly**: Labour, equipment, down time.
Maintenance optimization via fault trees

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Optimize:

- Performance benefits
- Maintenance cost
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- Model maintenance in fault trees
- Study effects
- Using model checking
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<tr>
<th>Nr. of inspections per year</th>
<th>Cost of inspections</th>
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<th>Cost of corrective and preventive maintenance</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
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</tr>
<tr>
<td>1</td>
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<tr>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
</tbody>
</table>
Fault maintenance trees (FMTs): 3 key ingredients

FMT goals:
- What is the effect of maintenance on system performance:
  - Reliability, availability, # of failures per year?
- Can we do better (lower costs / better performance)?

Model checking brings modularity and flexibility.
Ingredient #1: maintenance

Types:
- Corrective maintenance
- Preventive maintenance

Maintenance
Ingredient #1: maintenance

Types:
- Corrective maintenance
- Preventive maintenance

Strategies:
- Age-based
- Use-based
- Condition-based
Ingredient #2: fault trees

Tool for RAMS

- How do component failures propagate to system failures?
- $\mathbb{P}[$failure within mission time$]$ (reliability)
- $\mathbb{E}[$up-time$]$ (availability)
- MTTF, MTBF, etc.
**Ingredient #2: fault trees**

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- How do component failures propagate to system failures?
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- $\mathbb{E}[\text{up-time}]$ (availability)
- MTTF, MTBF, etc.

**Our addition**
- New gate: RDEP
- Trigger accelerates failure rates of dependent events
Ingredient #3: model checking

Model checking

- Using Uppaal-SMC
Ingredient #3: model checking

Model checking
- Using Uppaal-SMC
- Advantages:
  - Ease of modelling
- Disadvantages:
  - No guaranteed results
  - Not (currently) suitable for very rare events.
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Case study: Electrically insulated joint

- Electrically separates section of track.
- 50,000 EIJs in the Netherlands.
- Important cause of train service disruptions.

**Result:** Cost-optimal maintenance strategy.
EI-Joint

- Case study in collaboration with ProRail (Dutch railway asset management company).
- Data obtained from ProRail experts
- Maintenance: Periodic inspections, repairs
- Costs for inspections, repairs, and failures
Outline

1. Introduction
2. Fault maintenance trees
3. Case study
4. Conclusions
Fault trees

- Describe combinations of faults leading to failures
- Root of tree: Top Event; i.e. system failure
- Leaves: Basic Events; i.e. elementary failures and faults
- Nodes: Gates; describe how faults combine
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Images of the elements in a fault tree

Example fault tree
Maintenance in fault trees

- Many failures are not random events.
  - Wear over time

- Production faults caused by other failures

Maintenance is essential for reliability.
- Reduce or prevent wear
- Replace or repair worn components
- Correct failures when they occur

Maintenance is not explicitly modeled in standard fault trees.
Many failures are not random events.
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  - Production faults

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Maintenance is not explicitly modeled in standard fault trees.
- Timed automata with degradation stages.

\[ s_0 \xrightarrow{\lambda_1} s_1 \xrightarrow{\lambda_2 \text{ threshold!}} s_2 \xrightarrow{\lambda_3 \text{ fail!}} s_4 \]

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_0$</td>
<td>New</td>
</tr>
<tr>
<td>$s_1$</td>
<td>Okay</td>
</tr>
<tr>
<td>$s_2$</td>
<td>Degraded</td>
</tr>
<tr>
<td>$s_4$</td>
<td>Failed</td>
</tr>
</tbody>
</table>
Modelling BEs

- Timed automata with degradation stages.
- Signals for composition:
  - Maintenance threshold
  - Repair
  - Failure
- Other modules will send/receive these signals.
Rate-affecting failures

- Some failures accelerate wear of other components.
Rate-affecting failures

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- New variant on the FDEP gate: rate dependency (RDEP).
- Failure of trigger BE accelerates degradation.
- Rates increase by factor $\gamma$. 
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Repair of trigger BE does not repair triggered BE.
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Failure of trigger BE accelerates degradation.
Rates increase by factor $\gamma$.
Repair of trigger BE does not repair triggered BE.
Modelling inspections and repairs

**Repair module:**
- Periodically start repairs (optional)
- Inspection may trigger repairs early

![Diagram](attachment:image.png)

- $s_0$ to $s_1$: $T_p$
- $s_1$ to $s_0$: start_repair?
- $s_1$ to $s_2$: $T_r$
- $s_0$ to $s_2$: repair!
Modelling inspections and repairs

**Inspection module:**
- Periodically perform inspection
- If threshold reached: Start repair
- Otherwise: Do nothing
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Case study

Failure El-joint

Mechanical failure

Failure electrical isolation

Joint shorted

RDEP

1

2

3

4

5

6

RDEP

5a

5b

10a

10b

11

12

13

14

15
Obtaining quantitative parameters:
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Modelling

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Modelling

Obtaining quantitative parameters:

- Follow FMEA ProRail.
- Accelerating failure causes obtained by interviewing experts.
- Failure curves obtained by fitting against historical failure data.
- Most failures only occur in a subset of joints.
  - E.g. failures from steel shavings occur only in curved track.
  - These probabilities were obtained by questionnaire sent to experts.
## Failure modes

<table>
<thead>
<tr>
<th>BE nr.</th>
<th>Failure mode</th>
<th>ETTF (years)</th>
<th>Phases (thres.)</th>
<th>Prob. cnd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bad geometry</td>
<td>5</td>
<td>4 (3)</td>
<td>10%</td>
</tr>
</tbody>
</table>
## Failure modes

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</thead>
<tbody>
<tr>
<td>1</td>
<td>Bad geometry</td>
<td>5</td>
<td>4 (3)</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Broken fishplate</td>
<td>8</td>
<td>4 (3)</td>
<td>33%</td>
</tr>
<tr>
<td>BE nr.</td>
<td>Failure mode</td>
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<td>Phases (thres.)</td>
<td>Prob. cond.</td>
</tr>
<tr>
<td>-------</td>
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</tr>
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<td>1</td>
<td>Bad geometry</td>
<td>5</td>
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</tr>
<tr>
<td>2</td>
<td>Broken fishplate</td>
<td>8</td>
<td>4 (3)</td>
<td>33%</td>
</tr>
<tr>
<td>3</td>
<td>Broken bolt</td>
<td>15</td>
<td>4 (3)</td>
<td>33%</td>
</tr>
<tr>
<td>4</td>
<td>Rail head broken out</td>
<td>10</td>
<td>4 (3)</td>
<td>33%</td>
</tr>
<tr>
<td>5</td>
<td>Glue connection broken</td>
<td>10</td>
<td>4 (3)</td>
<td>33%</td>
</tr>
<tr>
<td>6</td>
<td>Battered head</td>
<td>20</td>
<td>4 (3)</td>
<td>5%</td>
</tr>
<tr>
<td>7</td>
<td>Arc damage</td>
<td>5</td>
<td>3 (2)</td>
<td>0.2%</td>
</tr>
<tr>
<td>8</td>
<td>End post broken out</td>
<td>7</td>
<td>3 (2)</td>
<td>33%</td>
</tr>
<tr>
<td>9</td>
<td>Joint bypassed: overhang</td>
<td>5</td>
<td>4 (2)</td>
<td>100%</td>
</tr>
<tr>
<td>10a</td>
<td>Joint shorted: shavings (normal)</td>
<td>1</td>
<td>4 (3)</td>
<td>12%</td>
</tr>
<tr>
<td>10b</td>
<td>Joint shorted: shavings (coated)</td>
<td>10</td>
<td>4 (3)</td>
<td>3%</td>
</tr>
<tr>
<td>11</td>
<td>Joint shorted: splinters</td>
<td>200</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>12</td>
<td>Joint shorted: foreign object</td>
<td>250</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>13</td>
<td>Joint shorted: shavings (grinding)</td>
<td>5000</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>14</td>
<td>Sleeper shifted</td>
<td>5000</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>15</td>
<td>Internal low resistance</td>
<td>5000</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>16</td>
<td>End post jutting out</td>
<td>20</td>
<td>1</td>
<td>100%</td>
</tr>
</tbody>
</table>
Analysis results

- Results are averages of 40,000 simulations.
- 95% Confidence window: width less than 1%.
- Computation time: Approx. 200 CPU-hours.
- Scales omitted for confidentiality.
## Analysis results: failure causes

<table>
<thead>
<tr>
<th></th>
<th>Mechanical</th>
<th>Other mech.</th>
<th>All failures</th>
<th>Electrical</th>
<th>Other elec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>9</td>
<td>10</td>
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<tr>
<td></td>
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</tr>
</tbody>
</table>

25 / 32
Analysis results: unreliability

![Graph showing unreliability over time with different inspection frequencies.](image)

- No inspections
- 1 inspection per year
- 2 inspections per year
- 4 inspections per year
- 8 inspections per year

Unreliability increases over time for all inspection frequencies, with more frequent inspections leading to lower unreliability.
Analysis results: costs

![Graph showing costs over years with different cost components: Total cost, Cost of inspections, Cost of corrective and preventive maintenance, Cost of failures.]

- Total cost: Increasing linearly with years.
- Cost of inspections: Increasing linearly with years.
- Cost of corrective and preventive maintenance: Increasing linearly with years.
- Cost of failures: Increasing linearly with years.
Analysis results: inspection rate

<table>
<thead>
<tr>
<th>Nr. of inspections per year</th>
<th>Total cost</th>
<th>Cost of inspections</th>
<th>Cost of corrective and preventive maintenance</th>
<th>Cost of failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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</tr>
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Cost / Total cost: 28 / 32
## Analysis results: other strategies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Failure rate</th>
<th>Total cost</th>
<th>Maint. cost</th>
</tr>
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<tbody>
<tr>
<td>Standard</td>
<td>1</td>
<td>1</td>
<td>0.76</td>
</tr>
<tr>
<td>Periodic replacement (5 yrs)</td>
<td>0.88</td>
<td>1.85</td>
<td>1.64</td>
</tr>
<tr>
<td>Periodic replacement (20 yrs)</td>
<td>0.98</td>
<td>1.17</td>
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</tr>
<tr>
<td>Reduced maint. threshold</td>
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Note: Reduced maintenance threshold may not be feasible in practice.
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Conclusions on EI-joints

- Cost-optimal inspection frequency around 4 times per year.
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- Cost approximately flat from 2 to 6 inspection per year.
Conclusions on EI-joints

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- Cost approximately flat from 2 to 6 inspection per year.
- More failures can be prevented, but not cost-effectively.
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- We have demonstrated our approach with a case study.