Better railway engineering through statistical model checking

Enno Ruijters and Mariëlle Stoelinga

10 October 2016

UNIVERSITY OF TWENTE.
1 Introduction
   • Maintenance
   • Fault Trees
   • Model checking

2 Fault maintenance trees
   • Modeling
   • Analysis

3 Case study
   • Electrically insulated joint
   • Pneumatic compressor

4 Conclusions
Do you think flying is safe?
Do you think flying is safe?

In an airplane unmaintained for a decade?
Dependability of many systems is critical.

- Airplanes
Dependability of many systems is critical.
- Airplanes
- Nuclear power stations
Dependability of many systems is critical.

- Airplanes
- Nuclear power stations
- Medical devices
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Traditional focus on design for dependability.
Dependability

- Dependability of many systems is critical.
  - Airplanes
  - Nuclear power stations
  - Medical devices

- Traditional focus on design for dependability.

- Even very reliable systems need maintenance.
Maintenance optimization via fault trees

Maintenance

Crucial: Large impact on reliability, availability, life span.
Maintenance optimization via fault trees

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

Support decision making to optimize maintenance plans.
Maintenance optimization via fault trees

**Maintenance**
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**Optimize:**
- Performance benefits
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![Cost vs. Nr. of inspections per year graph](chart.png)
Maintenance optimization via fault trees

Maintenance

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- **Costly**: Labour, equipment, down time.

Optimize:

- Performance benefits
- Maintenance cost

Support decision making to optimize maintenance plans.
Two case studies:

EI-Joint

Important cause of train service disruptions.

Result: Cost-optimization of maintenance

Pneumatic compressor

Powers brakes, doors, etc., fail-safe but source of disruptions.

Result: Reliability analysis.
Case studies

Two case studies:

**El-Joint**
- Important cause of train service disruptions.
- Result: Cost-optimization of maintenance
Case studies

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**Pneumatic compressor**
- Powers brakes, doors, etc., fail-safe but source of disruptions.
- Result: Reliability analysis.
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:

Maintenance
Ingredient #1: maintenance

Types:
- Corrective maintenance:
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Strategies:
- Age-based
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Maintenance
Ingredient #2: fault trees

Industry standard tool for reliability analysis

- How do component failures propagate to system failures?
Ingredient #2: fault trees

Industry standard tool for reliability analysis

- How do component failures propagate to system failures?
- Used by NASA, ESA, Boeing, ...
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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Diagram: A state transition diagram with states 1 to 6 and edges labeled with probabilities.
Ingredient #3: model checking

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Putting it all together

Summary of our approach:

- Combine maintenance planning into fault trees.
- Compositional conversion into (P)STA.
- Analysis via statistical model checking.
- Results on system reliability, availability, etc.

(a) FMT

(b) Transformation to UPPAAL-SMC

(c) Results
Outline

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2. Fault maintenance trees
   - Modeling
   - Analysis

3. Case study
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4. Conclusions
Fault trees

- Industry-standard tool for reliability analysis
Fault trees

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- Describe combinations of faults leading to failures

Images of the elements in a fault (maintenance) tree
Fault trees

- Industry-standard tool for reliability analysis
- 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

Images of the elements in a fault (maintenance) tree

BE  AND  OR  VOTE

RDEP
Fault tree of pneumatic compressor

Train stranded due to compressor failure

No operation

1: Safety relay engaged
2: De-aeration valve defective
...

Reduced capacity

1: Motor fails to start
2: De-aeration valve defective
...

Maintenance plan describes behaviour of leaves.
Many failures are not exponentially distributed random events.

- Wear over time

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, despite its critical effect on dependability.
Many failures are not exponentially distributed random events.
- Wear over time
- Production faults

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, despite its critical effect on dependability.
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- Wear over time
- Production faults
- Caused by other failures
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- Combine maintenance into fault trees.
- Basic events include degradation over time.
- Degradation of one component can affect other components.
- Repair modules remove degradation (periodically or condition-based).
- Inspection modules periodically check degradation and activate repairs if needed.
Modelling BEs

- Degradation modeled in distinct phases.
- Stochastic timed automaton:

\[ s_0 \xrightarrow{\lambda_1} s_1 \xrightarrow{\lambda_2} s_2 \xrightarrow{\lambda_3} s_4 \]

New \rightarrow Okay \rightarrow Degraded \rightarrow Failed
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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- Failure of trigger BE accelerates degradation.
- Rates increase by factor $\gamma$. 
Rate-affecting failures

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Some failures accelerate wear of other components.
Failure of trigger BE accelerates degradation.
Rates increase by factor $\gamma$.
Repair of trigger BE does not repair triggered BE.
Timed automaton of triggered BE:
Modelling inspections and repairs

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

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

Collaboration with ProRail (Dutch railway asset management company).

Electrically separates section of track.

Important cause of train service disruptions.

Result:

Cost-optimal maintenance strategy.
Case study: Electrically insulated joint

- Collaboration with ProRail (Dutch railway asset management company).
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Case study

Failure El-joint

Mechanical failure

Failure electrical isolation

Joint shorted
Obtaining quantitative parameters:

- Follow FMEA ProRail.
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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.
ETTF degrading BEs:

Red zone indicates detectable by inspection, color indicates percentage of susceptible joints.

- Bad geometry (1): 5
- Broken fishplage (2): 8
- Broken bolt (3): 15
- Rail head broken out (4): 10
- Glue connection broken (5): 10
- Battered head (6): 20
- Arc damage (7): 5
- End post broken out (8): 7
- Joint bypassed: overhang (9): 5
- Joint shorted: shavings (normal) (10a): 1
- Joint shorted: shavings (coated) (10b): 10
Failure modes EI-joint

**ETTF degrading BEs:**
Red zone indicates detectable by inspection, color indicates percentage of susceptible joints.

- **Bad geometry (1):** 5%
- **Broken fishplage (2):** 8%
- **Broken bolt (3):** 15%
- **Rail head broken out (4):** 10%
- **Glue connection broken (5):** 10%
- **Battered head (6):** 20%
- **Arc damage (7):** 5%
- **End post broken out (8):** 7%
- **Joint bypassed: overhang (9):** 5%
- **Joint shorted: shavings (normal) (10a):** 1%
- **Joint shorted: shavings (coated) (10b):** 10%
### ETTF degrading BEs:

Red zone indicates detectable by inspection, color indicates percentage of susceptible joints.

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad geometry (1)</td>
<td>5</td>
</tr>
<tr>
<td>Broken fishplage (2)</td>
<td>8</td>
</tr>
<tr>
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<td>15</td>
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</tr>
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</tr>
<tr>
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<td>10</td>
</tr>
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**Failure modes El-joint**

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```
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```

**ETTF exponential failures** (logarithmic scale):

```
Joint shorted: splinters (11): 200
Joint shorted: foreign object (12): 250
Joint shorted: shavings (grinding) (13): 5000
Damage due to maintenance (14): 5000
Internal low resistance (15): 2500
```
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: unreliability

Unreliability

Years

No inspections
1 inspection per year
2 inspections per year
4 inspections per year
8 inspections per year
Analysis results: costs

<table>
<thead>
<tr>
<th>Years</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></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
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<td>30</td>
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<td>40</td>
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<td></td>
<td>50</td>
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Analysis results: inspection rate

Cost
Nr. of inspections per year
Total cost
Cost of inspections
Cost of corrective and preventive maintenance
Cost of failures

Nr. of inspections per year
Case study: Pneumatic compressor

- Powers brakes, doors, etc.
- Fail-safe but failures cause disruptions.
- Maintenance is essential for normal operation.

**Result:** Analysis of maintenance effectiveness.
Train stranded due to compressor failure

No operation

1: Motor fails to start
2: De-aeration valve defective
...

Safety relay engaged

Oil temperature safety engaged

Reduced capacity

Compressor screws worn
### Failure modes

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</tr>
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<td>200</td>
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<tr>
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<td>0.001</td>
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<tr>
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<tr>
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<td>16.6</td>
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<tr>
<td>Low oil level (6)</td>
<td>5.5</td>
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<tr>
<td>Pressure valve leakage (7)</td>
<td>3.3</td>
</tr>
<tr>
<td>Air filter obstructed (8)</td>
<td>500</td>
</tr>
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- Bars show MTTF (years, logarithmic), whiskers show std. deviation
- Estimates from maintenance engineers, system experts.
- Experiment reports from simulation environment.
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Maintenance actions:
- **I1**: Bi-daily visual inspection (oil leaks, ...)
- **S1**: Three-monthly service (test pressure, replace filters, ...)
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## Maintenance plan

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<table>
<thead>
<tr>
<th>Phase</th>
<th>Action</th>
<th>Result</th>
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<tbody>
<tr>
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<td>1</td>
</tr>
<tr>
<td>1</td>
<td>O1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>O1</td>
<td>1</td>
</tr>
<tr>
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<td>O2</td>
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<td>S1</td>
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<tr>
<td>8</td>
<td>Any</td>
<td>O1</td>
</tr>
</tbody>
</table>

### Maintenance actions:

- **I1**: Bi-daily visual inspection (oil leaks, ...)
- **S1**: Three-monthly service (test pressure, replace filters, ...)
- **S2**: Nine-monthly service (like S1, also replace oil, ...)
- **O1**: Minor overhaul (disassemble, replace worn parts, ...)
- **O2**: Major overhaul (return to as-good-as-new)
### Analysis results: failure causes

<table>
<thead>
<tr>
<th>No operation</th>
<th>Reduced capacity</th>
<th>Other no op.</th>
<th>Other red. cap.</th>
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<tbody>
<tr>
<td>1</td>
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<td>5</td>
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</tr>
<tr>
<td></td>
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<td>13</td>
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</tbody>
</table>

- Failure mode 4 (radiator obstructed) major cause of disruptions.
- Many failure modes rarely occur.
Analysis results: Current policy

Validation: Predictions are close to reality.
Reliability heavily depends on maintenance interval.

With costs, optimal inspection interval can be found.
Scheduled overhauls do not appear to have much effect.
Costs are confidential, but overhauls are probably not cost-effective.
Conclusions on the compressor

- Number of failures in current maintenance policy agrees with reality.
Conclusions on the compressor

- Number of failures in current maintenance policy agrees with reality.
- Frequency of minor service has major influence on reliability.
Conclusions on the compressor

- Number of failures in current maintenance policy agrees with reality.
- Frequency of minor service has major influence on reliability.
- Periodic overhauls do not appear very significant.
Conclusions

- FMTs integrates maintenance in fault trees.
Conclusions

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- FT and maintenance plan can be separately developed.
Conclusions

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  - FT and maintenance plan can be separately developed.
- Useful decision support tool to compare dependability characteristics under different maintenance strategies.

Demonstration FMTs in collaboration with ProRail and NedTrain. Applicable in practice.

Future work:
- Replacing phased degradation by a continuous model (SHA).
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