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

Outline

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

Importance of maintenance

- Even very reliable systems need maintenance

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Maintenance optimization via fault trees

Maintenance

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

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- Maintenance cost

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- Model maintenance in fault trees
- Study effects
- Using model checking

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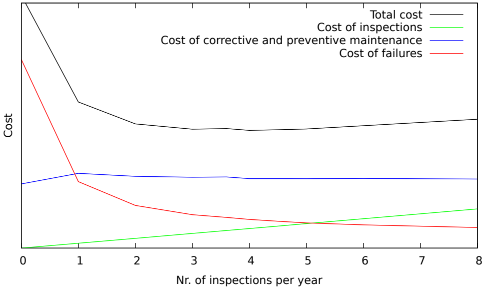
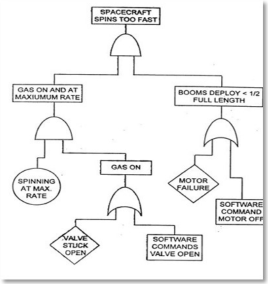
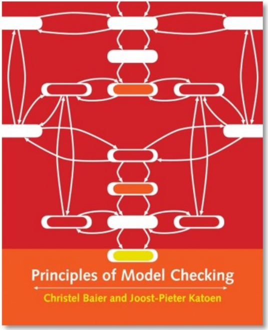


Fault maintenance trees (FMTs): 3 key ingredients

Maintenance



Fault Trees



Model Checking

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

Maintenance

Types:

- Corrective maintenance
- Preventive maintenance

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- Corrective maintenance
- Preventive maintenance

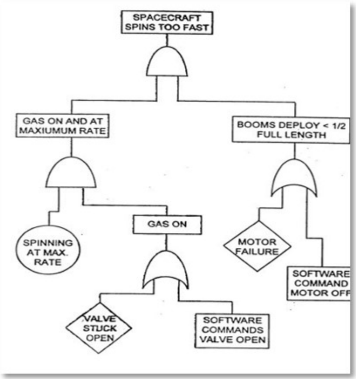
Strategies:

- 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.



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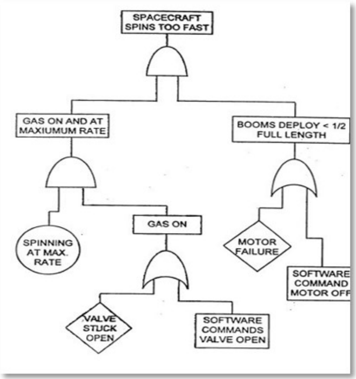


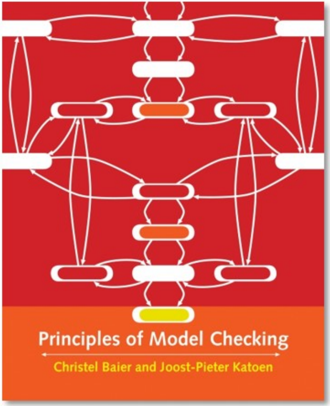
Our addition

- New gate: RDEP
- Trigger accelerates failure rates of dependent events

Ingredient #3: model checking

Model checking

- Using Uppaal-SMC



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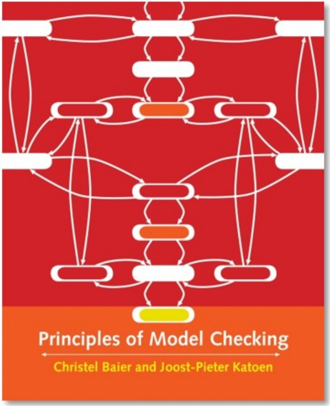

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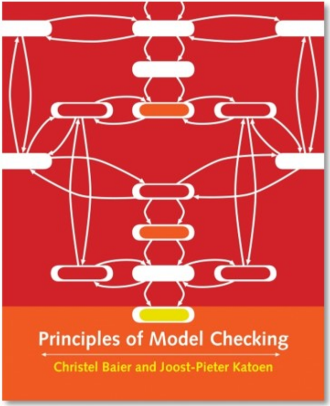

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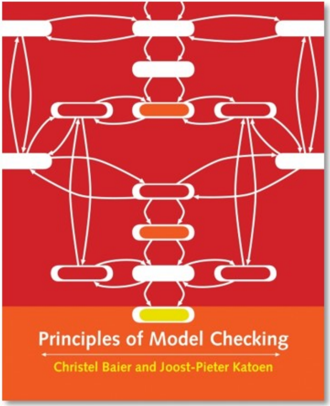

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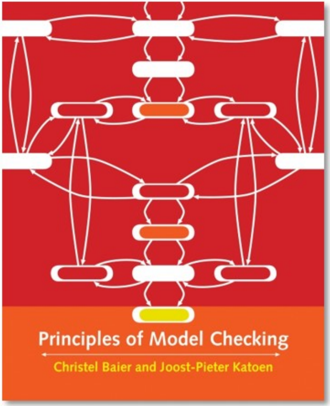

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Model checking

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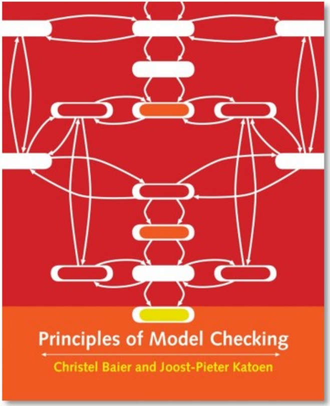
  - Not (currently) suitable for very rare events.



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.

El-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

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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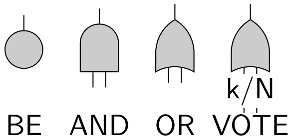
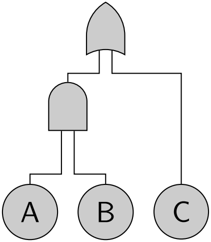


Images of the elements in a fault tree



Example fault tree

Maintenance in fault trees

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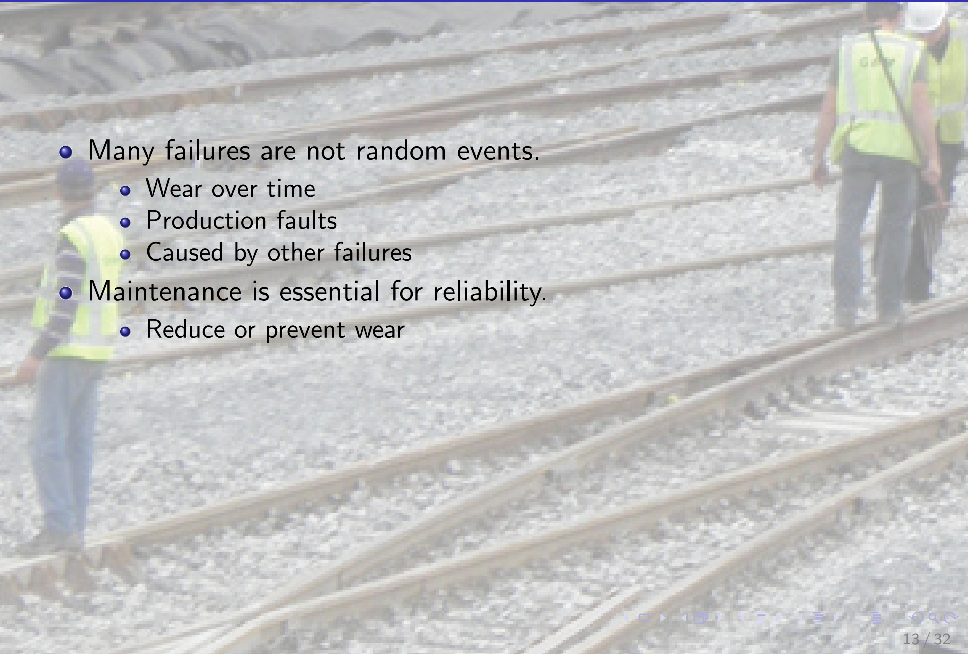

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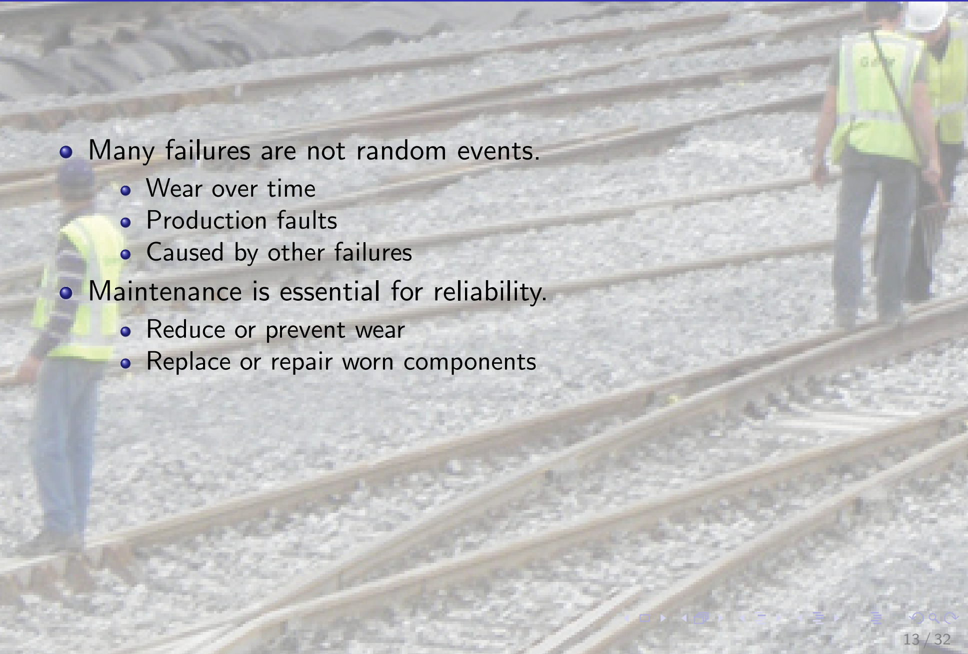

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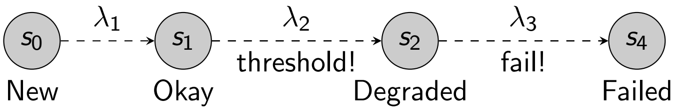
- **Maintenance is not explicitly modeled in standard fault trees.**

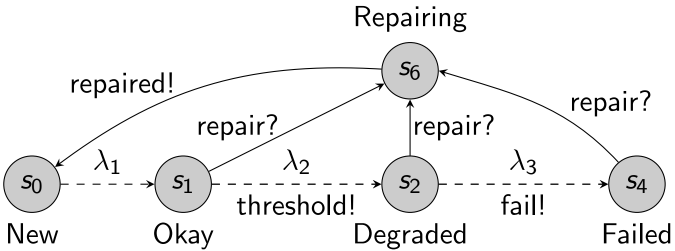
Modelling BEs

- Timed automata with degradation stages.



Modelling BEs

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



Rate-affecting failures

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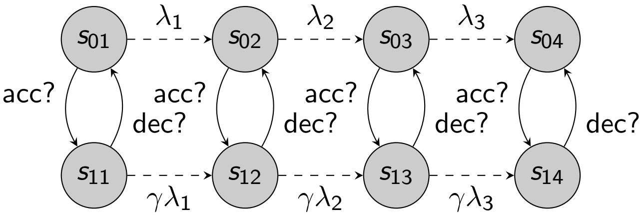
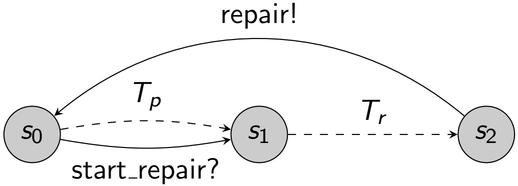


Modelling inspections and repairs

Repair module:

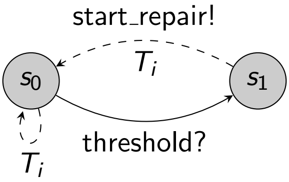
- Periodically start repairs (optional)
- Inspection may trigger repairs early



Modelling inspections and repairs

Inspection module:

- Periodically perform inspection
- If threshold reached: Start repair
- Otherwise: Do nothing



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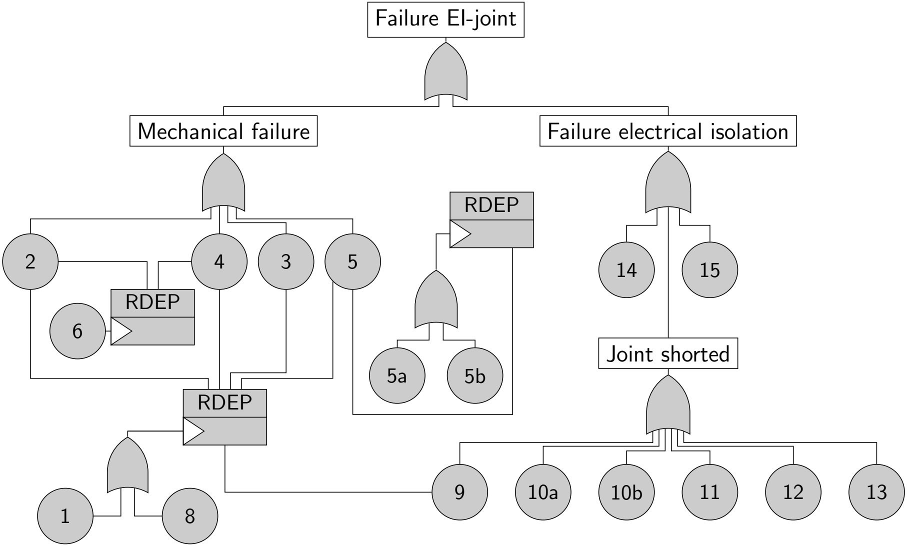
Failure El-joint
Mechanical failure
Failure electrical isolation
2
4
3
5
RDEP
6
RDEP
RDEP
5a
5b
14
15
Joint shorted
1
8
9
10a
10b
11
12
13

Modelling

Obtaining quantitative parameters:

- Follow FMEA ProRail.

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Obtaining quantitative parameters:

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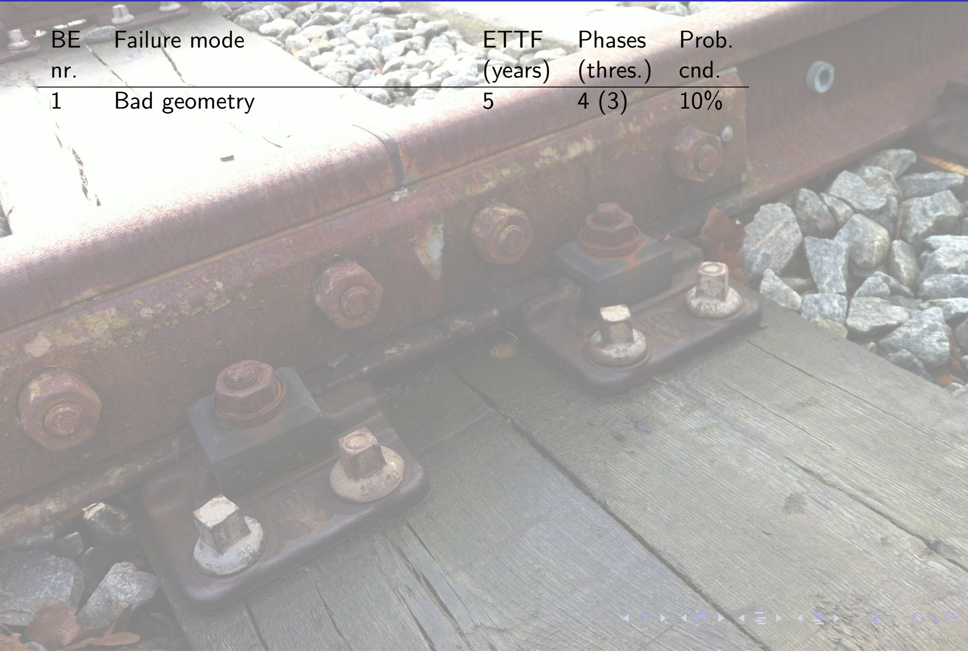
- Failure curves obtained by fitting against historical failure data.
- Most failures only occur in a subset of joints.
  - E.g. failures from steel shavings occur only in curved track.
  - These probabilities were obtained by questionnaire sent to experts.

Failure modes

BE nr.	Failure mode	ETTF (years)	Phases (thres.)	Prob. cnd.
1	Bad geometry	5	4 (3)	10%



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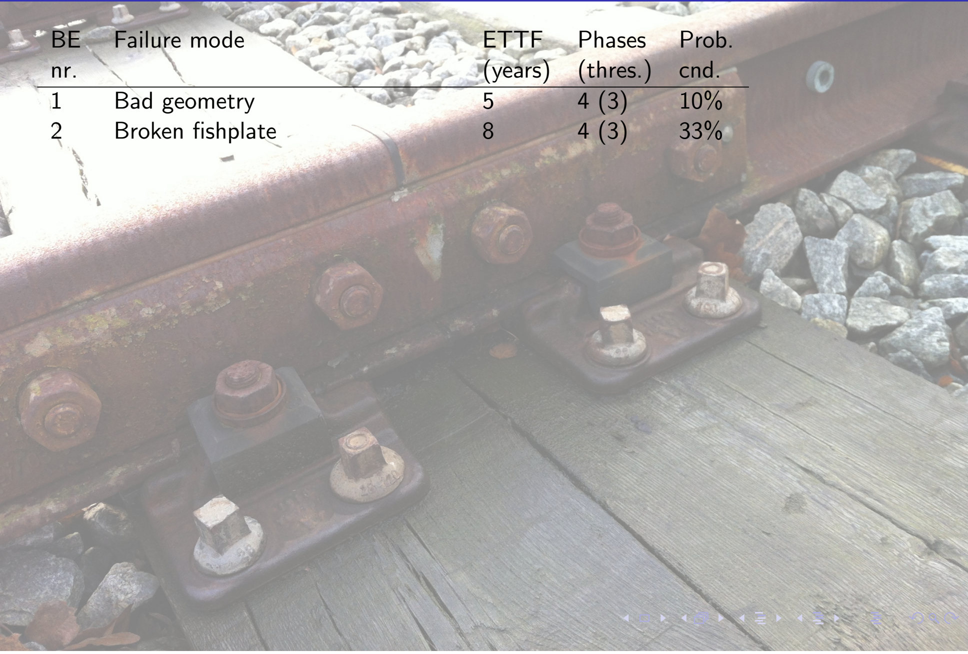

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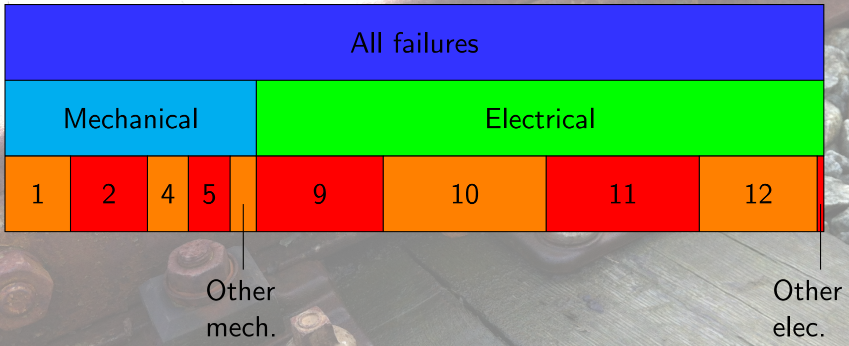
1	Bad geometry	5	4 (3)	10%
2	Broken fishplate	8	4 (3)	33%
3	Broken bolt	15	4 (3)	33%
4	Rail head broken out	10	4 (3)	33%
5	Glue connection broken	10	4 (3)	33%
6	Battered head	20	4 (3)	5%
7	Arc damage	5	3 (2)	0.2%
8	End post broken out	7	3 (2)	33%
9	Joint bypassed: overhang	5	4 (2)	100%
10a	Joint shorted: shavings (normal)	1	4 (3)	12%
10b	Joint shorted: shavings (coated)	10	4 (3)	3%
11	Joint shorted: splinters	200	1	100%
12	Joint shorted: foreign object	250	1	100%
13	Joint shorted: shavings (grinding)	5000	1	100%
14	Sleeper shifted	5000	1	100%
15	Internal low resistance	5000	1	100%
16	End post jutting out	20	1	100%

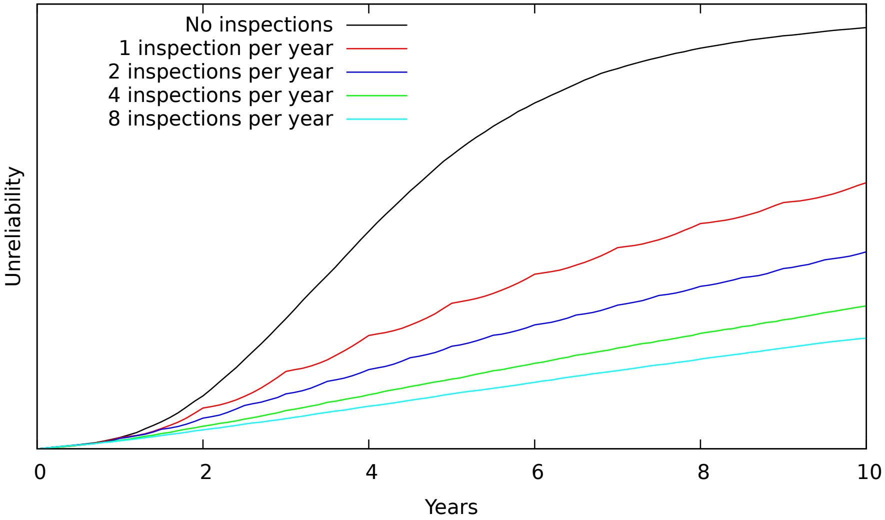
Analysis results

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

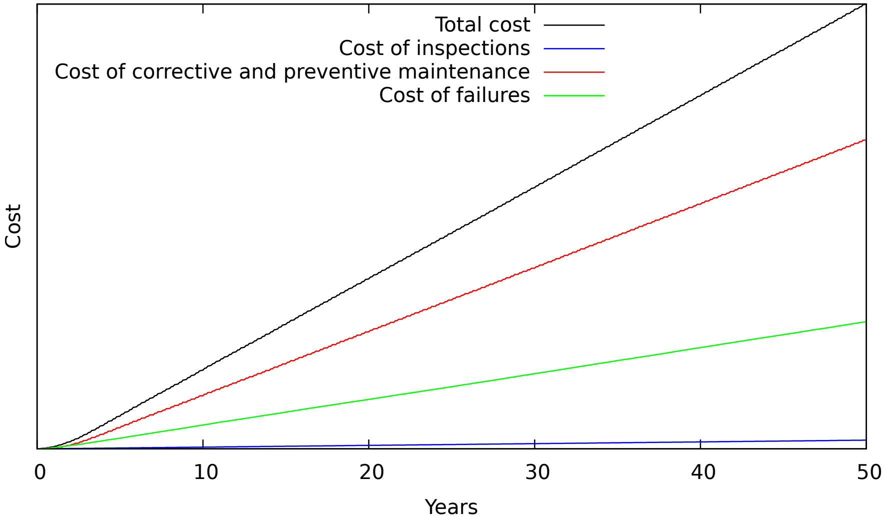
Analysis results: failure causes



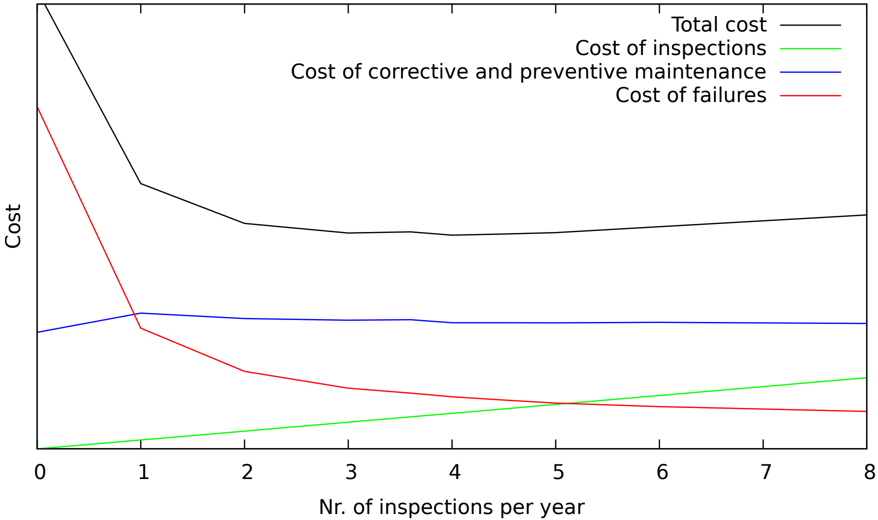
Analysis results: unreliability



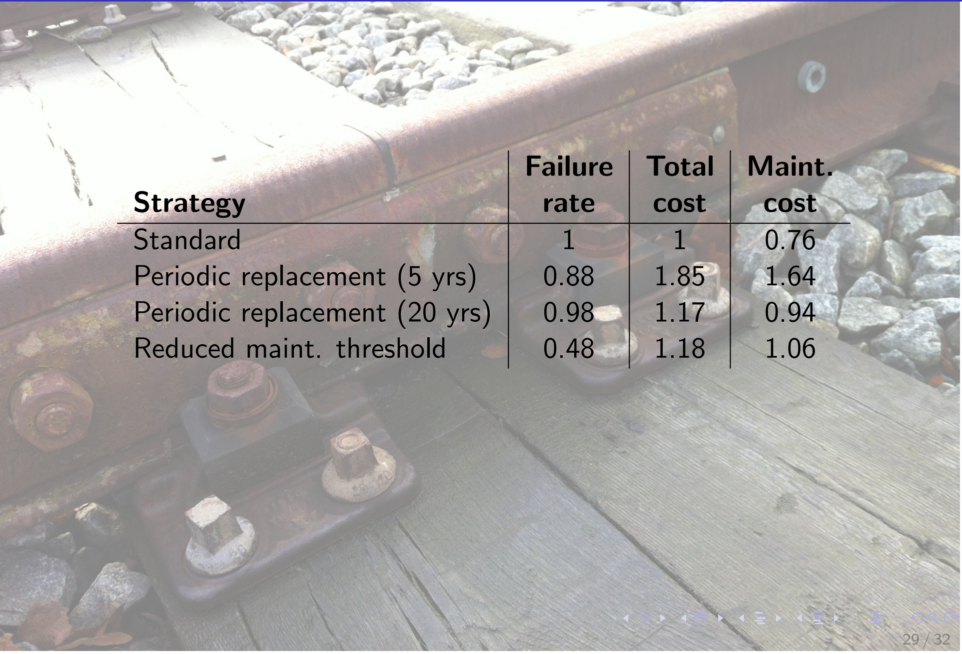
Analysis results: costs



Analysis results: inspection rate



Analysis results: other strategies



Strategy	Failure rate	Total cost	Maint. cost
Standard	1	1	0.76
Periodic replacement (5 yrs)	0.88	1.85	1.64
Periodic replacement (20 yrs)	0.98	1.17	0.94
Reduced maint. threshold	0.48	1.18	1.06

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- Note: Reduced maintenance threshold may not be feasible in practice.

Conclusions on EI-joints

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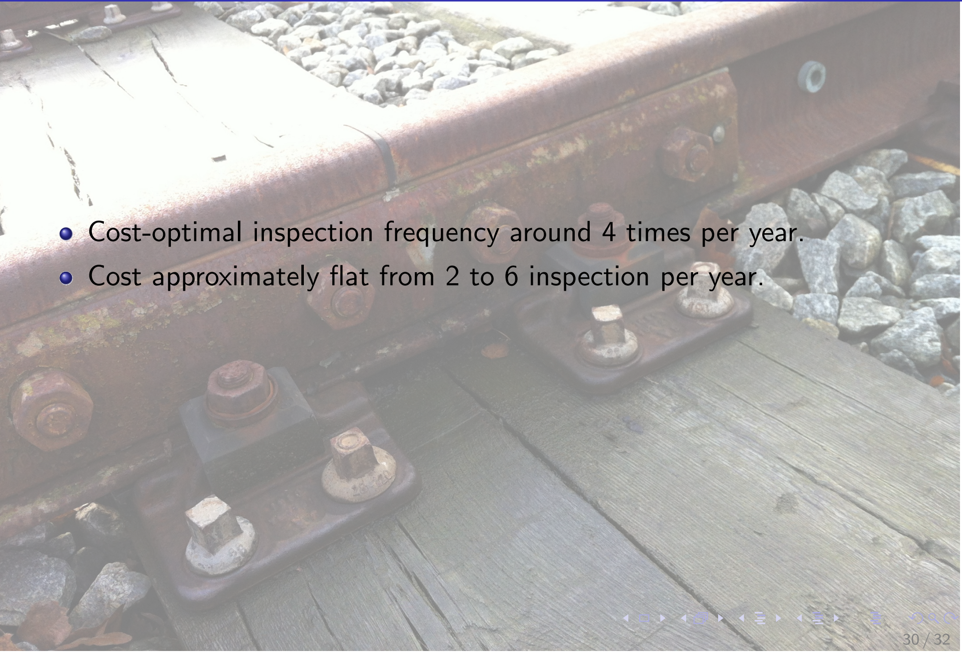

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- Cost approximately flat from 2 to 6 inspection per year.

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 can compute how dependability characteristics vary with different maintenance strategies.
- We have demonstrated our approach with a case study.