Delft University of Technology

A framework for critical infrastructure safety

“The RAIN Risk Analysis Framework”

RAIN Workshop

Critical Infrastructure Safety in the Context of Climate Change

Delft

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This project is funded by the European Union

With a focus on

Modelling Cascading Effects
Using
The Probability Sort Algorithm

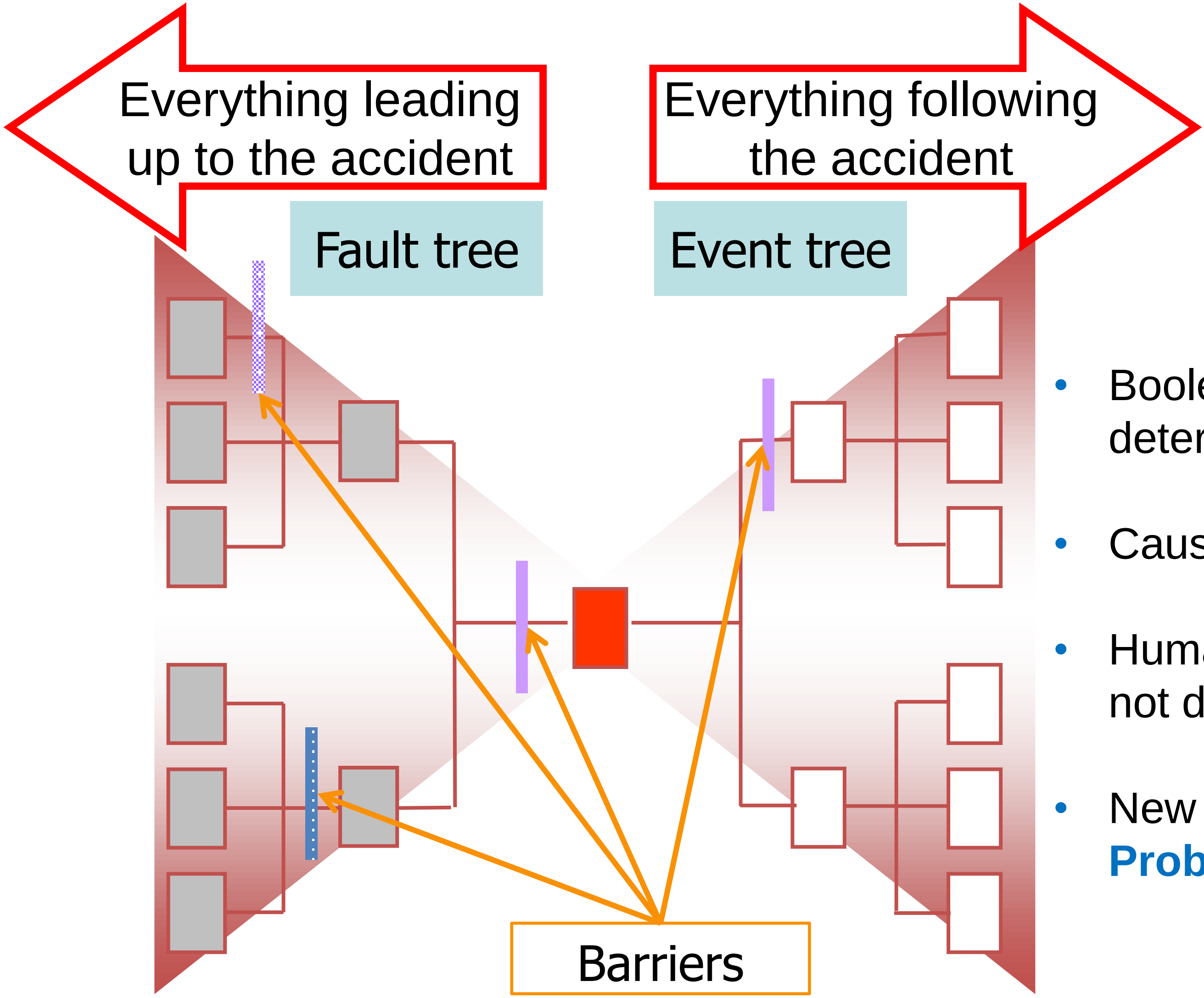
This project is funded by
the European Union

Risk Analysis Framework

The risk framework addresses the quantitative modelling approaches for critical transport -, energy- and telecom infrastructures which are highly interconnected and form ‘systems of systems’ that tend to be vulnerable during extreme hydro-meteorological events.

This project is funded by the European Union

Bow-tie Model



Everything leading up to the accident

Everything following the accident

Fault tree

Event tree

Barriers

BUT:

- Boolean logic is deterministic
- Causality is probabilistic
- Human influence certainly not deterministic
- New sort of construct: **Probabilistic logic**

This project is funded by the European Union

Cascade Effect:
Exploding Fuel Storage Container

```
0       0       0       0       0
0       0       0       0       0
0       0       1       0       0
0       0       0       0       0
0       0       0       0       0
```

Overpressure gives probability
map for additional explosions

```
0.000420084     0.00151553      0.00294877      0.00151553      0.000420084
0.00151553      0.0271149       0.225597        0.0271149       0.00151553
0.00294877      0.225597        1               0.225597        0.00294877
0.00151553      0.0271149       0.225597        0.0271149       0.00151553
0.000420084     0.00151553      0.00294877      0.00151553      0.000420084
```

Damage state space: 2^24 = 16.777.216

Probability Sort Algorithm

- Based on ML-principle:
  - Go from the most probable damage state.
  - To the next most probable damage state.
  - To the next most probable damage state.
  - Etc…
- Fast algorithm:
  - Thousands of optimal scenarios may be selected within minutes.
- Practicality:
  - Active probability components often in exponentially small region of state space.

Active Probability Components

16777216 damage states with P > 0

modelled by way of

1094 damage states with P > 10^-6

Probability coverage = 0.9994

Approximation

generating probability map

0.000420084	0.00151553	0.00294877	0.00151553	0.000420084
0.00151553	0.0271149	0.225597	0.0271149	0.00151553
0.00294877	0.225597	1	0.225597	0.00294877
0.00151553	0.0271149	0.225597	0.0271149	0.00151553
0.000420084	0.00151553	0.00294877	0.00151553	0.000420084

0.000398076	0.00147386	0.00288034	0.00147386	0.000398076
0.00147386	0.0270219	0.225515	0.0270219	0.00147386
0.00288034	0.225515	1.	0.225515	0.00288034
0.00147386	0.0270219	0.225515	0.0270219	0.00147386
0.000398076	0.00147386	0.00288034	0.00147386	0.000398076

weighted sum of 1094 damage states

Cascade t = 1:
ML-Scenarios

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.31404

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.09149

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.09149

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.09149

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.09149

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.02665

Dynamic Probability Maps

0	0	0	0	0
0	0	0	0	0
0	0	1	0	0
0	0	1	0	0
0	0	0	0	0

→

0.01288	0.0445976	0.0777906	0.0445976	0.01288
0.060528	0.445854	0.893723	0.445854	0.060528
0.16738	0.981007	1	0.981007	0.16738
0.16738	0.981007	1	0.981007	0.16738
0.060528	0.445854	0.893723	0.445854	0.060528

0	0	0	0	0
0	0	1	0	0
0	1	1	0	0
0	0	0	0	0
0	0	0	0	0

→

0.594253	0.968829	0.998799	0.899388	0.329622
0.968829	1.	1	0.999944	0.618042
0.998799	1	1	0.999977	0.643848
0.899388	0.999944	0.999977	0.950805	0.387652
0.329622	0.618042	0.643848	0.387652	0.13127

Time Step t = 2

Number of State Space Routes:

$$2^{24} + \sum_{i=1}^{24} \frac{24!}{i!\,(24-i)!}\, 2^{24-i} = 2.8 \times 10^{11}$$

33100 secondary scenarios with P > 10^-6

Probability coverage = 0.9177

57589 routes with 33100 unique end points

Cascade Time Step t = 2:
Marginal Probabilities

t = 1: weighted sum of 1094 damage states

```
0.000398076      0.00147386      0.00288034      0.00147386      0.000398076
0.00147386       0.0270219       0.225515        0.0270219       0.00147386
0.00288034       0.225515        1.              0.225515        0.00288034
0.00147386       0.0270219       0.225515        0.0270219       0.00147386
0.000398076      0.00147386      0.00288034      0.00147386      0.000398076
```

```
0.133864      0.27903       0.357555      0.27903       0.133864
0.27903       0.548398      0.722427      0.548398      0.27903
0.357555      0.722427      1.            0.722427      0.357555
0.27903       0.548398      0.722427      0.548398      0.27903
0.133864      0.27903       0.357555      0.27903       0.133864
```

t = 2: weighted sum of 33100 damage states

Cascade t = 2:
ML-Scenarios

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.09862

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.02873

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.02873

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.02873

$$\begin{matrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{matrix}$$

0.02873

$$\begin{matrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{matrix}$$

0.02783

Cascade t = 2:
ML-Scenarios

0	0	0	0	0
0	0	1	0	0
0	1	1	0	0
0	0	0	0	0
0	0	0	0	0

0.00837

Etc…

Things are most likely to go either (relatively) well or catastrophically wrong.

Time Step t = 3

16104 secondary scenarios with P > 10^-6

Probability coverage = 0.8745

57523 routes with 16104 unique end points

Cascade Time Step t = 3: Marginal Probabilities

t = 2: weighted sum of 33100 damage states

```
0.133864     0.27903      0.357555     0.27903      0.133864
0.27903      0.548398     0.722427     0.548398     0.27903
0.357555     0.722427     1.           0.722427     0.357555
0.27903      0.548398     0.722427     0.548398     0.27903
0.133864     0.27903      0.357555     0.27903      0.133864
```

```
0.729317     0.773141     0.796751     0.773141     0.729317
0.773141     0.854677     0.909533     0.854677     0.773141
0.796751     0.909533     1.           0.909533     0.796751
0.773141     0.854677     0.909533     0.854677     0.773141
0.729317     0.773141     0.796751     0.773141     0.729317
```

t = 3: weighted sum of 16104 damage states

Cascade t = 3:
ML-Scenarios

1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1
1	1	1	1	1

0.61260

0	0	0	0	0
0	0	0	0	0
0	0	1	0	0
0	0	0	0	0
0	0	0	0	0

0.03097

0	0	0	0	0
0	0	0	0	0
0	1	1	0	0
0	0	0	0	0
0	0	0	0	0

0.00902

0	0	0	0	0
0	0	0	0	0
0	0	1	1	0
0	0	0	0	0
0	0	0	0	0

0.00902

0	0	0	0	0
0	0	0	0	0
0	0	1	0	0
0	0	1	0	0
0	0	0	0	0

0.00902

0	0	0	0	0
0	0	0	0	0
0	0	1	0	0
0	0	1	0	0
0	0	0	0	0

0.00902

Cascade t = 3:
ML-Scenarios

```
  0         0         0         0         0
  0         0         1         0         0
  0         1         1         0         0
  0         0         0         0         0
  0         0         0         0         0
```

0.00263

Etc…

Things are very much likely to go catastrophically wrong.

Time Step t = 4

7069 secondary scenarios with P > 10^-6

Probability coverage = 0.8529

```
0.919999    0.931846    0.938323    0.931846    0.919999
0.931846    0.95475     0.971239    0.95475     0.931846
0.938323    0.971239    1.          0.971239    0.938323
0.931846    0.95475     0.971239    0.95475     0.931846
0.919999    0.931846    0.938323    0.931846    0.919999
```

```
1    1    1    1    1              0    0    0    0    0
1    1    1    1    1              0    0    0    0    0
1    1    1    1    1              0    0    1    0    0
1    1    1    1    1              0    0    0    0    0
1    1    1    1    1              0    0    0    0    0
```

0.77874

0.00973

Probability Sort and Cut-Offs

Time Step	Cut-off = 10^-6	Cut-off = 10^-7
1	0.9995 (1094)	0.9999 (2459)
2	0.9177 (33100)	0.9754 (111430)
3	0.8745 (16104)	0.9608 (61476)
4	0.8530 (7069)	0.9527 (32864)

Conclusion

- The Probability Sort algorithm can be used to study cascading effects/domino models.
- The Probability Sort algorithm takes advantage of the fact that active probability components are often in an exponential small region of the state space.
- The Probability Sort algorithm lies on a continuum between a simple ML-estimation and a full Bayesian probability analysis.

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PROJECT

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TU Delft

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