Natural hazards risk assessment using Bayesian networks

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**Problem statement**

- Experienced damages from natural hazards increase worldwide
- (Financial) resources for protection are limited
- Suitable tools are required for risk assessment & management
- A risk assessment (& management) framework and tool should have the following properties:
  - Include entire systems & networks with dependent elements
  - It should allow for combining different models and data
  - It should be applicable to different types of hazards
  - Easy to understand and communicate
Contents

- Presentation of a general framework
- Short introduction to Bayesian networks (BN)
- Demonstration of the capabilities of BN for natural hazards risk assessment
A general framework

System exposure

System vulnerability

System robustness

Direct consequences

Indirect consequences

Indicators

Actions
A general framework

- Multidisciplinary:

  Natural scientist

  Engineer

  Economist

  System exposure

  System vulnerability

  System robustness

  Indirect consequences

  Direct consequences
Bayesian networks

- Probabilistic models based on directed acyclic graphs
- Represent the joint probability distribution of a set of variables
- Efficient due to the factoring of the joint probability distribution into conditional (local) distributions given the parents

\[
P(x_1, x_2, x_3) = P(x_1)P(x_2 | x_1)P(x_3 | x_1)
\]

General:
\[
P(x) = P(x_1, \ldots, x_n) = \prod_{i=1}^{n} P(x_i | pa_i)
\]
Bayesian networks

- Facilitates updating when additional information (evidence) is available

\[
P(x_1, x_3 | e) = \frac{P(x_1, e, x_3)}{P(e)} = \frac{P(x_1)P(e| x_1)P(x_3| x_1)}{\sum_{x_1} P(x_1)P(e| x_1)}
\]

- BN are (in general) restricted to variables with discrete states
Example – Rockfall hazard risk rating system
Example – Rockfall hazard risk rating system

- A typical rating system from the literature:
- Nine indicators are considered for rockfall risk along a road:
  - Slope height
  - Ditch effectiveness
  - Average vehicle risk (the traffic volume)
  - Decision sight distance
  - Roadway width
  - Slope Mass Ratio (A description of the geological character)
  - Block size / Volume of rock-fall per event
  - Annual rainfall and freezing periods
  - Observed rock-fall frequency
- Each indicator has 4 intervals
- Points are assigned for each indicator: 3, 9, 27 or 81
- The points from all indicators are summed up
### Example – Rockfall hazard risk rating system

<table>
<thead>
<tr>
<th>Category</th>
<th>Rating criteria by score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Points 3</td>
</tr>
<tr>
<td>Slope height</td>
<td>7.5 m</td>
</tr>
<tr>
<td>Ditch effectiveness</td>
<td>Good catchment</td>
</tr>
<tr>
<td>Average vehicle risk (% of time)</td>
<td>25%</td>
</tr>
<tr>
<td>Decision sight distance (% of design value)</td>
<td>Adequate (100%)</td>
</tr>
<tr>
<td>Roadway width (including paved shoulders)</td>
<td>13.20 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geologic characteristics Case 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural condition</td>
</tr>
<tr>
<td>Friction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geologic characteristics Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural condition</td>
</tr>
<tr>
<td>Difference in erosion rates</td>
</tr>
<tr>
<td>Block size</td>
</tr>
<tr>
<td>Volume of rockfall per event</td>
</tr>
<tr>
<td>Rockfall history</td>
</tr>
</tbody>
</table>
Example – BN for hazard rating

- Use the same indicators to model the rockfall risk using a BN
Example – BN for hazard rating

- Block size
- Annual rainfall
- Slope mass rating
- Rockfall frequency
- Observed rockfall frequency
- Rock detached?
- Volume of detached rocks
- Direct impact on car
- Impact strength
- Road width
- Average vehicle
- Indirect mega cons.
- Direct mega cons.
- Road closure
- Road damaged
- People killed/injured
- Deaths/injuries
- Indirect accident
- Indirect accident magnitude
- Sight distance
- Ditch effectiveness
- Impact on road
- Impact energy
- Slope height

Exposure
Resistance
Robustness
A part of the net – exposure

- The causal relations are correctly modelled
- As a consequence, the dependencies between indicators is consistently accounted for
- The node rock-fall frequency has five states, each representing a different exceedance frequency curve
A part of the net – exposure

- The node “Volume of detached rocks” (child of rock-fall frequency)

<table>
<thead>
<tr>
<th>Volume of rock</th>
<th>Curve 1</th>
<th>Curve 2</th>
<th>Curve 3</th>
<th>Curve 4</th>
<th>Curve 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.97</td>
<td>0.99</td>
<td>0.99</td>
<td>0.999</td>
<td>0.999839</td>
</tr>
<tr>
<td>0 - 0.3</td>
<td>0.017</td>
<td>0.0047</td>
<td>0.0076</td>
<td>6.30E-04</td>
<td>1.00E-04</td>
</tr>
<tr>
<td>0.3 - 1</td>
<td>0.01</td>
<td>0.004</td>
<td>0.002</td>
<td>3.00E-04</td>
<td>5.00E-05</td>
</tr>
<tr>
<td>1 - 3</td>
<td>0.002</td>
<td>0.001</td>
<td>3.00E-04</td>
<td>5.00E-05</td>
<td>1.00E-05</td>
</tr>
<tr>
<td>3 - 10</td>
<td>0.001</td>
<td>3.00E-04</td>
<td>1.00E-04</td>
<td>2.00E-05</td>
<td>1.00E-06</td>
</tr>
</tbody>
</table>

Daily probability of rock detachment

![Graph showing the relationship between volume and daily probability of rock detachment]
Example – BN for hazard rating

Including consequences in the net
Comparing the ratings

Table 1. Investigated cases.

<table>
<thead>
<tr>
<th>Cases</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope height</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Ditch effect.</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Vehicles</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Sight distance</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Roadway width</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>SMR</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
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<tr>
<td>Block size</td>
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<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Rain &amp; Freezing</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Observed freq.</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Comparing the ratings

- Results for some example cases:
Comparing the ratings

- Results for some example cases:

```
Case | Normalized scoring
-----|------------------
A    | 100
B    | 10
C    | 100
D    | 10
E    | 100
F    | 10
G    | 100
H    | 10
```

Graph showing normalized scoring for cases A to H, with a highlighted section for Case B.
## Comparing the ratings

**Table 1. Investigated cases.**

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<tr>
<td>Sight distance</td>
<td>1</td>
<td>1</td>
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Comparing the ratings

• Results for some example cases:

![Graph showing normalized scoring for different cases with Case E highlighted]
# Comparing the ratings

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<td>4</td>
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<td>3</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Discussion & conclusions

- The BN provides a simple but consistent model for risk assessment
- The BN can consistently include contradicting information
- The BN can cope with the unavailability of indicators
- Different levels of detailing can be incorporated into a common model – e.g. an improved geological model could be included in the example
- The net can be extended to include mitigation actions for optimisation purposes
- The net can be easily extended to model an entire road link
• Thank you for your attention!

• Questions?