



Pacific Earthquake Engineering Research Center

2011 PEER ANNUAL MEETING

September 30 - October 1, 2011

Berkeley, California

Bayesian network for infrastructure seismic risk assessment and decision support

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Armen Der Kiureghian

University of California, Berkeley

Daniel Straub

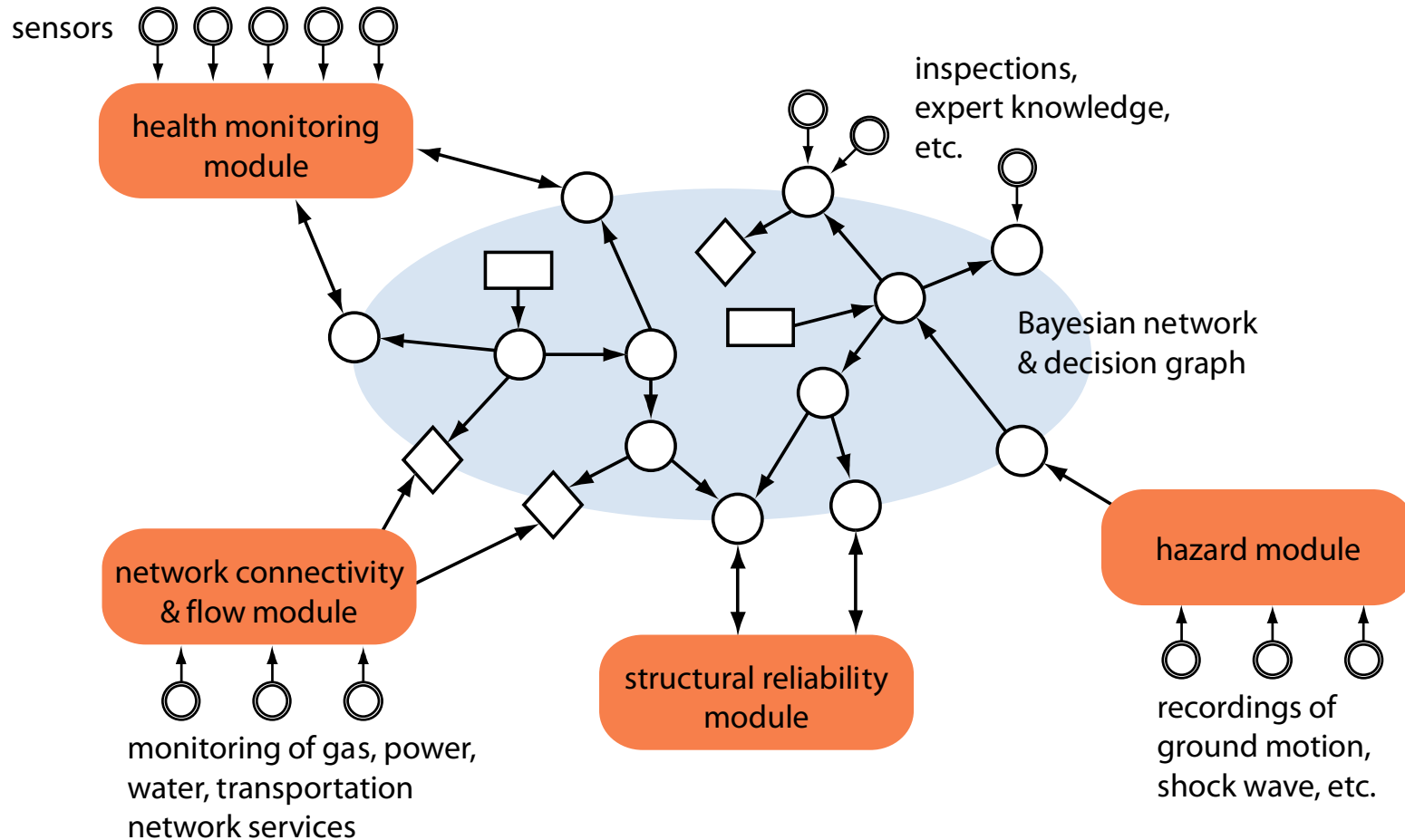
Technical University of Munich

Research motivation

- ▶ **Civil infrastructure systems:**
 - ▶ Are logistical backbones of societies
 - ▶ Have far-reaching consequences if disrupted
 - ▶ Are vulnerable to natural/man-made hazards
- ▶ **Risk assessment of spatially-distributed infrastructure differs from point-site components:**
 - ▶ Higher rate of exposure
 - ▶ Subject to multitude of hazards
 - ▶ Requires consideration of random field effects
 - ▶ Requires application of system analysis methods to assess system reliability
- ▶ **Long-term goal: Bayesian network framework for seismic infrastructure risk assessment & decision-support**
 - ▶ Before an event
 - ▶ Immediately following an event
 - ▶ In the longer term post-event recovery phase

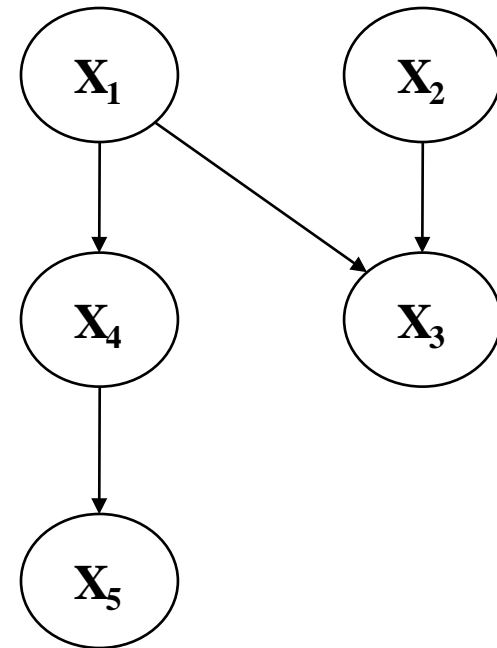


Research motivation



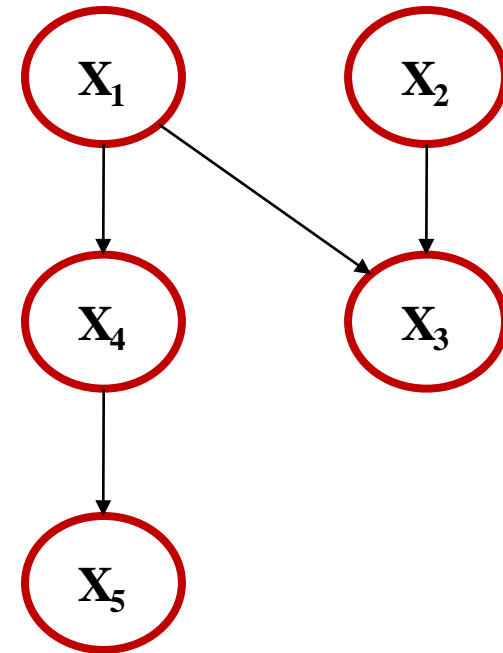
What is a BN?

- ▶ A probabilistic graphical model that encodes a set of random variables and their probabilistic (in)dependencies:
 - ▶ A set of variables (nodes) and directed links
 - ▶ Each variable has mutually exclusive states
 - ▶ To each variable we attach a CPT representing discrete probabilities
- ▶ Facilitate information updating
- ▶ Highly demanding of computer memory



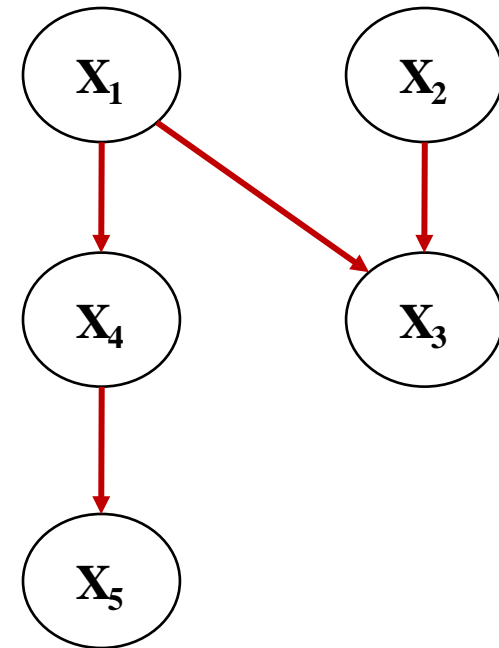
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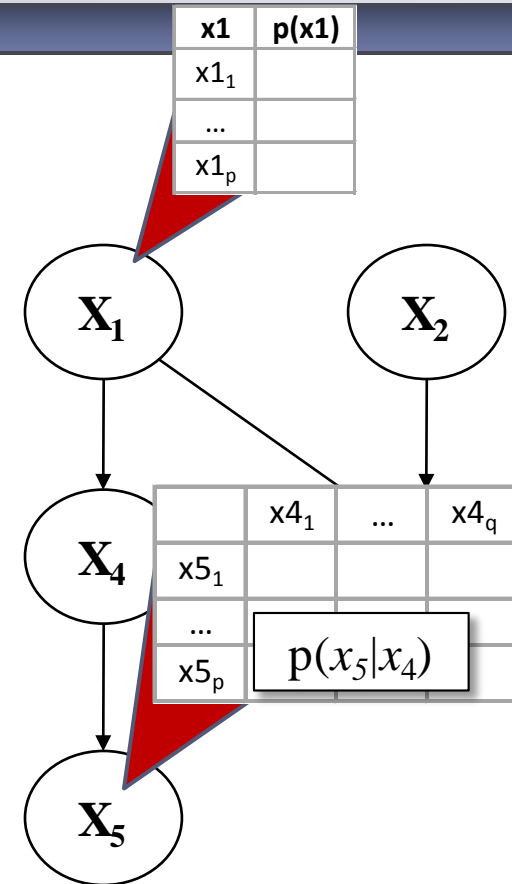
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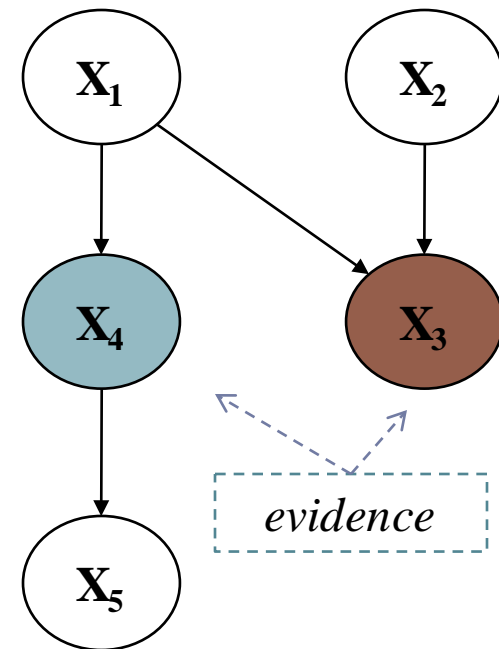
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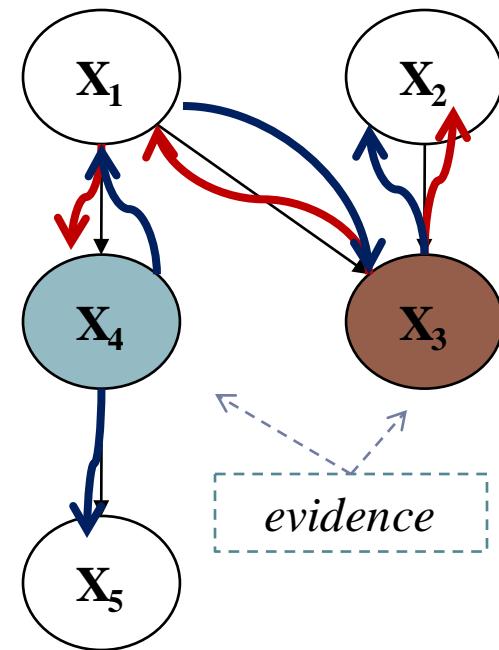
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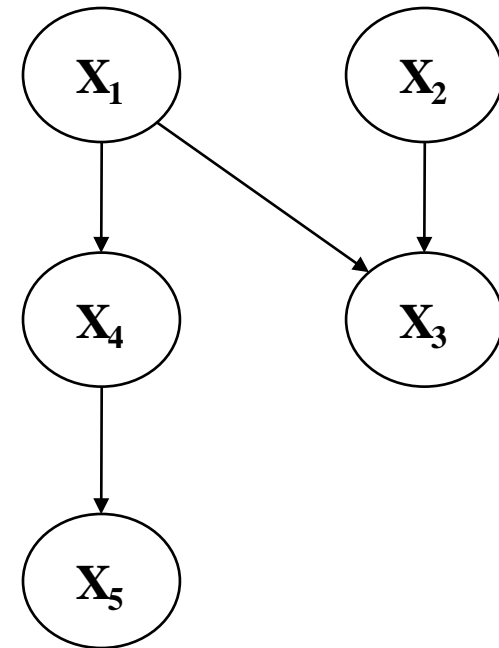
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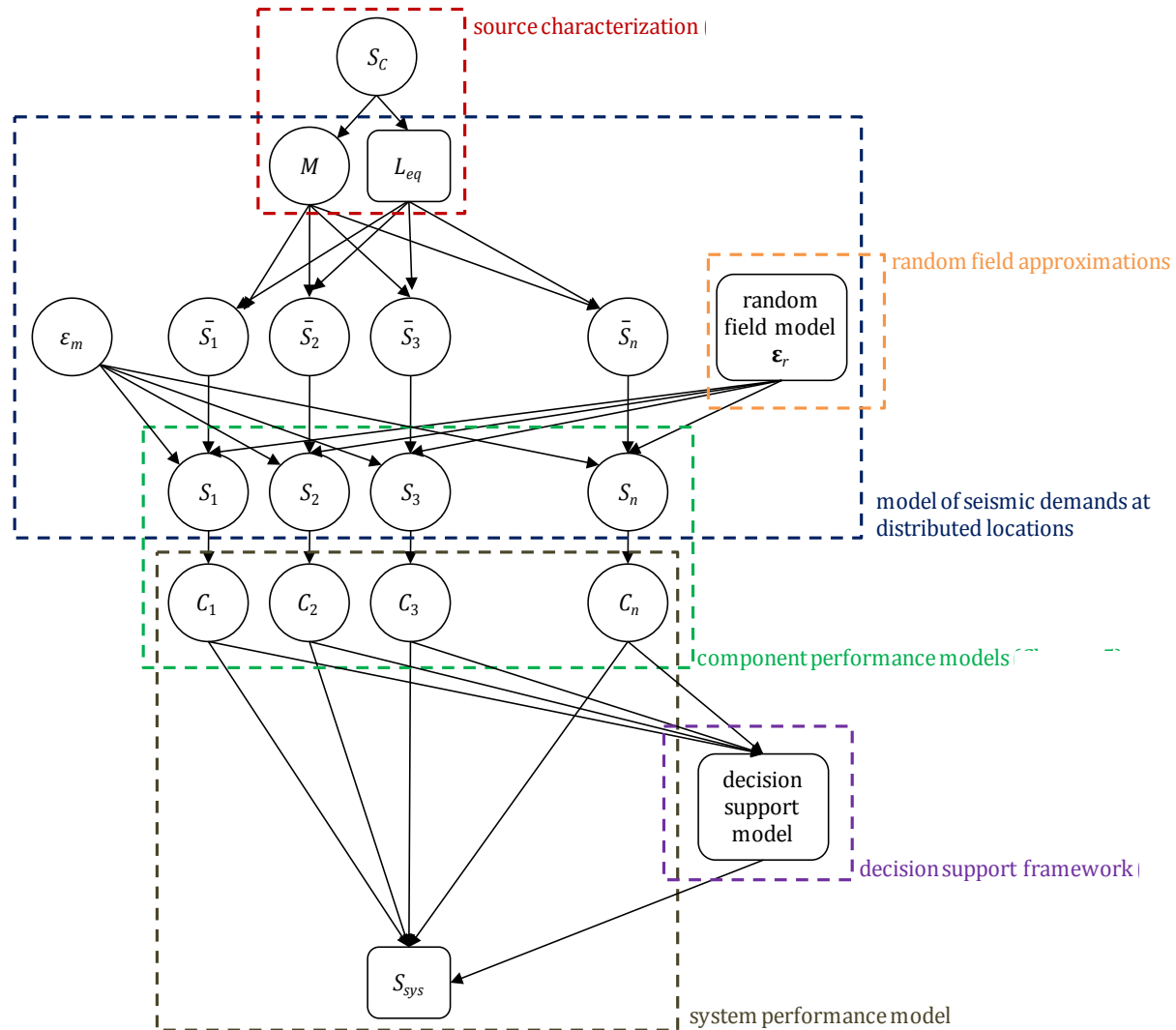


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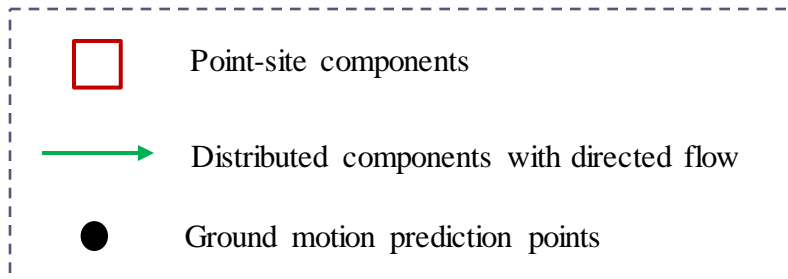
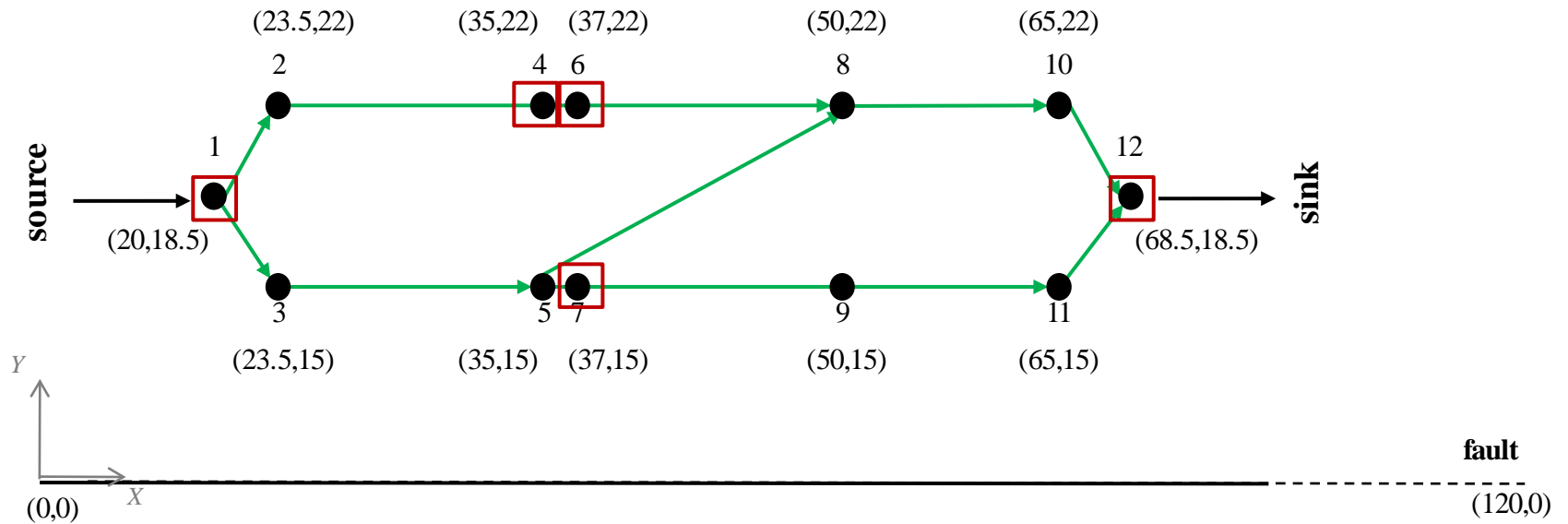
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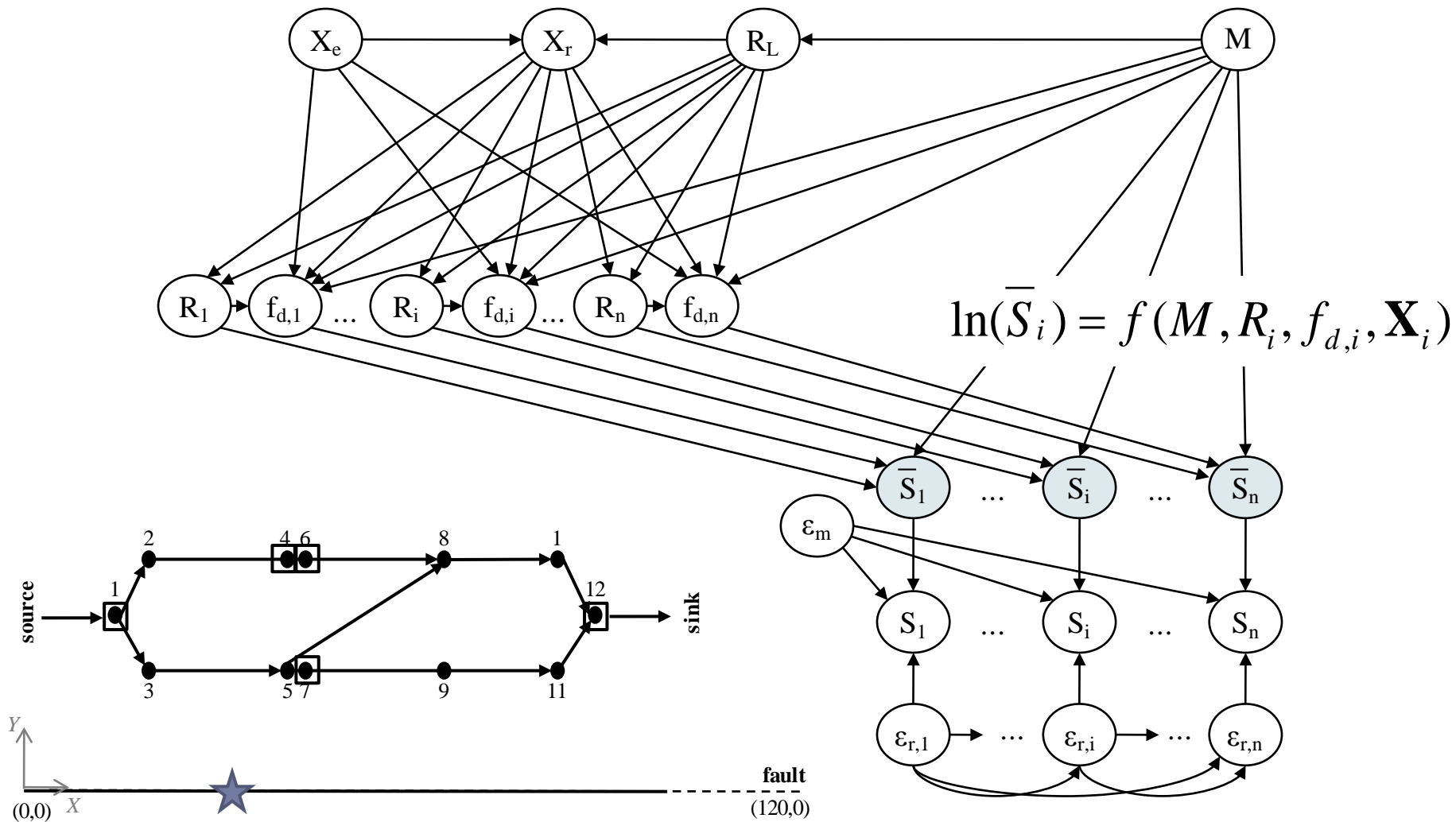
Big Picture: BN for seismic infrastructure risk assessment and decision support



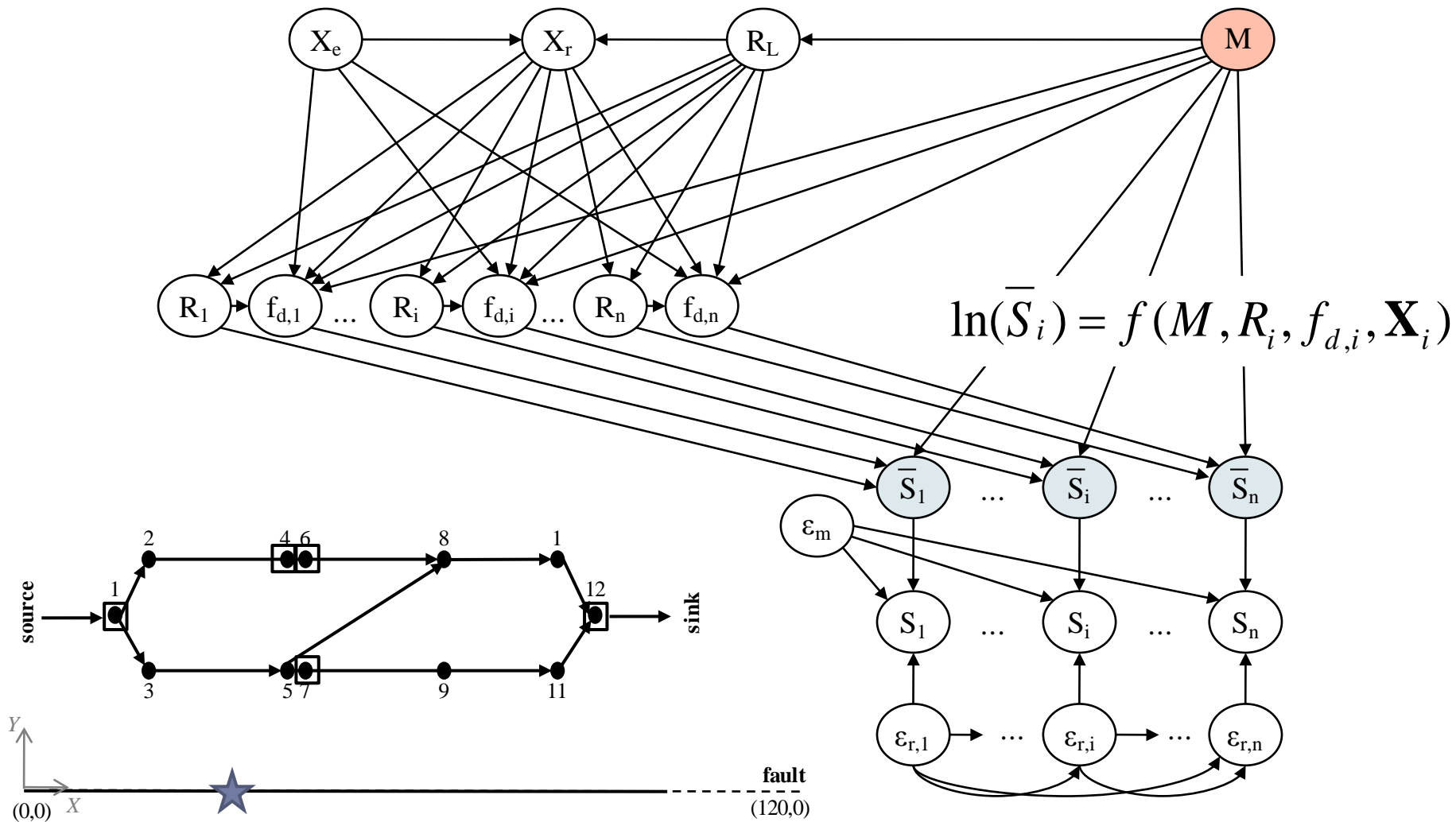
Example



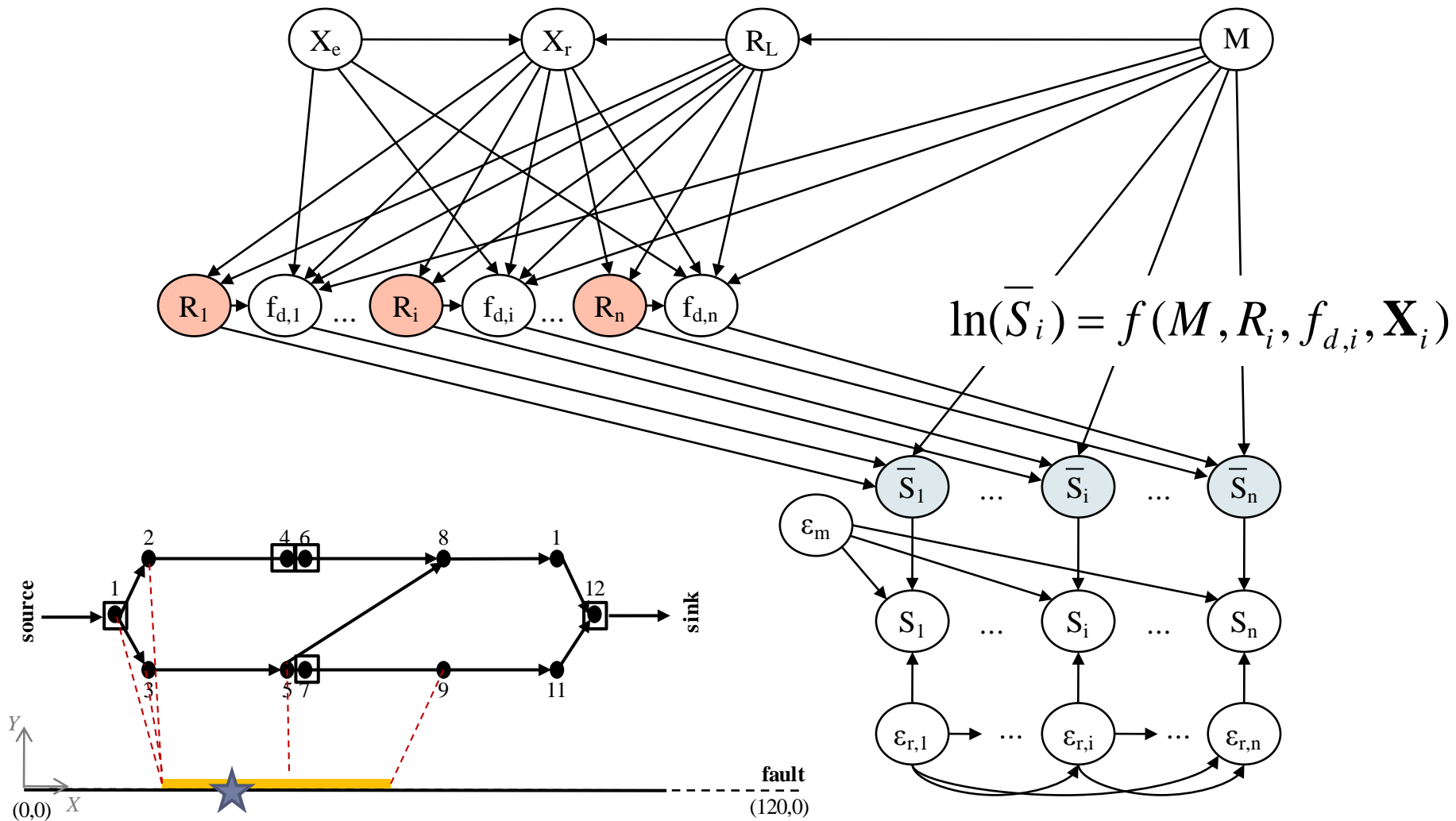
(1) Seismic Demand Model



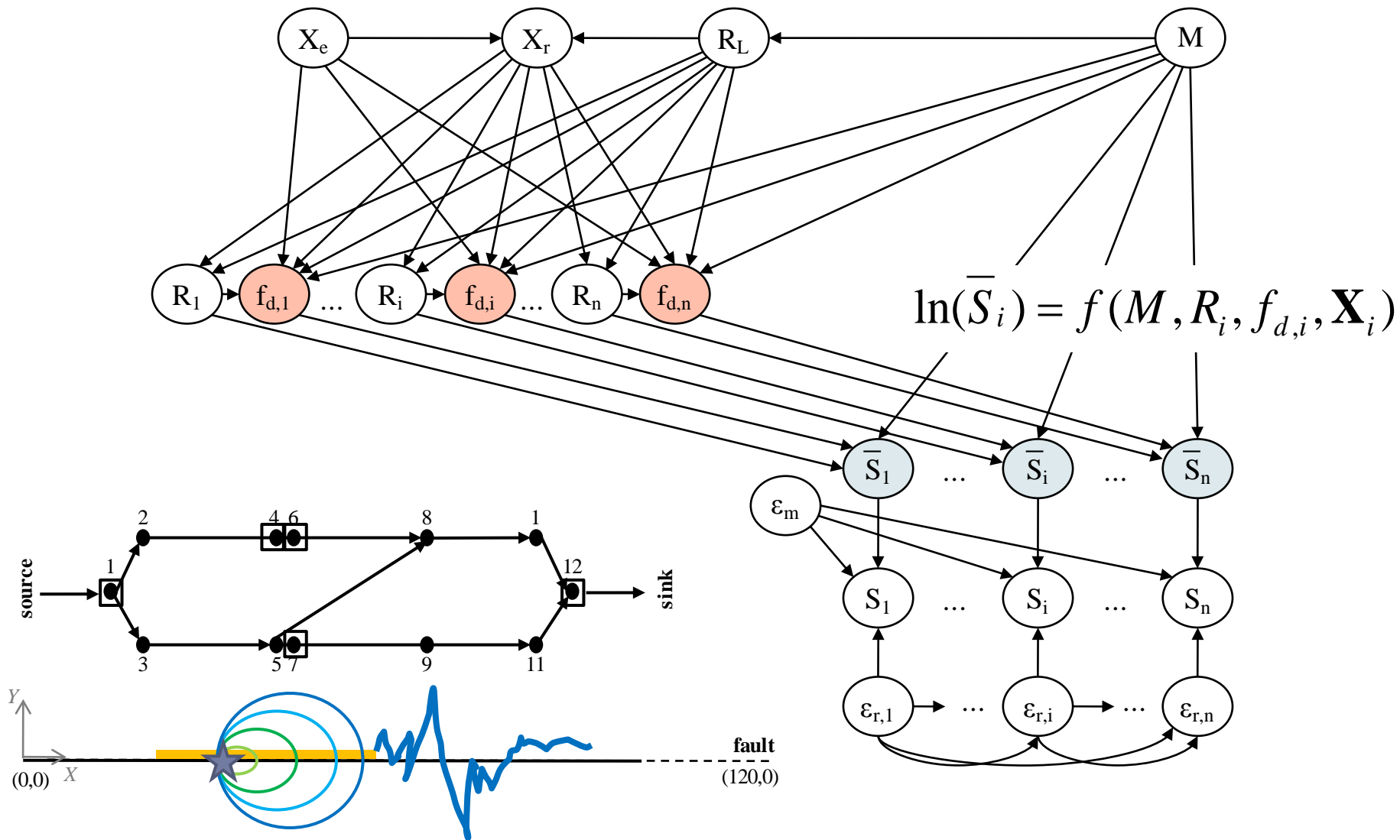
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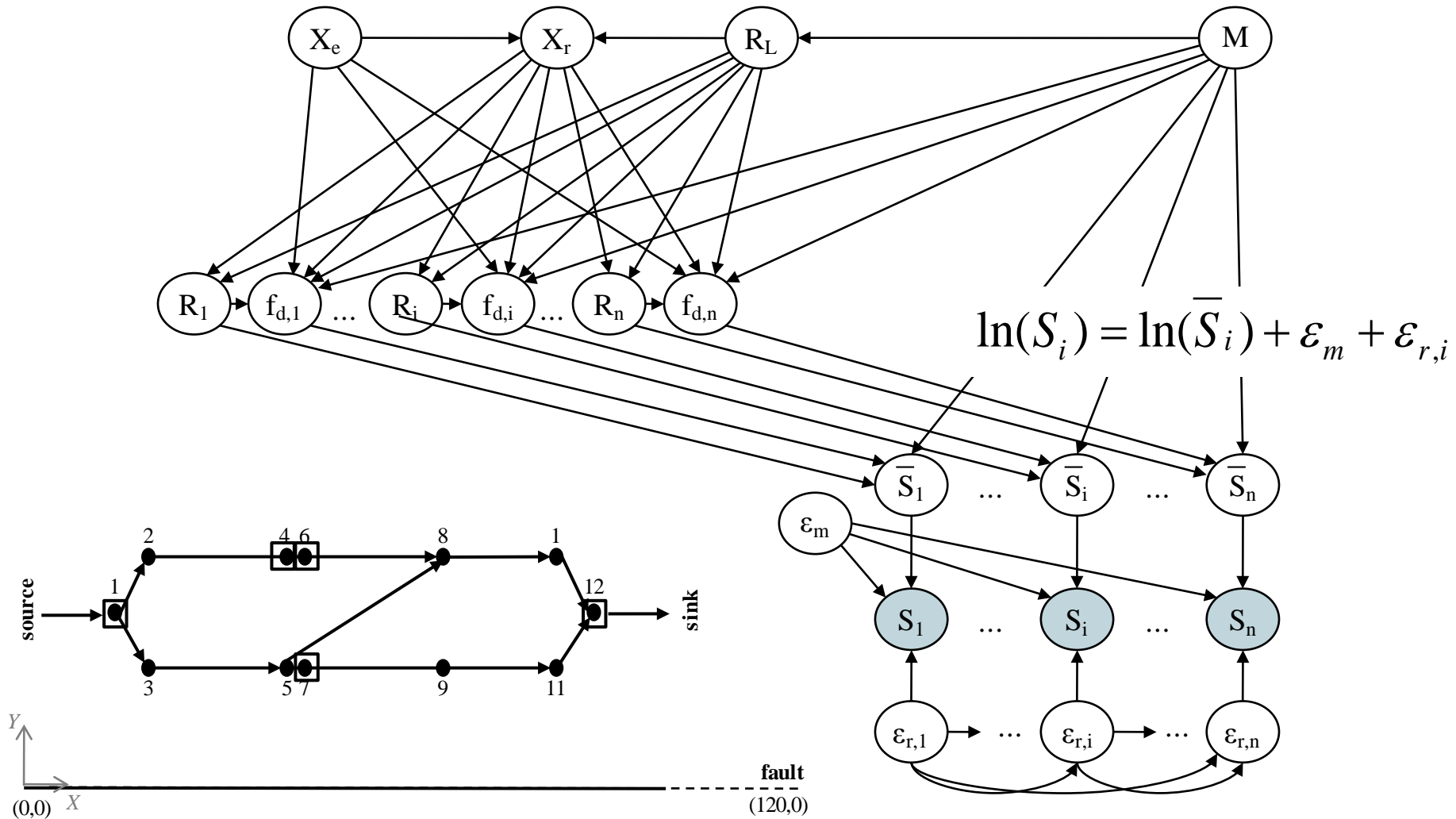
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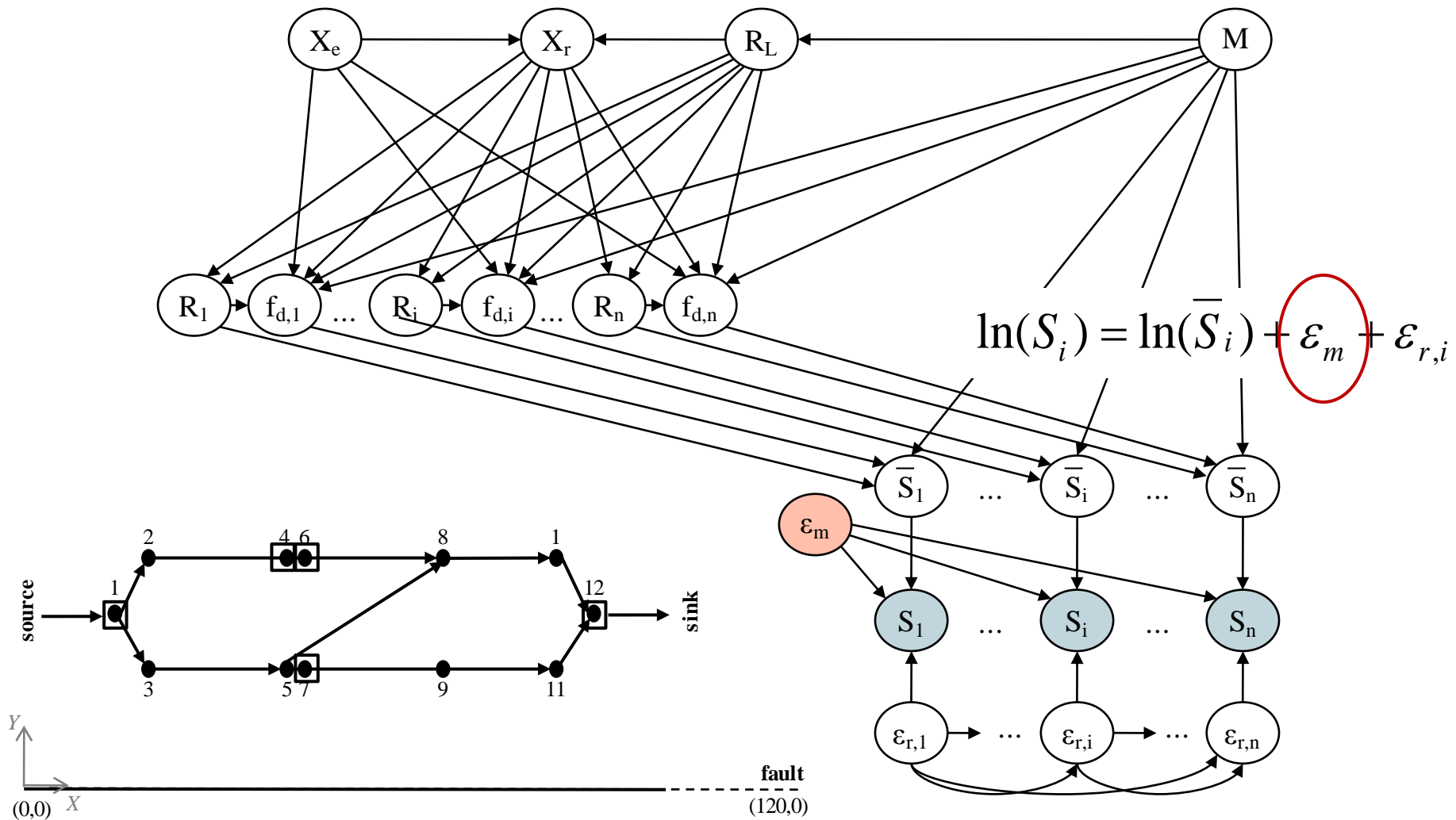
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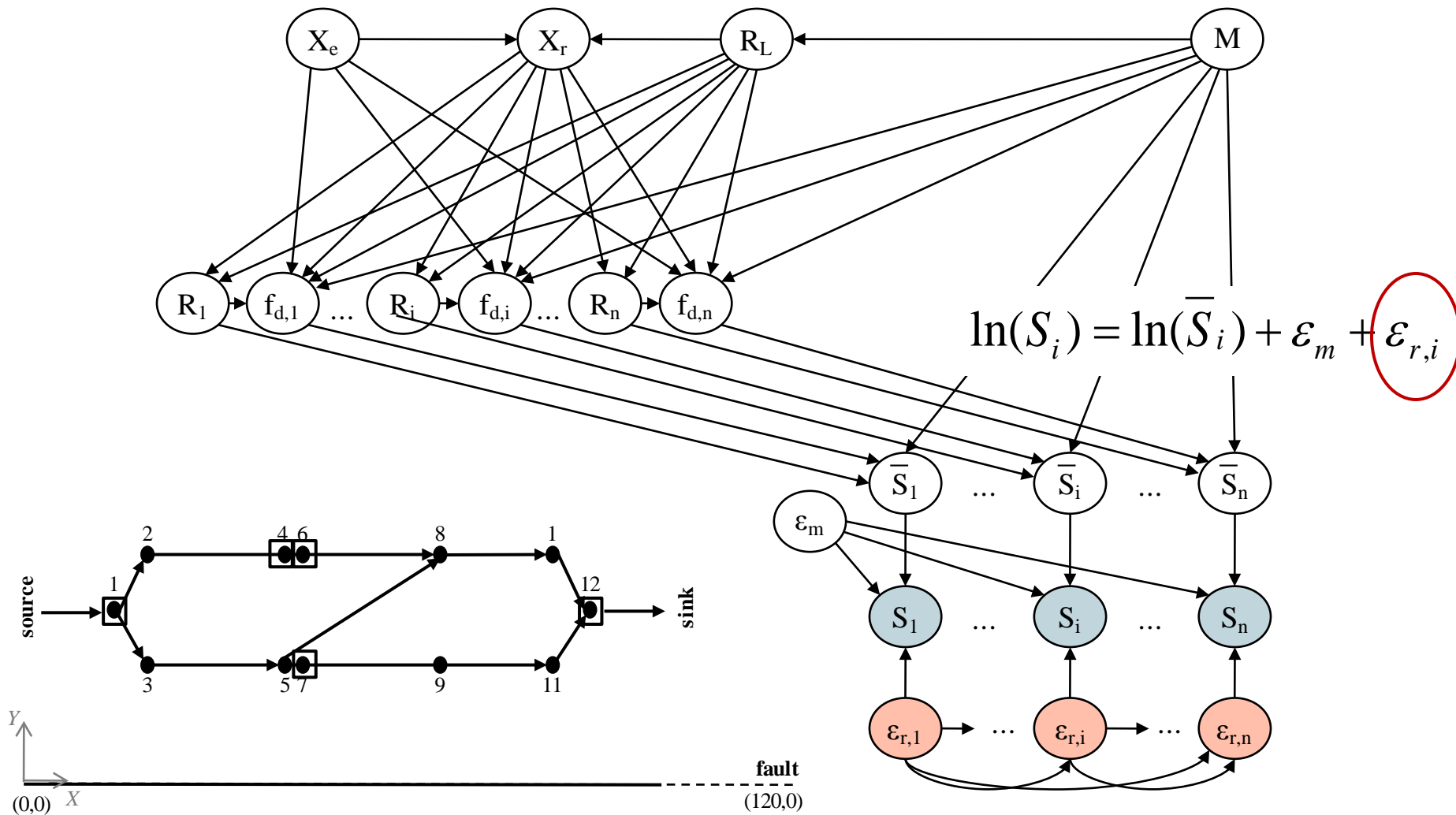
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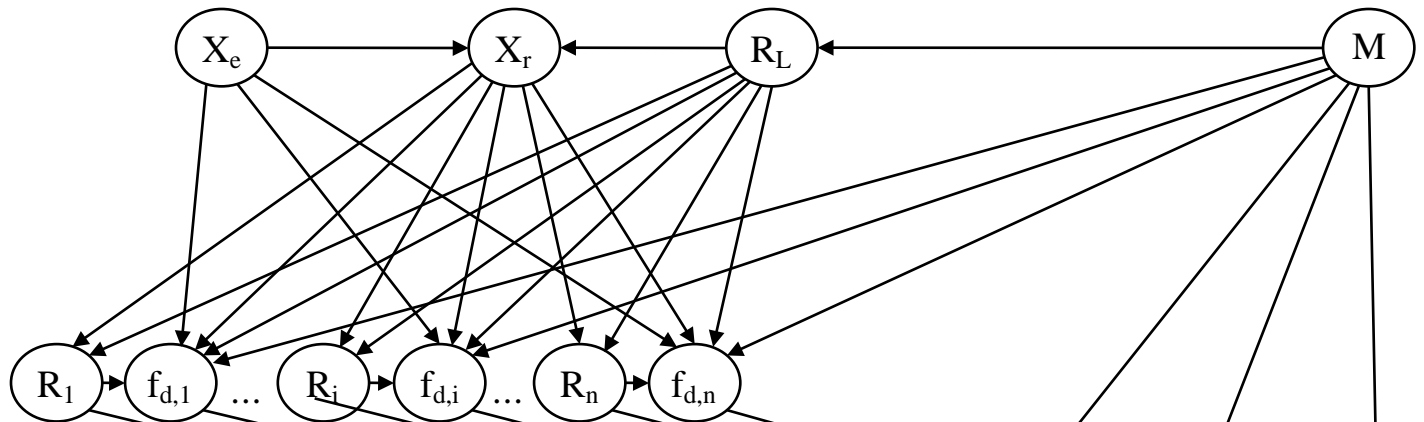
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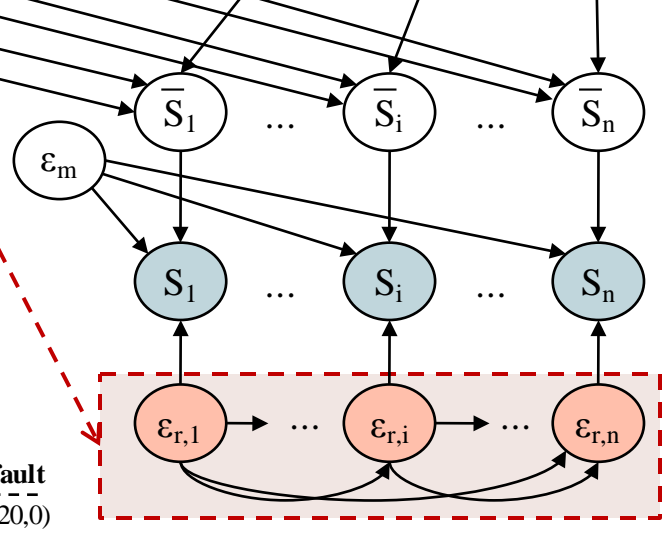
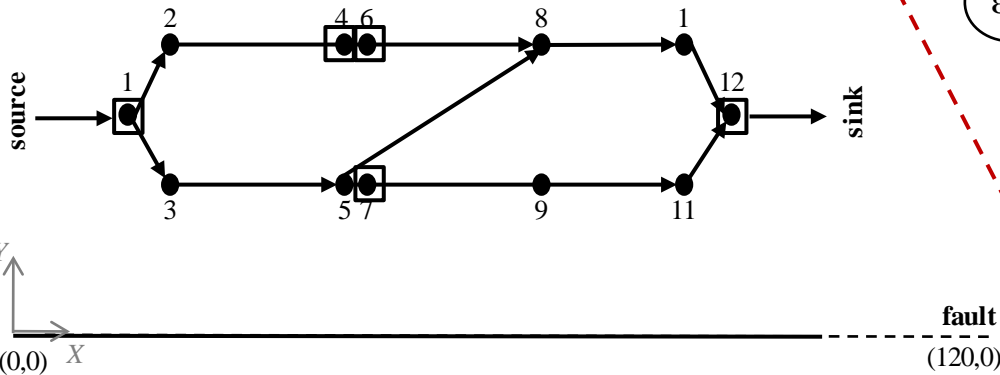
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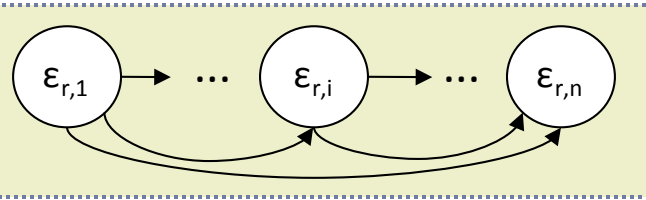
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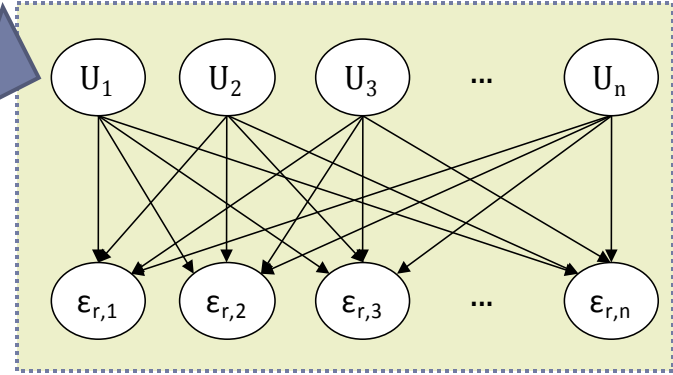
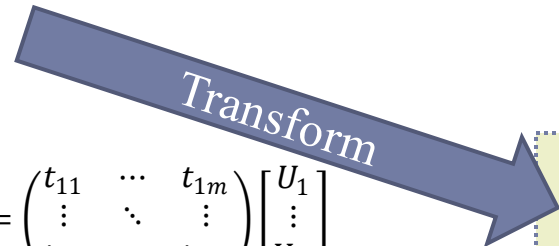
Must be modeled as Gaussian random field \rightarrow
 Densely connected BN \rightarrow
 Computationally demanding (possibly intractable)



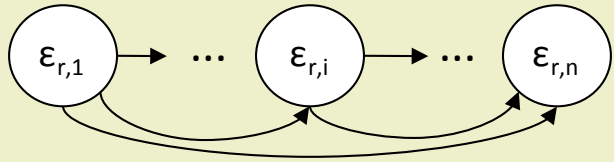
(1) Seismic demand model: Approximation of error correlation



$$\epsilon = \mathbf{TU} = \begin{pmatrix} t_{11} & \dots & t_{1m} \\ \vdots & \ddots & \vdots \\ t_{n1} & \dots & t_{nm} \end{pmatrix} \begin{bmatrix} U_1 \\ \vdots \\ U_m \end{bmatrix}$$

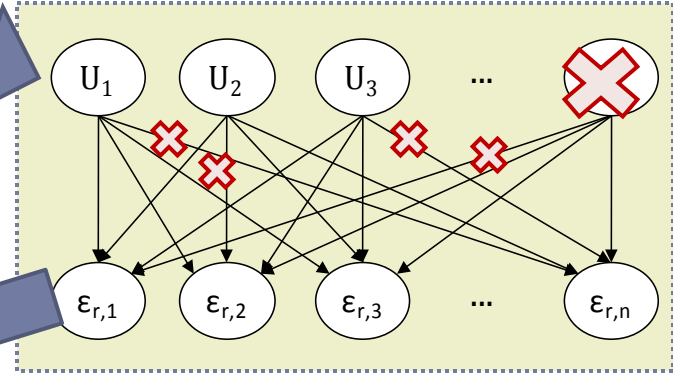


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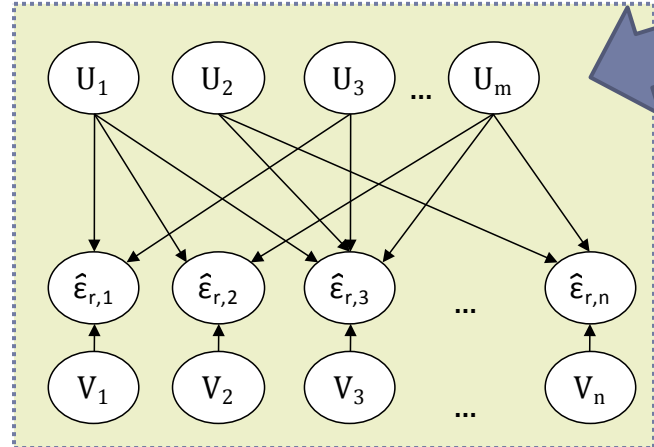
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Transform

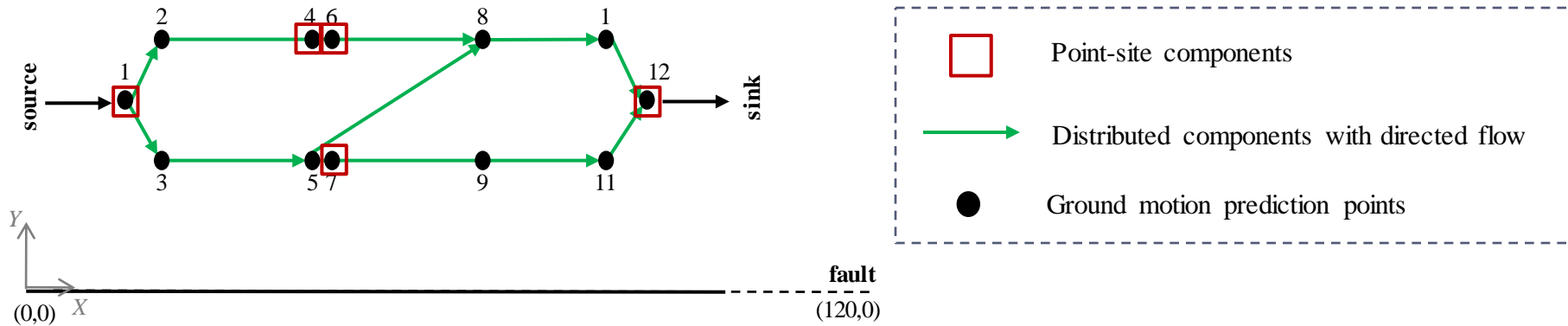


Eliminate nodes/links

$$\hat{\epsilon} = \mathbf{SV} + \hat{\mathbf{T}}\mathbf{U} = \begin{pmatrix} s_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & s_n \end{pmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_n \end{bmatrix} + \begin{pmatrix} \hat{t}_{11} & \dots & \hat{t}_{1m} \\ \vdots & \ddots & \vdots \\ \hat{t}_{n1} & \dots & \hat{t}_{nm} \end{pmatrix} \begin{bmatrix} U_1 \\ \vdots \\ U_m \end{bmatrix}$$



(2) Component Performance



Point site components:

seismic demand model

$S_1 \quad \dots \quad S_i \quad \dots \quad S_n$

$C \quad \dots \quad C_i \quad \dots \quad C_n$

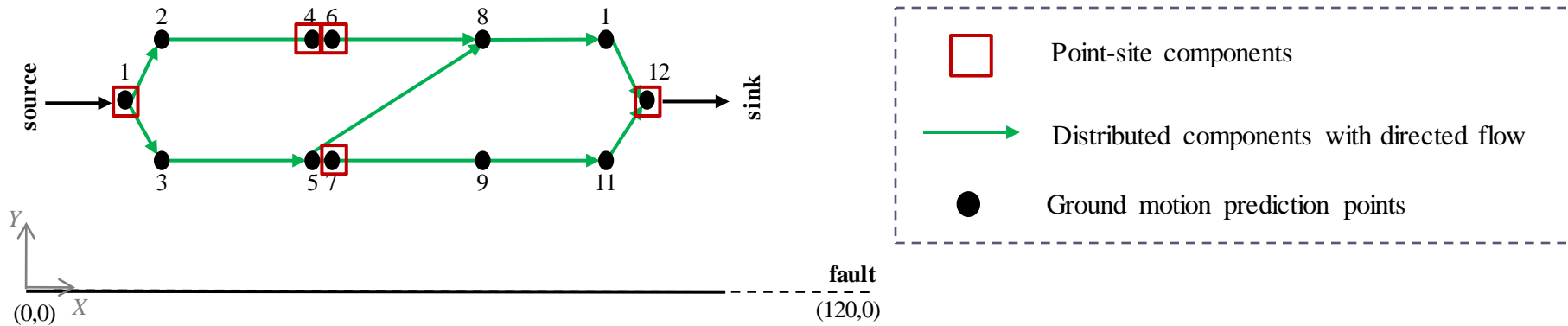
Distributed components:

seismic demand model

$S_1 \quad S_2 \quad \dots \quad S_{i-1} \quad S_i \quad S_{i+1} \quad \dots \quad S_{n-1} \quad S_n$

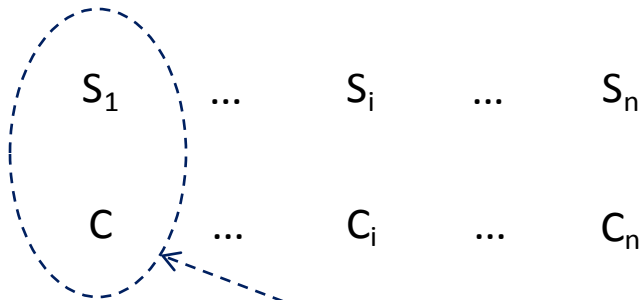
$C_{1,2} \quad \dots \quad C_{i-1,i} \quad C_{i,i+1} \quad \dots \quad C_{n-1,n}$

(2) Component Performance



Point site components:

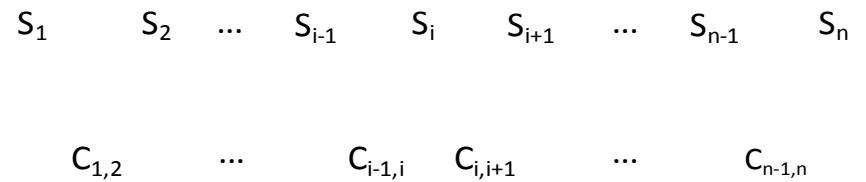
seismic demand model



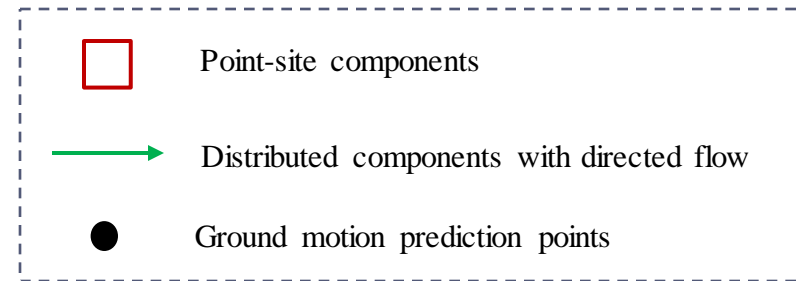
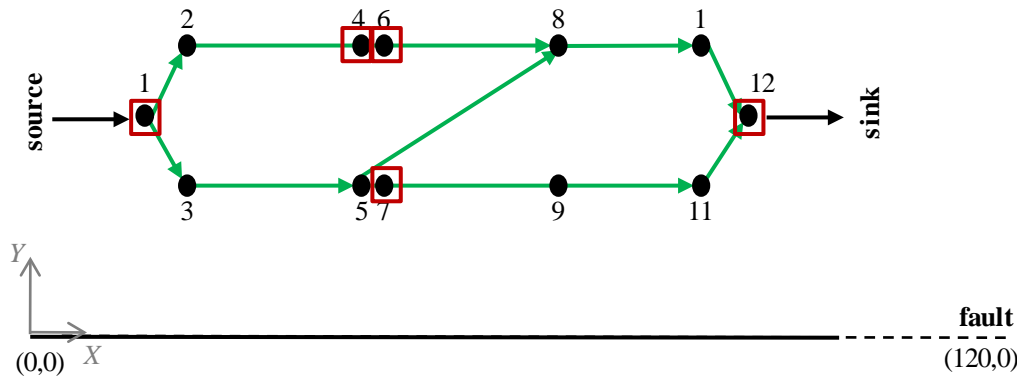
CPTs specified using fragility functions
(or other analysis methods)

Distributed components:

seismic demand model

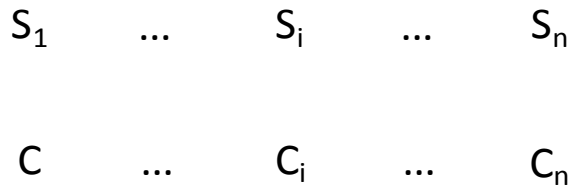


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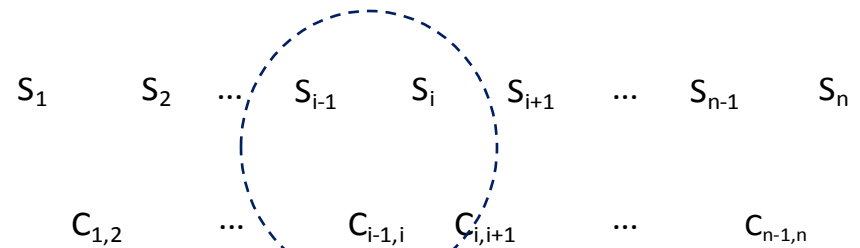
Point site components:

seismic demand model



Distributed components:

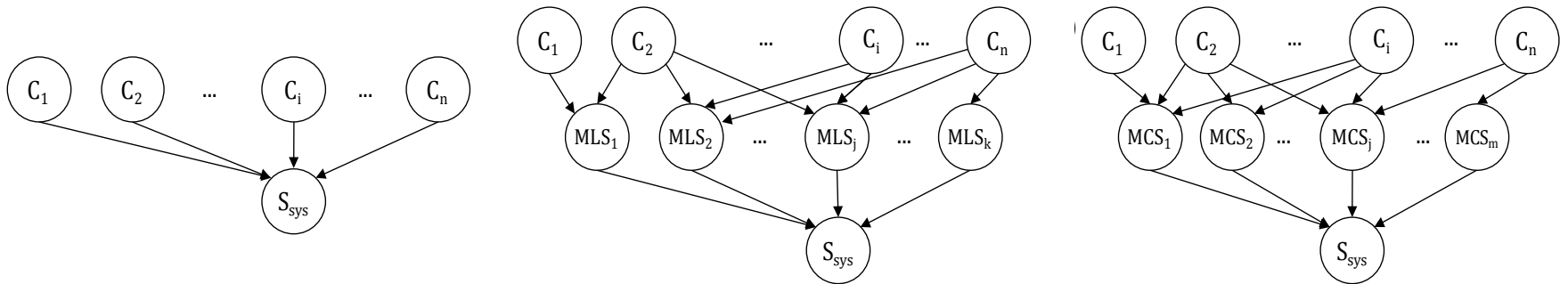
seismic demand model



CPTs specified using performance functions and assuming non-homogenous Poisson process

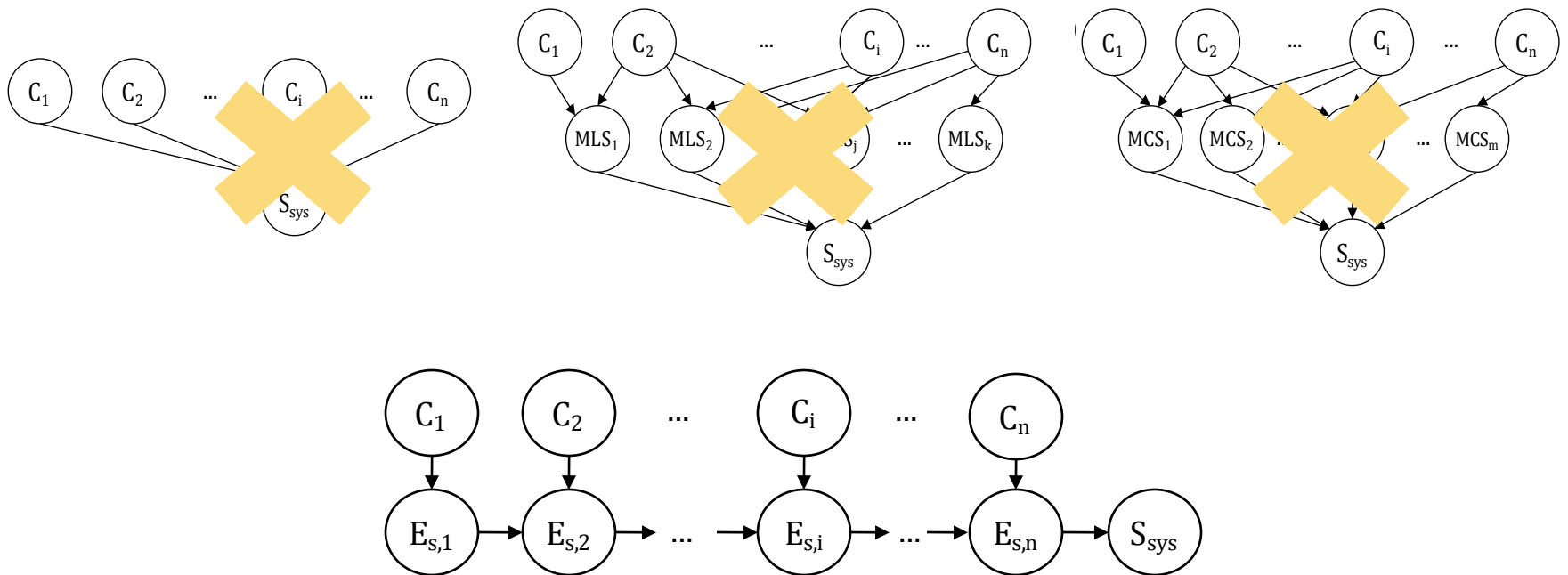
(3) System performance:

- ▶ A collection of system performance BN formulations developed based on:
 - ▶ Adaptation of classical systems analysis methods
 - ▶ Ease of facilitating third party interaction
 - ▶ Issues related to computational efficiency:



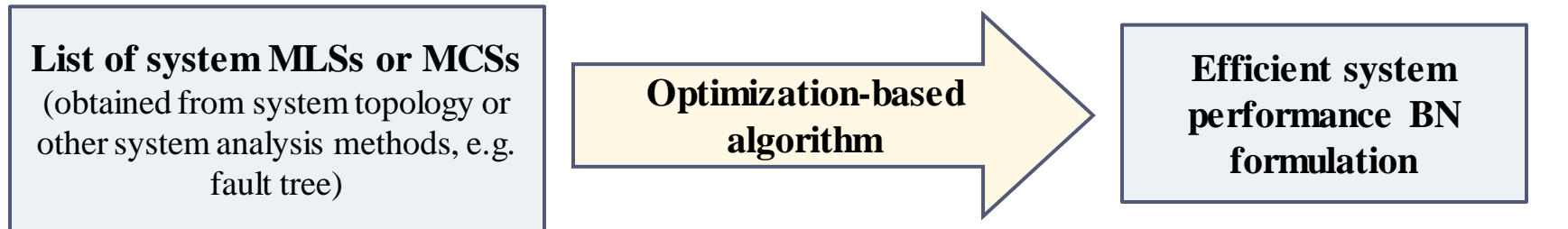
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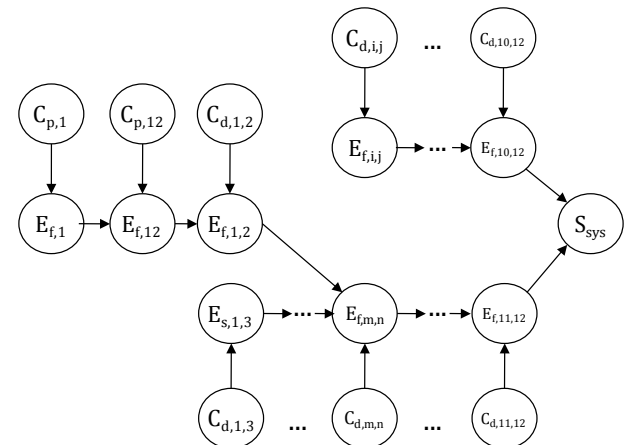


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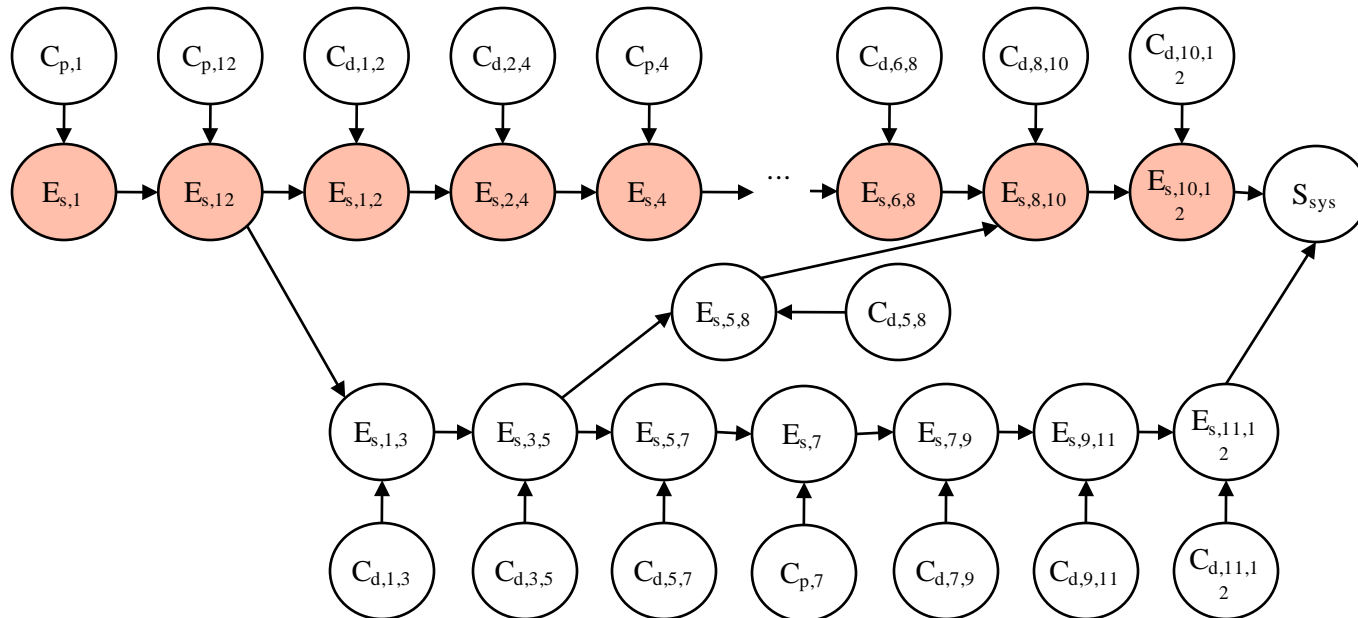
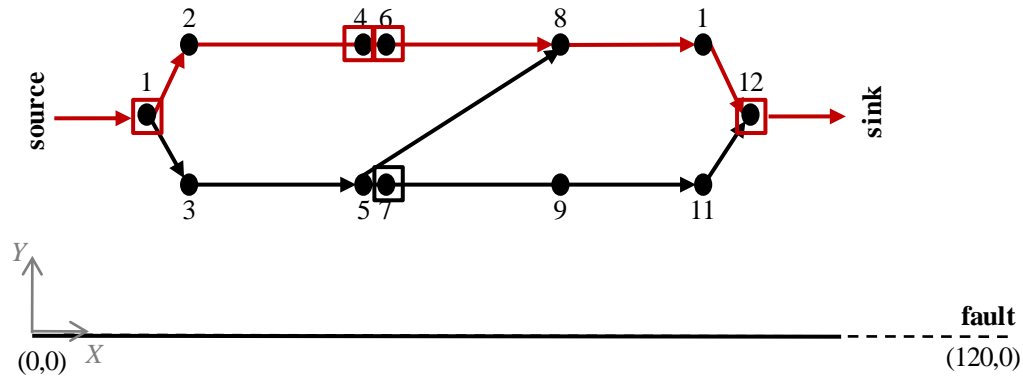
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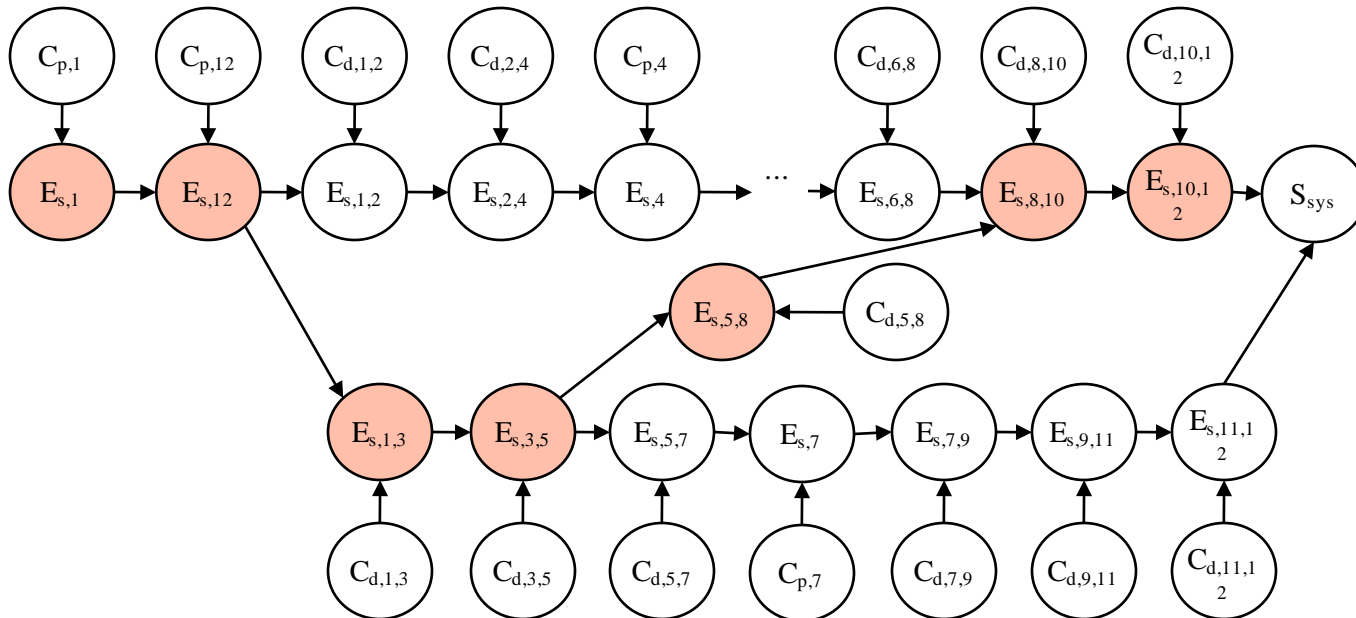
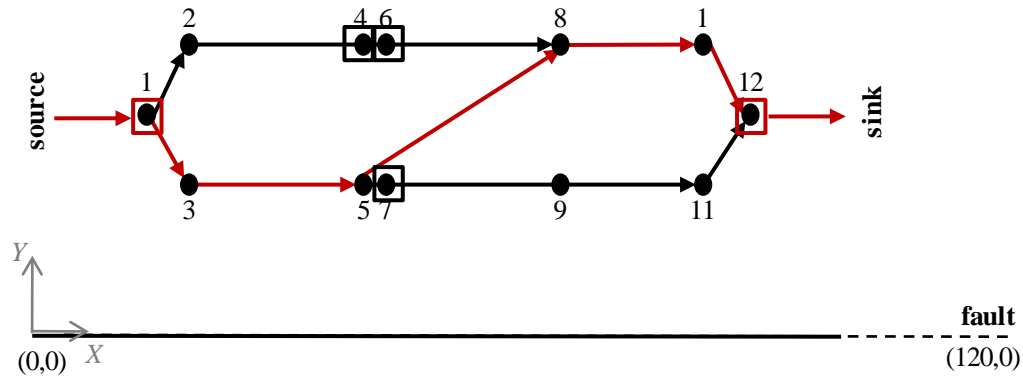
- ▶ Heuristically augmented binary optimization algorithm:
 - ▶ Automates generation of efficient formulations
 - ▶ Increases computational efficiency by order(s) of magnitude



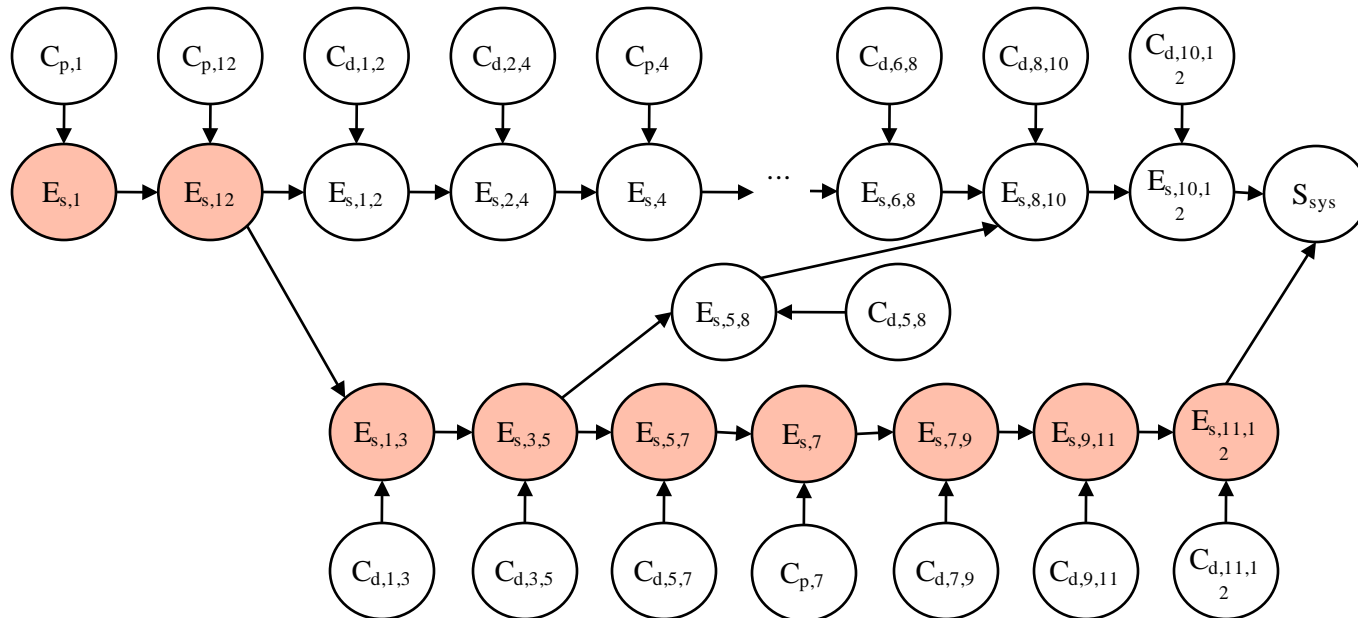
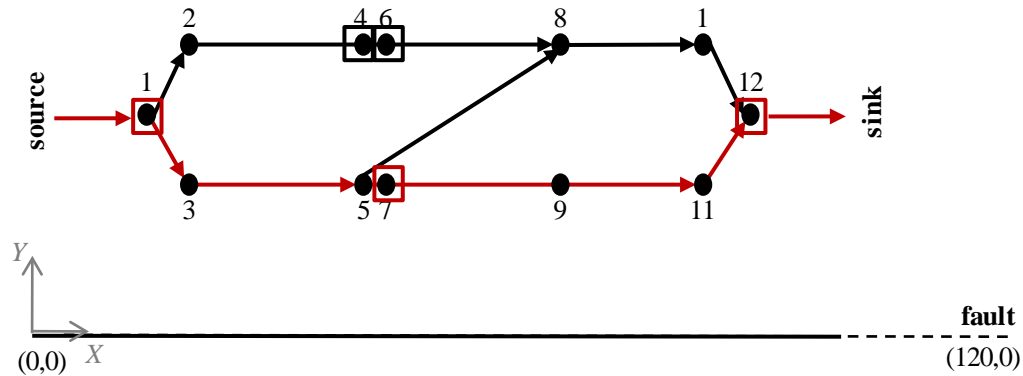
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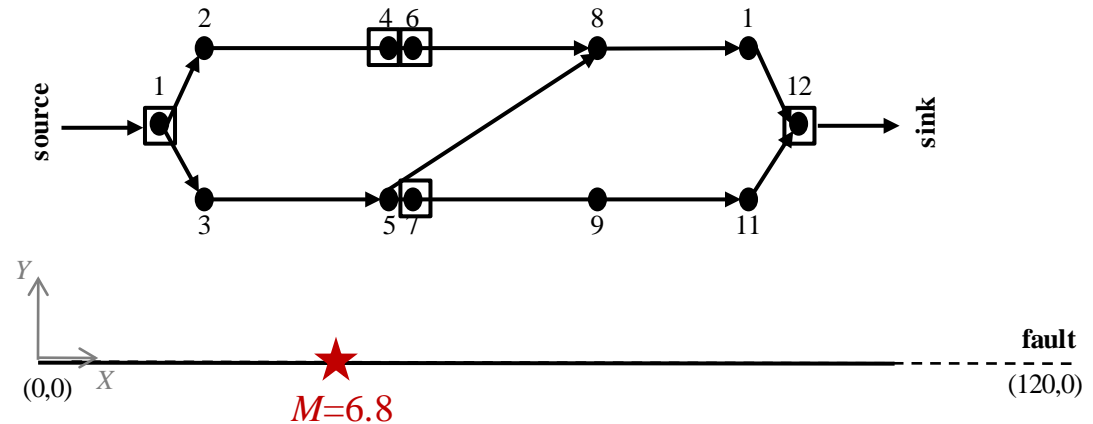


Example: Information Updating

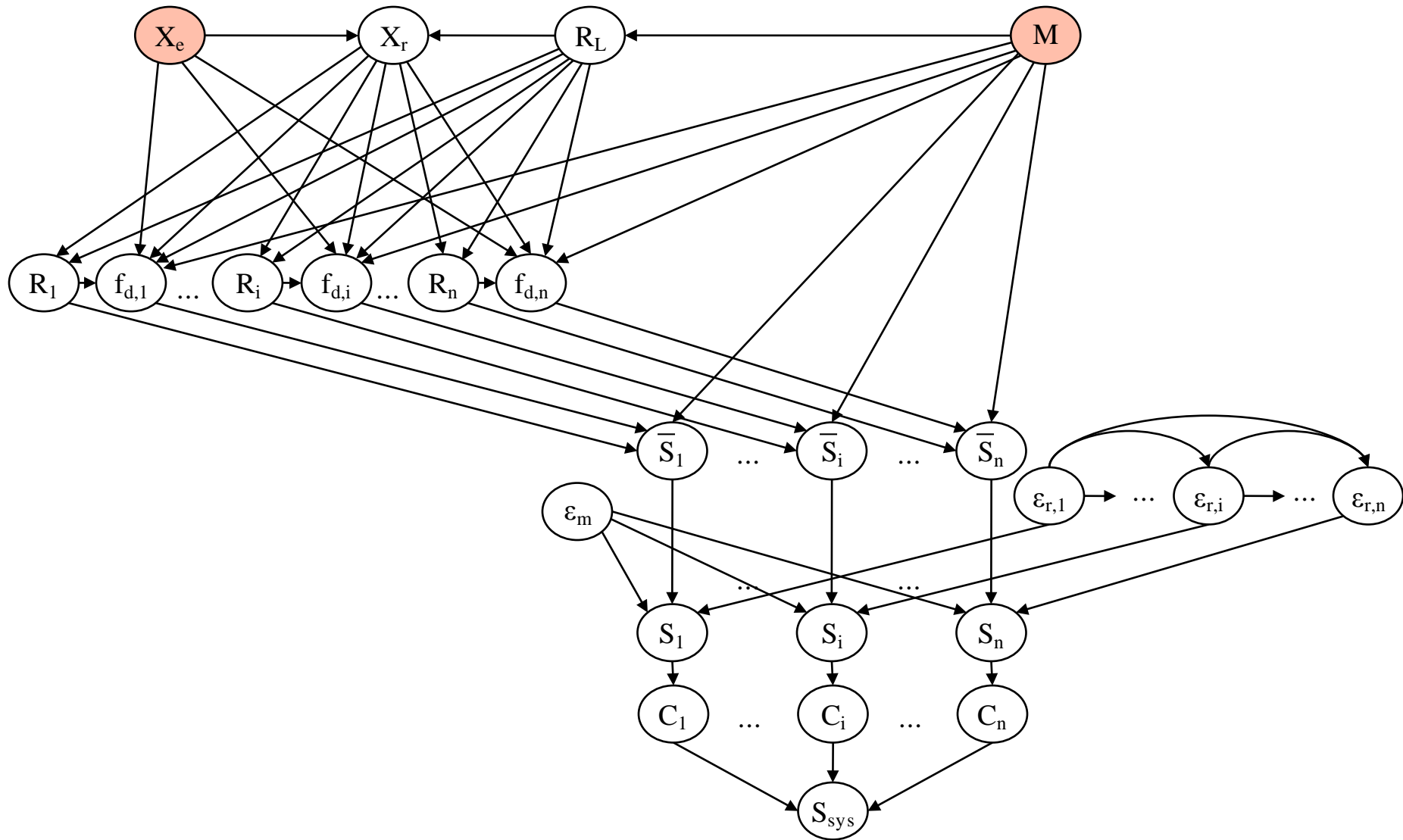
Evidence Cases:

- (1) A $M=6.8$ EQ occurs with epicenter located 30km from left end of the fault
- (2) EC (1) + PGV at GMPP 3 is measured to be 23cm/sec.
- (3) EC (2) + component is observed to have failed.
- (4) EC (2) + component is observed to have survived.

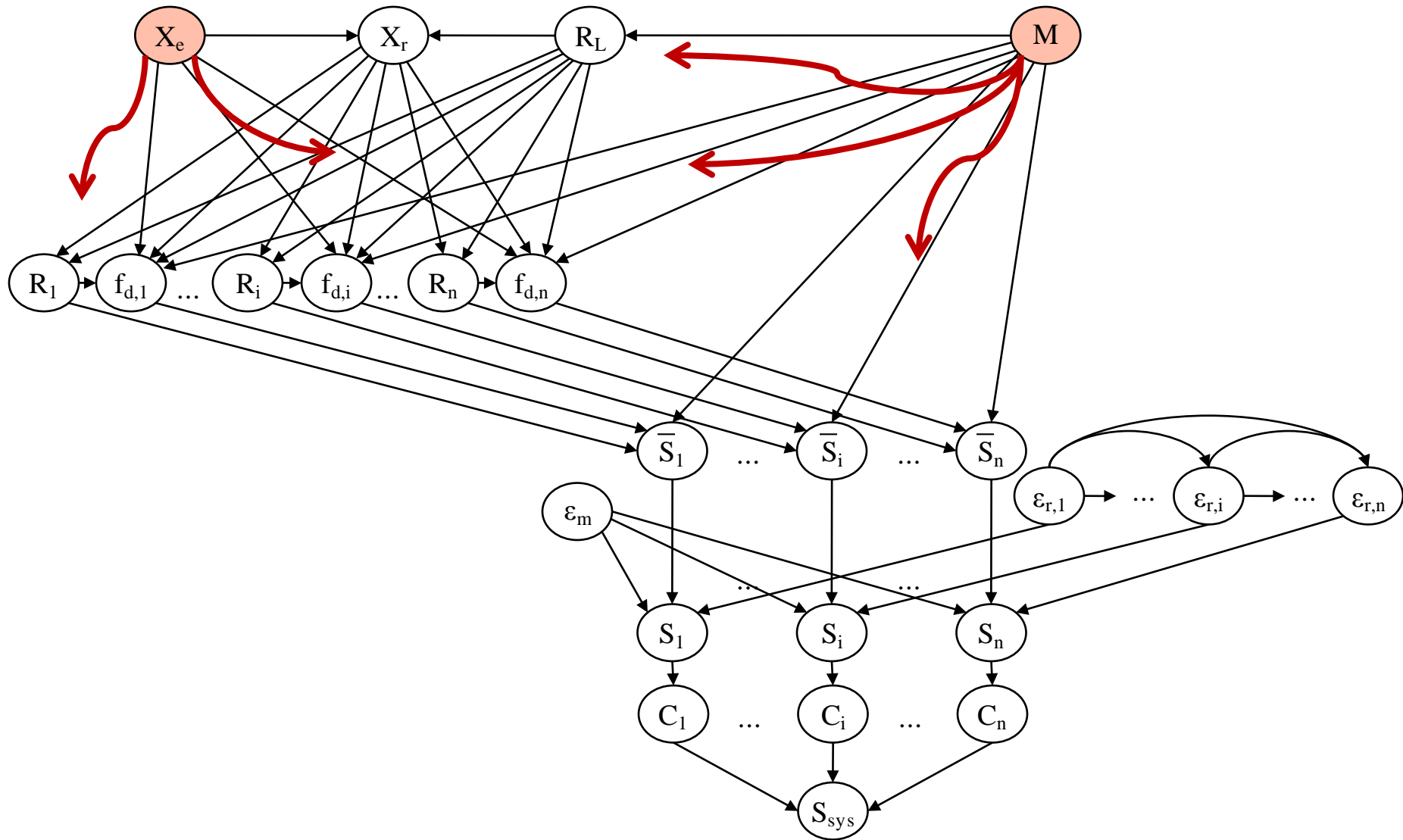
| | EC(1) | EC(2) | EC(3) | EC(4) |
|---------------|--------------|--------------|--------------|--------------|
| $C_{p,1}$ | 4.5 | 8.1 | 9.0 | 8.0 |
| $C_{d,1,2}$ | 2.7 | 4.3 | 4.7 | 4.3 |
| $C_{d,1,3}$ | 3.8 | 7.9 | 8.1 | 7.9 |
| $C_{d,2,4}$ | 5.0 | 6.5 | 8.1 | 6.4 |
| $C_{d,3,5}$ | 9.7 | 17.0 | 18.3 | 16.9 |
| $C_{d,4,6}$ | 0.9 | 1.0 | 1.6 | 1.0 |
| $C_{p,4}$ | 3.2 | 3.9 | 6.2 | 3.7 |
| $C_{d,5,7}$ | 1.8 | 2.1 | 2.7 | 2.1 |
| $C_{d,5,8}$ | 10.2 | 11.5 | 15.8 | 11.3 |
| $C_{p,6}$ | 2.6 | 3.1 | 5.9 | 2.9 |
| $C_{d,6,8}$ | 5.4 | 6.2 | 10.0 | 0.00 |
| $C_{p,7}$ | 6.6 | 7.8 | 10.3 | 7.6 |
| $C_{d,7,9}$ | 10.4 | 11.8 | 14.7 | 11.6 |
| $C_{d,8,10}$ | 5.5 | 6.2 | 8.9 | 6.1 |
| $C_{d,9,11}$ | 9.6 | 10.9 | 13.1 | 10.7 |
| $C_{d,10,12}$ | 1.8 | 2.1 | 2.4 | 2.1 |
| $C_{d,11,12}$ | 2.4 | 2.7 | 3.1 | 2.7 |
| $C_{p,12}$ | 2.2 | 2.7 | 3.2 | 2.6 |
| System | 12.05 | 18.91 | 39.82 | 17.53 |



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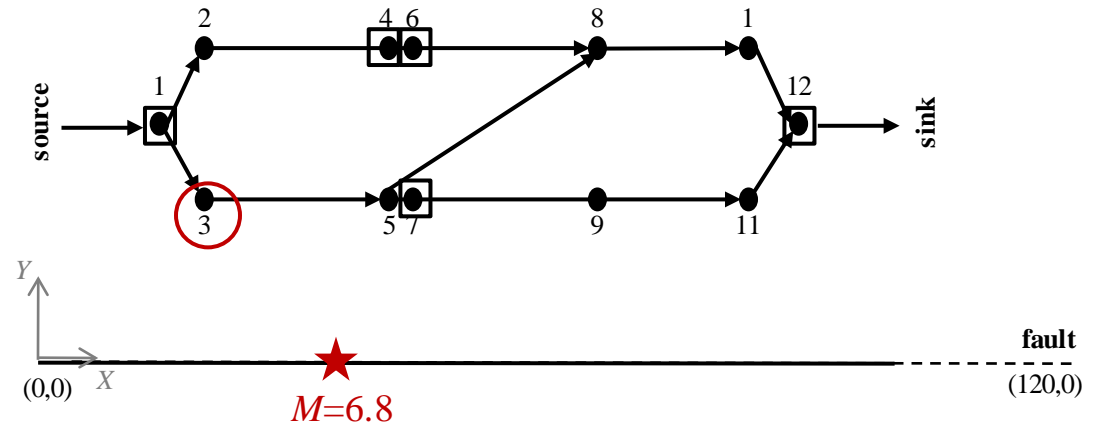


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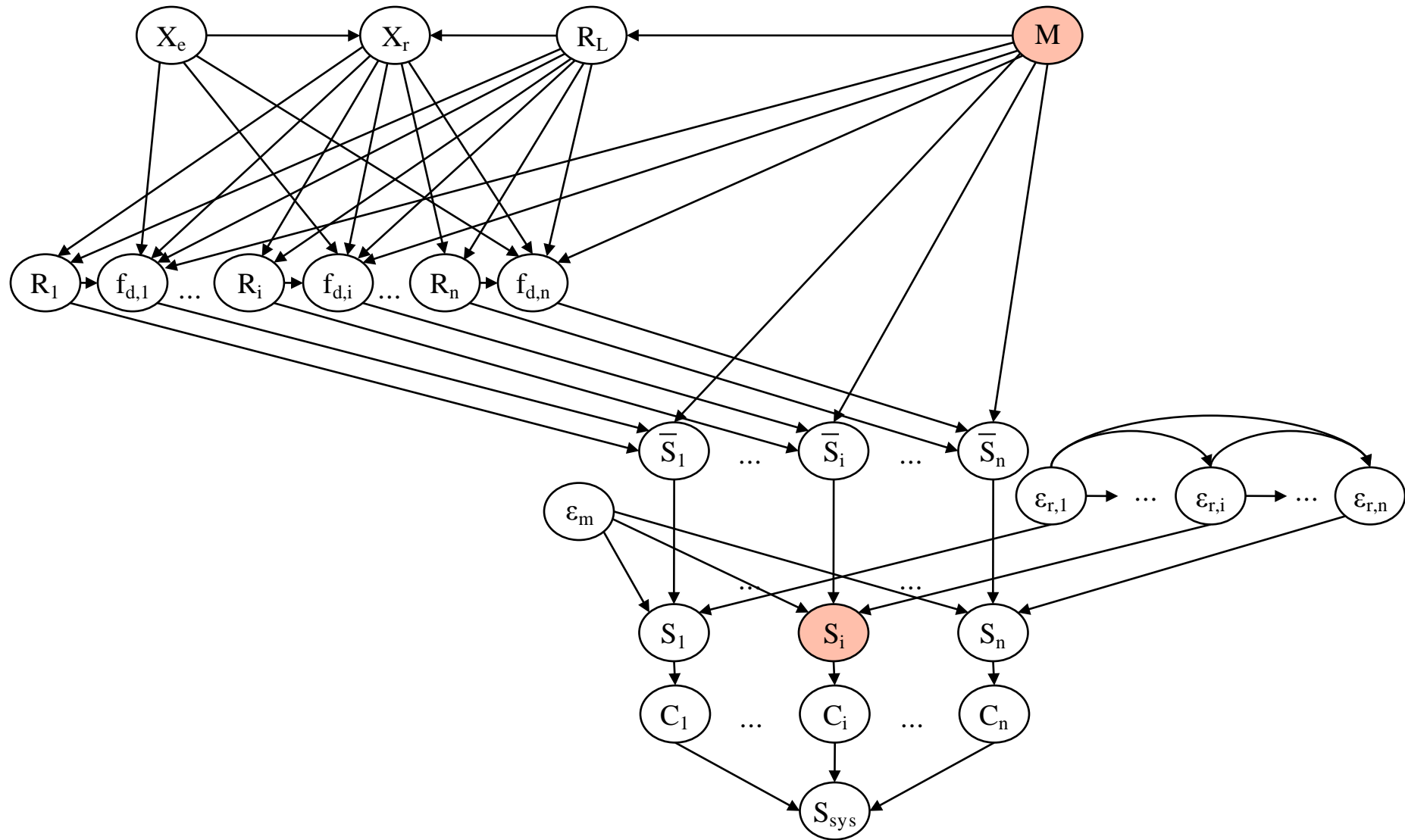
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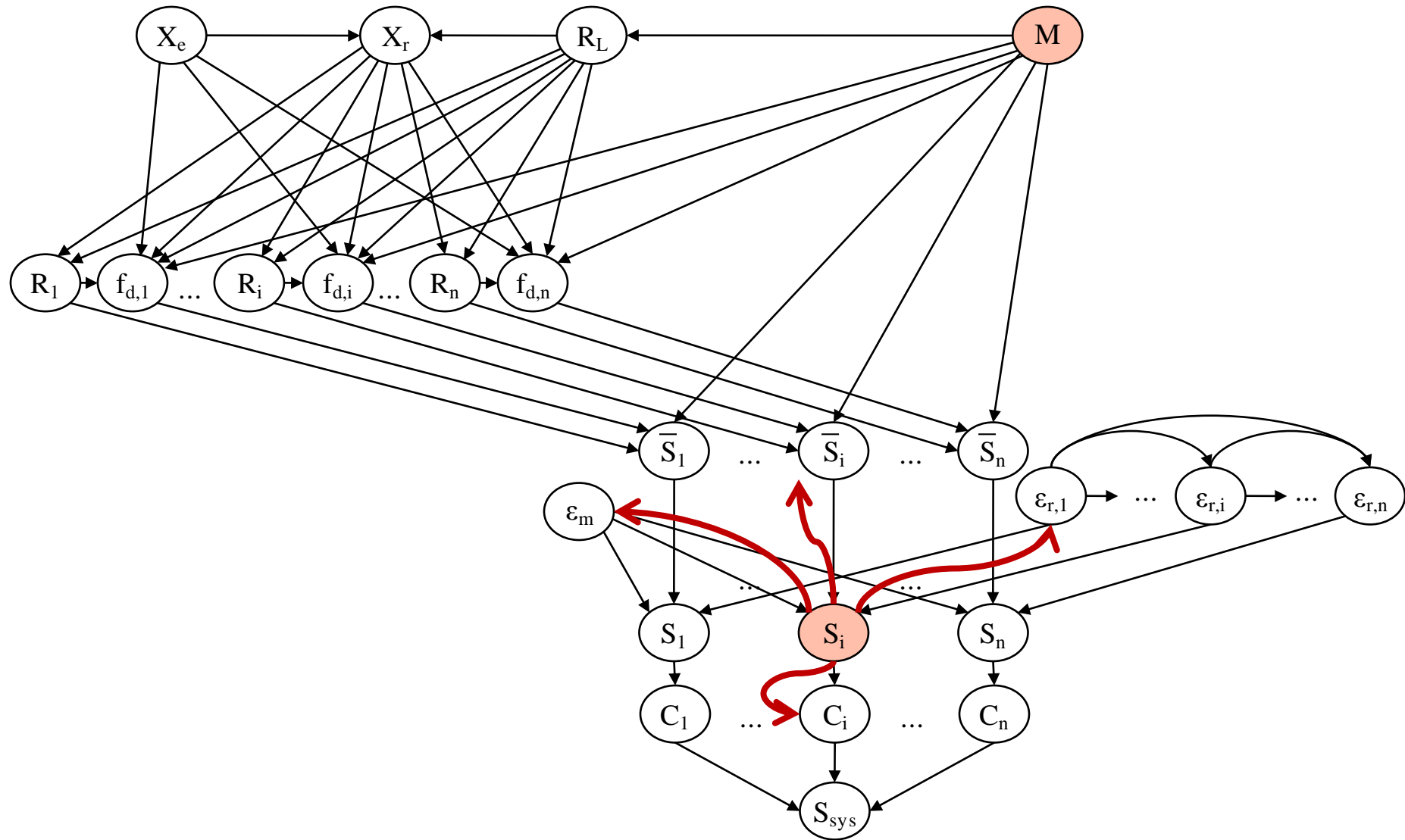
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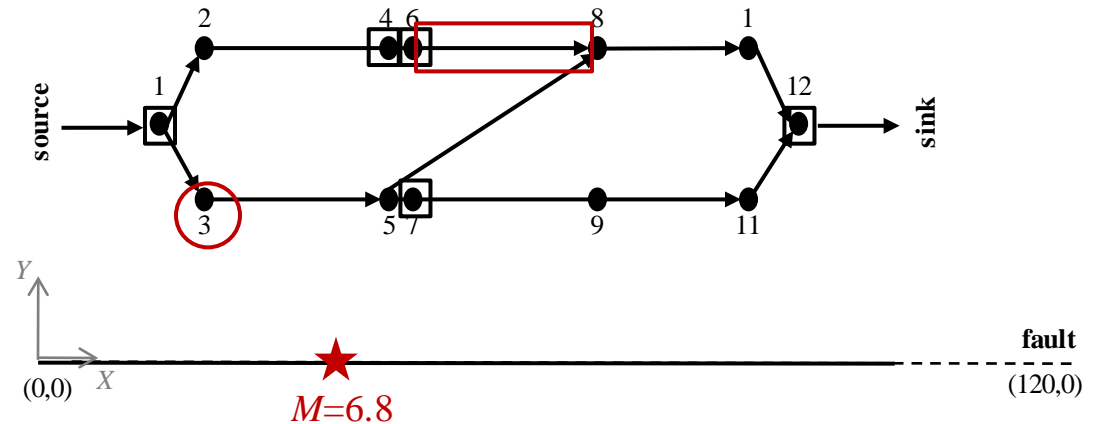


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| $C_{d,5,7}$ | 1.8 | 2.1 | 2.7 | 2.1 |
| $C_{d,5,8}$ | 10.2 | 11.5 | 15.8 | 11.3 |
| $C_{p,6}$ | 2.6 | 3.1 | 5.9 | 2.9 |
| $C_{d,6,8}$ | 5.4 | 6.2 | 10.0 | 0.00 |
| $C_{p,7}$ | 6.6 | 7.8 | 10.3 | 7.6 |
| $C_{d,7,9}$ | 10.4 | 11.8 | 14.7 | 11.6 |
| $C_{d,8,10}$ | 5.5 | 6.2 | 8.9 | 6.1 |
| $C_{d,9,11}$ | 9.6 | 10.9 | 13.1 | 10.7 |
| $C_{d,10,12}$ | 1.8 | 2.1 | 2.4 | 2.1 |
| $C_{d,11,12}$ | 2.4 | 2.7 | 3.1 | 2.7 |
| $C_{p,12}$ | 2.2 | 2.7 | 3.2 | 2.6 |
| System | 12.05 | 18.91 | 39.82 | 17.53 |

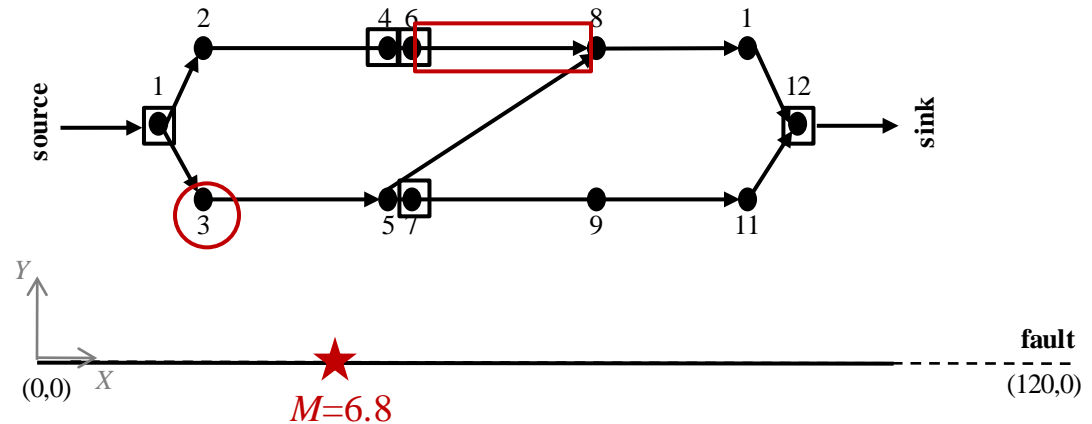


Example: Information Updating

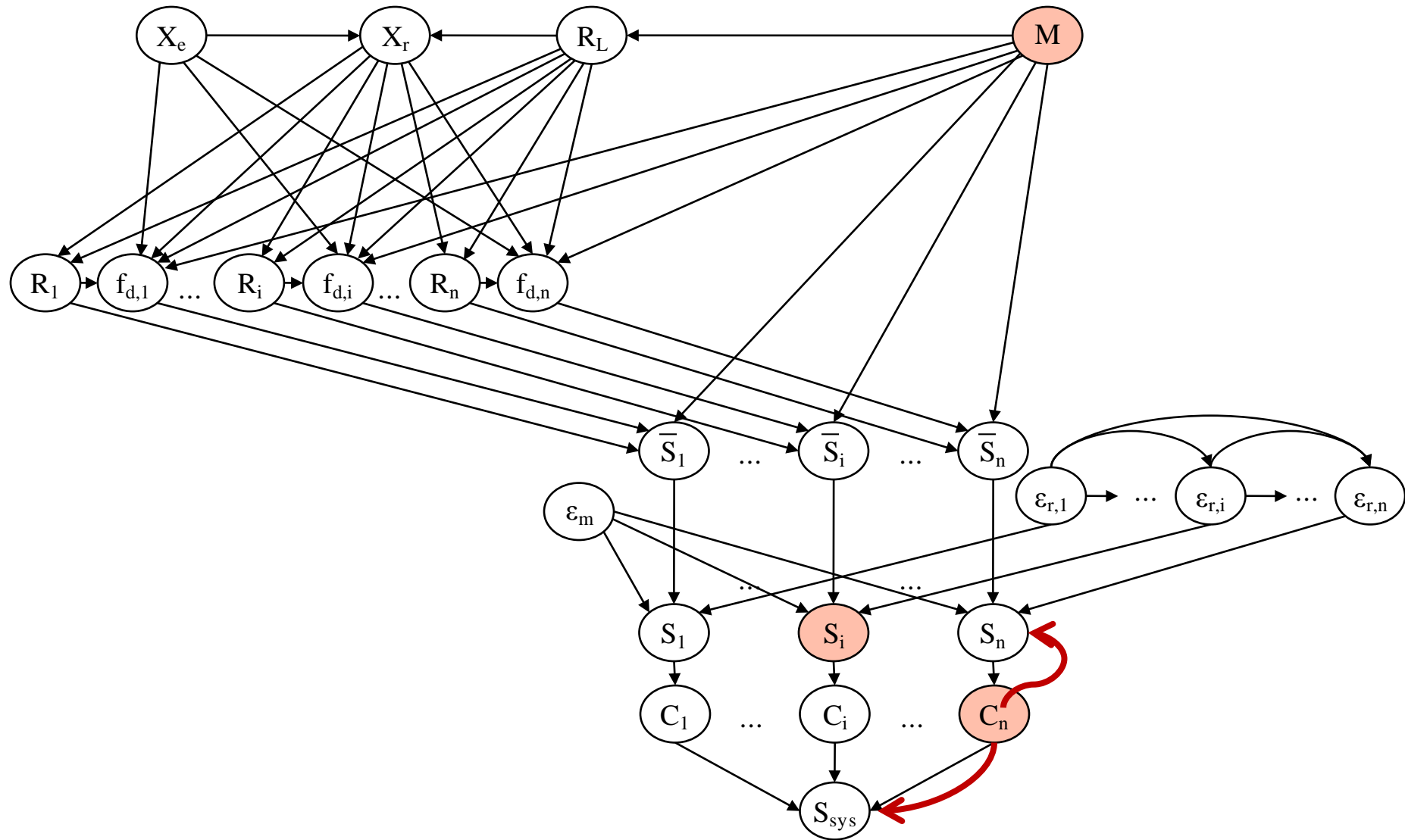
Evidence Cases:

- (1) A $M=6.8$ EQ occurs with epicenter located 30km from left end of the fault
- (2) EC (1) + PGV at GMPP 3 is measured to be 23cm/sec.
- (3) EC (2) + component is observed to have failed.
- (4) EC (2) + component is observed to have survived.

| | EC(1) | EC(2) | EC(3) | EC(4) |
|---------------|--------------|--------------|--------------|--------------|
| $C_{p,1}$ | 4.5 | 8.1 | 9.0 | 8.0 |
| $C_{d,1,2}$ | 2.7 | 4.3 | 4.7 | 4.3 |
| $C_{d,1,3}$ | 3.8 | 7.9 | 8.1 | 7.9 |
| $C_{d,2,4}$ | 5.0 | 6.5 | 8.1 | 6.4 |
| $C_{d,3,5}$ | 9.7 | 17.0 | 18.3 | 16.9 |
| $C_{d,4,6}$ | 0.9 | 1.0 | 1.6 | 1.0 |
| $C_{p,4}$ | 3.2 | 3.9 | 6.2 | 3.7 |
| $C_{d,5,7}$ | 1.8 | 2.1 | 2.7 | 2.1 |
| $C_{d,5,8}$ | 10.2 | 11.5 | 15.8 | 11.3 |
| $C_{p,6}$ | 2.6 | 3.1 | 5.9 | 2.9 |
| $C_{d,6,8}$ | 5.4 | 6.2 | 10.0 | 0.00 |
| $C_{p,7}$ | 6.6 | 7.8 | 10.3 | 7.6 |
| $C_{d,7,9}$ | 10.4 | 11.8 | 14.7 | 11.6 |
| $C_{d,8,10}$ | 5.5 | 6.2 | 8.9 | 6.1 |
| $C_{d,9,11}$ | 9.6 | 10.9 | 13.1 | 10.7 |
| $C_{d,10,12}$ | 1.8 | 2.1 | 2.4 | 2.1 |
| $C_{d,11,12}$ | 2.4 | 2.7 | 3.1 | 2.7 |
| $C_{p,12}$ | 2.2 | 2.7 | 3.2 | 2.6 |
| System | 12.05 | 18.91 | 39.82 | 17.53 |



Example: Information Updating

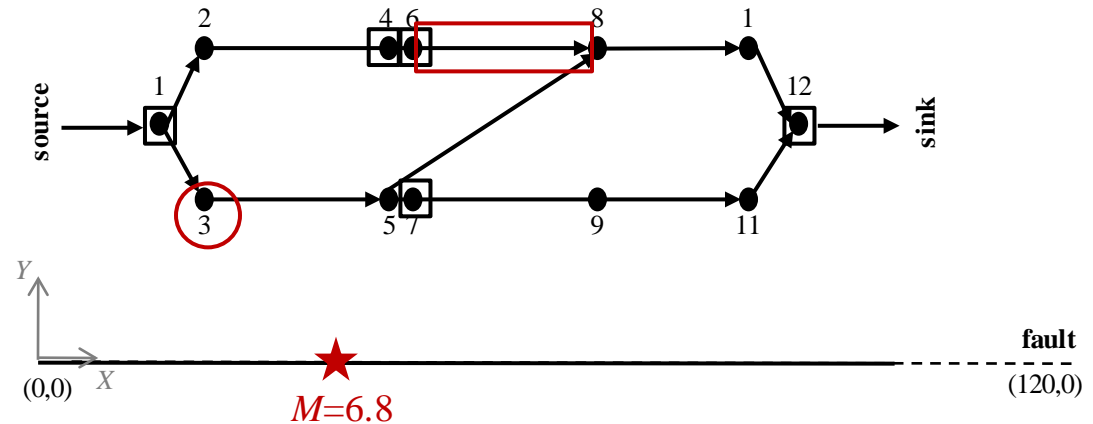


Example: Information Updating

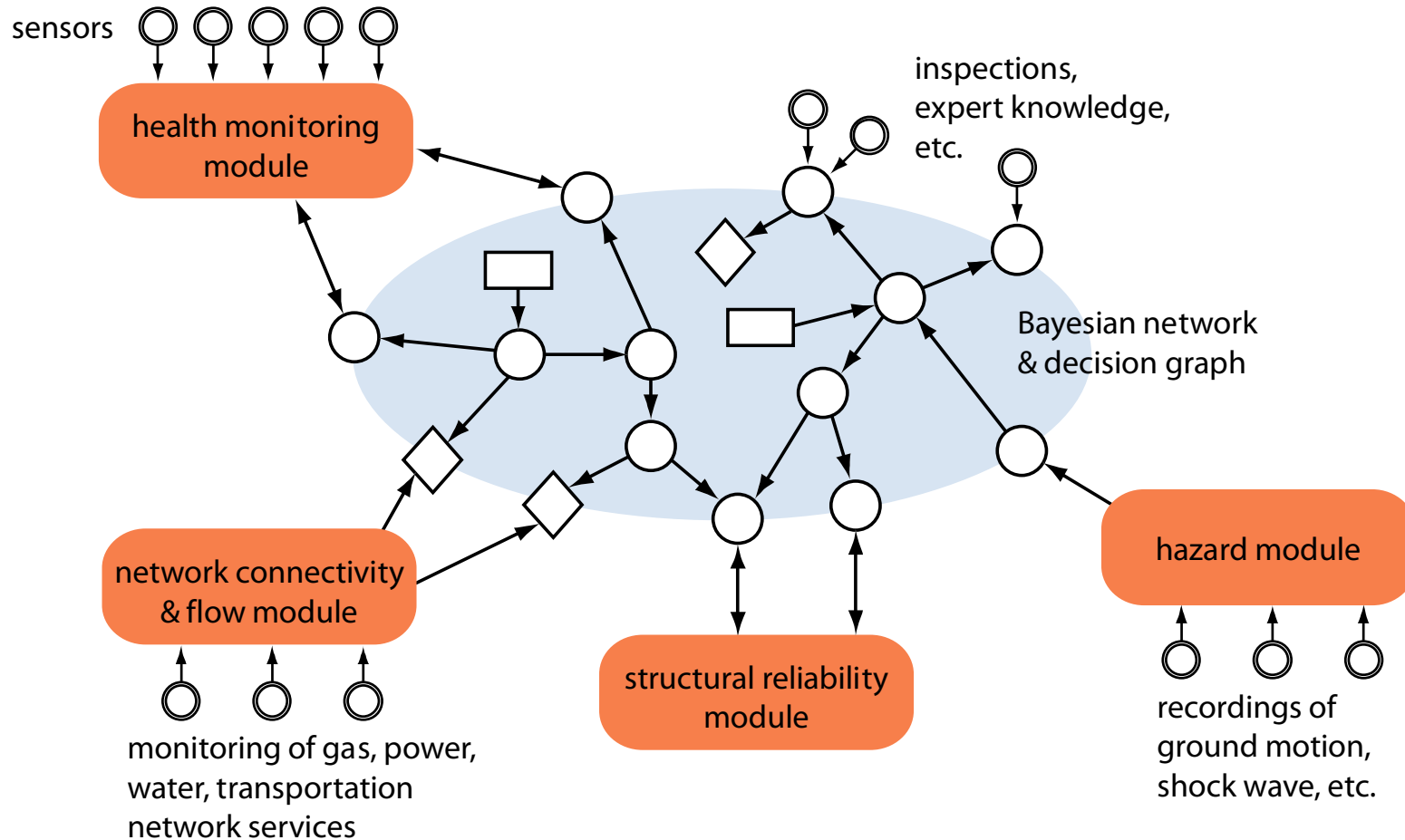
Evidence Cases:

- (1) A $M=6.8$ EQ occurs with epicenter located 30km from left end of the fault
- (2) EC (1) + PGV at GMPP 3 is measured to be 23cm/sec.
- (3) EC (2) + component is observed to have failed.
- (4) EC (2) + component is observed to have survived.

| | EC(1) | EC(2) | EC(3) | EC(4) |
|---------------|--------------|--------------|--------------|--------------|
| $C_{p,1}$ | 4.5 | 8.1 | 9.0 | 8.0 |
| $C_{d,1,2}$ | 2.7 | 4.3 | 4.7 | 4.3 |
| $C_{d,1,3}$ | 3.8 | 7.9 | 8.1 | 7.9 |
| $C_{d,2,4}$ | 5.0 | 6.5 | 8.1 | 6.4 |
| $C_{d,3,5}$ | 9.7 | 17.0 | 18.3 | 16.9 |
| $C_{d,4,6}$ | 0.9 | 1.0 | 1.6 | 1.0 |
| $C_{p,4}$ | 3.2 | 3.9 | 6.2 | 3.7 |
| $C_{d,5,7}$ | 1.8 | 2.1 | 2.7 | 2.1 |
| $C_{d,5,8}$ | 10.2 | 11.5 | 15.8 | 11.3 |
| $C_{p,6}$ | 2.6 | 3.1 | 5.9 | 2.9 |
| $C_{d,6,8}$ | 5.4 | 6.2 | 10.0 | 0.00 |
| $C_{p,7}$ | 6.6 | 7.8 | 10.3 | 7.6 |
| $C_{d,7,9}$ | 10.4 | 11.8 | 14.7 | 11.6 |
| $C_{d,8,10}$ | 5.5 | 6.2 | 8.9 | 6.1 |
| $C_{d,9,11}$ | 9.6 | 10.9 | 13.1 | 10.7 |
| $C_{d,10,12}$ | 1.8 | 2.1 | 2.4 | 2.1 |
| $C_{d,11,12}$ | 2.4 | 2.7 | 3.1 | 2.7 |
| $C_{p,12}$ | 2.2 | 2.7 | 3.2 | 2.6 |
| System | 12.05 | 18.91 | 39.82 | 17.53 |

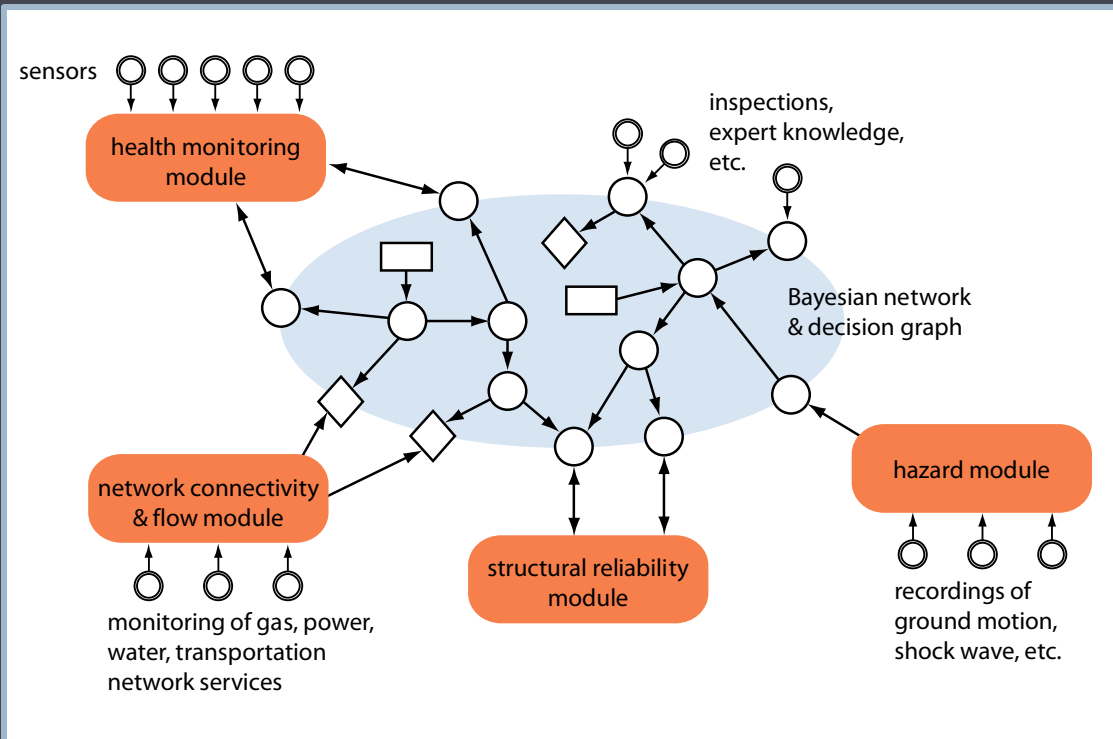


Summary



Future work...

- ▶ Examples for future extensions and refinements may include:
 - ▶ Expanded models
 - ▶ Source characterization (beyond line source assumption)
 - ▶ Liquefaction and fault rupture seismic demand models
 - ▶ Revised heuristics for optimization (improve scalability)
 - ▶ Discipline specific performance formulations
 - ▶ System interdependency
 - ▶ More extensive decision formulations
 - ▶ Integration with external information sources
 - ▶ E.g. structural health monitoring systems
 - ▶ Improved algorithms/ formulations (computational issues)
 - ▶ Multi-scale modeling
 - ▶ Application specific inference algorithms
 - ▶ Additional applications (hazards beyond earthquakes)
-
- Current/near term
- Longer term



Thank you

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