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Protecting Infrastructures: The Role of Risk Analysis

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Presented at the Swiss Federal Institute of Technology
Zurich, Switzerland
May 25, 2005

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Risk Analysis for Technological Systems

- The system is viewed as an integrated *socio-technical* system.
- Probabilistic Risk Assessment (PRA) answers the following questions:
  - What can go wrong? (accident sequences or scenarios)
  - How likely are these scenarios?
  - What are their consequences?
- PRA supports risk management by:
  - Identifying accident scenarios
  - Ranking these scenarios according to their probabilities of occurrence

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Observations on Infrastructures

- **Large, diffuse, inter-connected networks, as opposed to well defined systems such as nuclear power plants and the International Space Station.**
- **Difficult to analyze using top-down conventional mathematical theories, such as Probabilistic Risk Assessment.**
- **Infrastructure systems were never intended by their designers to resist the consequences of planned malicious destruction.**

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Objective

- **To rank the elements of an infrastructure according to their risk value for "random" failures or their vulnerability to terrorism.**
- **In both cases, the value of the element to the Decision Maker (DM) is assessed using a value tree and disutility functions.**
- **For random failures, the expected disutilities are the basis for ranking the infrastructure elements.**
- **For malevolent acts, probabilities are difficult to evaluate. The element's value is combined with its susceptibility to attack to develop a vulnerability ranking.**

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The Case Studies

- **Specific Assets**
  - Six buildings on the MIT campus
  - Three infrastructures (electric power, water, natural gas)
  - Binary logic for the elements
  - Critical locations identified via minimal cut sets
- **A Town**
  - Water infrastructure of a European city
  - Network's capacity and time included.
- **In both cases**
  - An objectives hierarchy (value tree) is developed with the DM
  - The threat is assumed to be minor.

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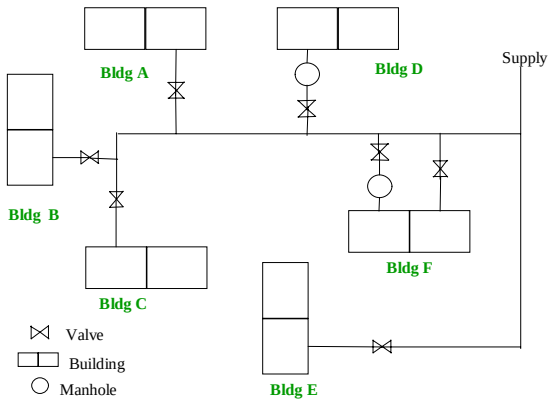
MIT Natural Gas Infrastructure



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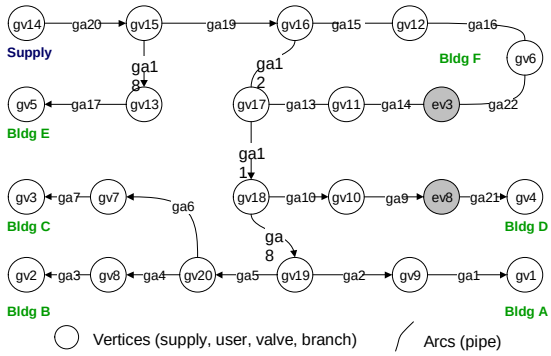
Natural Gas Network Digraph



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Minimal Cut Sets (Scenarios) Affecting the Assets

Number of mcs	Number of Users Impacted
7	6
7	5
11	4
107	3
256	2
275	1

663 total mcs

Example: (ev1, ev2) impacts electrical service to all six buildings.

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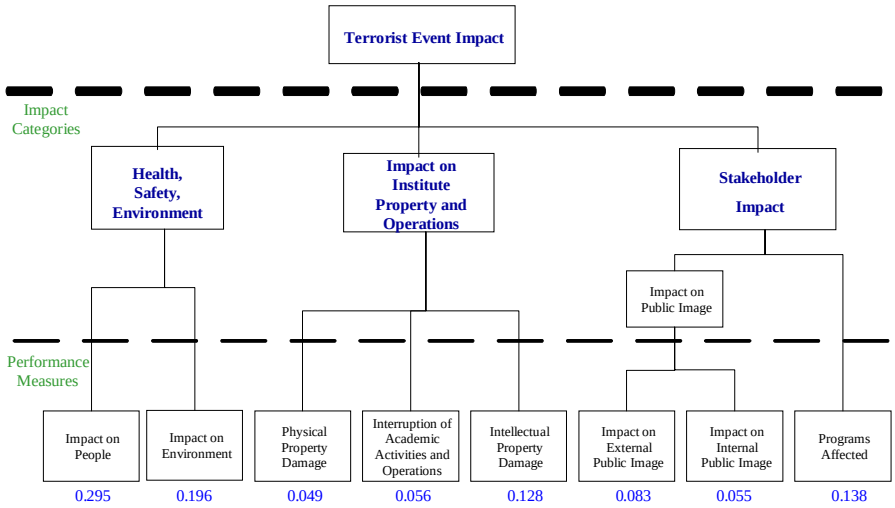
The Value Tree



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Constructed Scale:
Interruption of Academic Activities & Operations

Level	Description	Disutility
4	Extreme interruption (greater than 6 months)	1.00
3	Major interruption (1 to 6 months)	0.57
2	Moderate interruption (1 to 4 weeks)	0.19
1	Minor interruption (less than 1 week)	0.06
0	No interruption	0.00

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Prioritization Methodology

- **Performance Index (expected disutility)**

$$\overline{PI}_j = \sum_{i}^{K_{pm}} w_i \bar{d}_{ij}$$

$\overline{PI}_j$ **expected performance index for vulnerability *j***

w_i **weight of the performance measure *i***

$\bar{d}_{ij}$ **expected disutility of performance measure *i* for vulnerability *j***

K_{pm} **number of performance measures**

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Problems with Expected Values

$$\bar{d}_{ij} = Pr(A \cap mcs_j) x \sum_{k} \left[Pr(d_i^k / mcs_j) x d_i^k \right]$$

$$\mathbf{Pr(A \cap mcs_j) = Pr(A) x Pr(mcs_j / A)}$$

- **Assume the presence of a minor threat → Ignore Pr(A).**
- **Handle $Pr(mcs_j/A)$ qualitatively in susceptibility assessment.**
- **$Pr(d_i^k / mcs_j)$ Probability of disutility level k for PM_i**
- **Assess disutility level k for PM i conservatively**

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Performance Index for Screening

$$PI_j = \sum_{i=1}^{K_{pm}} w_i d_{ij}$$

PI_j performance index for minimal cut set j

d_{ij} disutility of performance measure *i* for minimal cut set *j* (assessed conservatively)

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PI Values for MCS

PI	Number of mcs	Minimal cut sets
0.24742	1	(ev1,ev2)
0.15881	47	(ev23,ev6), (ev1,ev5), (ea20,ev4), …….
0.11508	1	(ev8)
0.11370	3	(wv14), (wv15), (wa20)
0.09391	48	(ev21,ev6), (ev20,ev5), (ea17,ev2), …….
0.09030	2	(wv16), (wa19)
0.08861	55	(ev24,ev42), (ea40,ev42), (ea39,ev38), …….
…….	……	…….

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Susceptibility Categories

- Extreme - Completely open, no controls, no barriers
- High - Unlocked, non-complex barriers (door or access panel)
- Moderate - Complex barrier, security patrols, video monitor
- Low - Secure area, locked, complex closure
- Very Low - Guarded, secure area, locked, alarmed, complex closure
- Zero - Completely secure, no susceptibility

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Vulnerability Ranking

Vulnerability Category	Number of mcs	Minimal Cut Sets
Red	1	(ev8)
Orange	0	none
Yellow	5	(ev21), (ev22), (ev3), (ev34), (ev9)
Blue	19	(wa20), (wv14), (wv15), (ev11), (ev18), (ev19), (ev25), (gv1), (gv2), (gv3), (gv4), (gv5), (gv6), (wv1), (wv2), (wv3), (wv4), (wv5), (wv6)
Green	638	All remaining mcs

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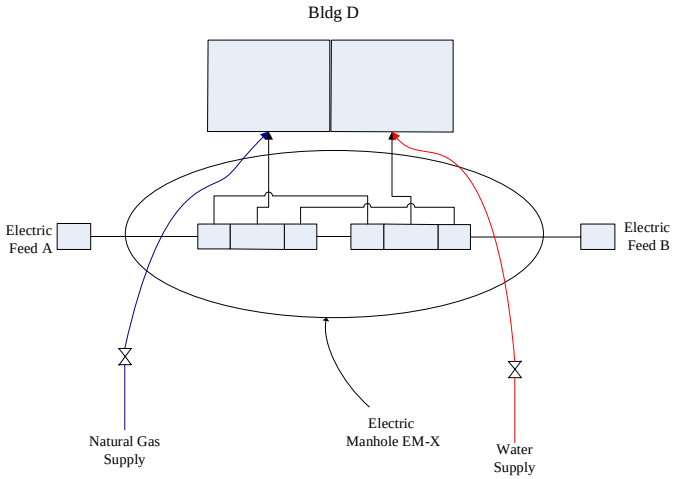
Red MCS: *ev8* (Electric Manhole, PI = 0.11508)



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City Water Service (Pressure Zones)

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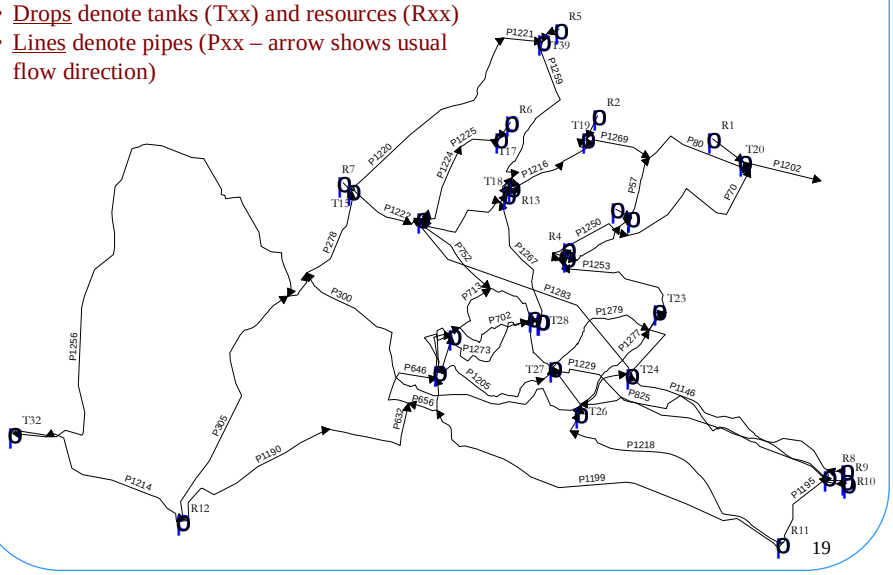
Water Supply Network

- Drops denote tanks (Txx) and resources (Rxx)
- Lines denote pipes (Pxx – arrow shows usual flow direction)



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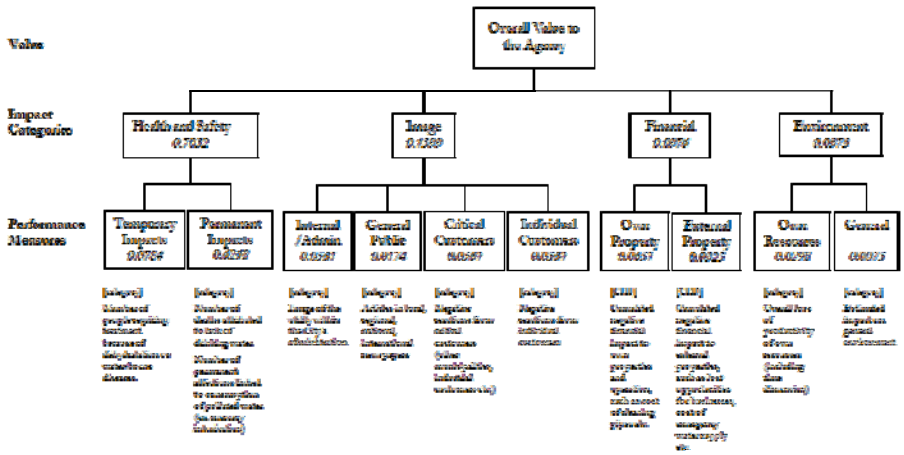
Value Tree of the Water Supply Agency



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Consequence Matrices

Objective	Level	Description	Individual Customers		
		Unit	Number		
		Duration of Interruption	6 hrs	1 day	1 week
Temporary Impacts	4	A large share of the served population requires treatment because of water-borne conditions	NA	NA	NA
	3	Hundreds of persons require treatment, dozens of them hospitalization for water-borne conditions	NA	NA	100,000
	2	Dozens of persons require treatment, some of them hospitalization for water-born conditions	100,000	100,000	50,000
	1	A few persons require light treatment for water-borne conditions	50,000	50,000	20,000
	0	No health impact	0	0	0

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Risk Categories (Random Failures)

Disutility Categories	From	To	Pipes	Tanks or Resources	Total
I	0.049987	0.250000	0	2	2
II	0.009985	0.049987	0	4	4
III	0.001984	0.009985	7	10	17
IV	0.000384	0.001984	16	1	17
V	0.000064	0.000384	4	0	4
VI	0.000000	0.000064	115	16	131
TOTAL			142	33	175

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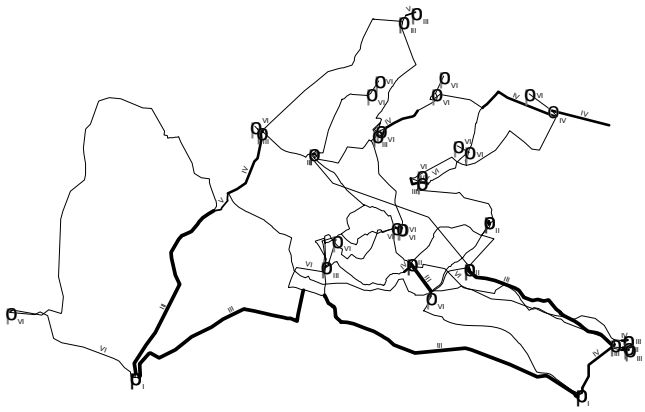
Risk Prioritization Map (Random Failures)



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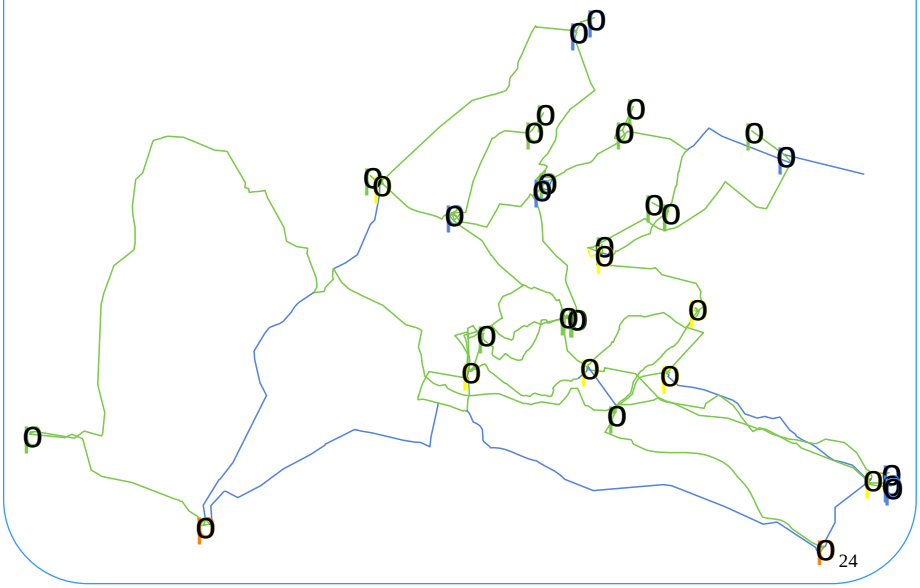
Vulnerability Prioritization Map (Malevolent Acts)



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