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Application of Interdependency Models to Infrastructure Risk Assessment

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Risk Assessment Process

- **Risk assessment in general involves assessing the likelihood of various negative events and their impacts if the events should occur**
- **For risk to infrastructure, these impacts are the consequences of loss or degradation of functionality due to:**
  - Accidentally failures
  - Terrorist events
  - Natural disasters
- **Some of the consequences are direct:**
  - Direct losses due to lost productivity of the infrastructure
  - Replacement and cleanup costs associated with the event
- **Other losses are indirect:**
  - Loss of containment of large amounts of water or hazardous materials
  - Cascading losses as failures in one infrastructure degrade another

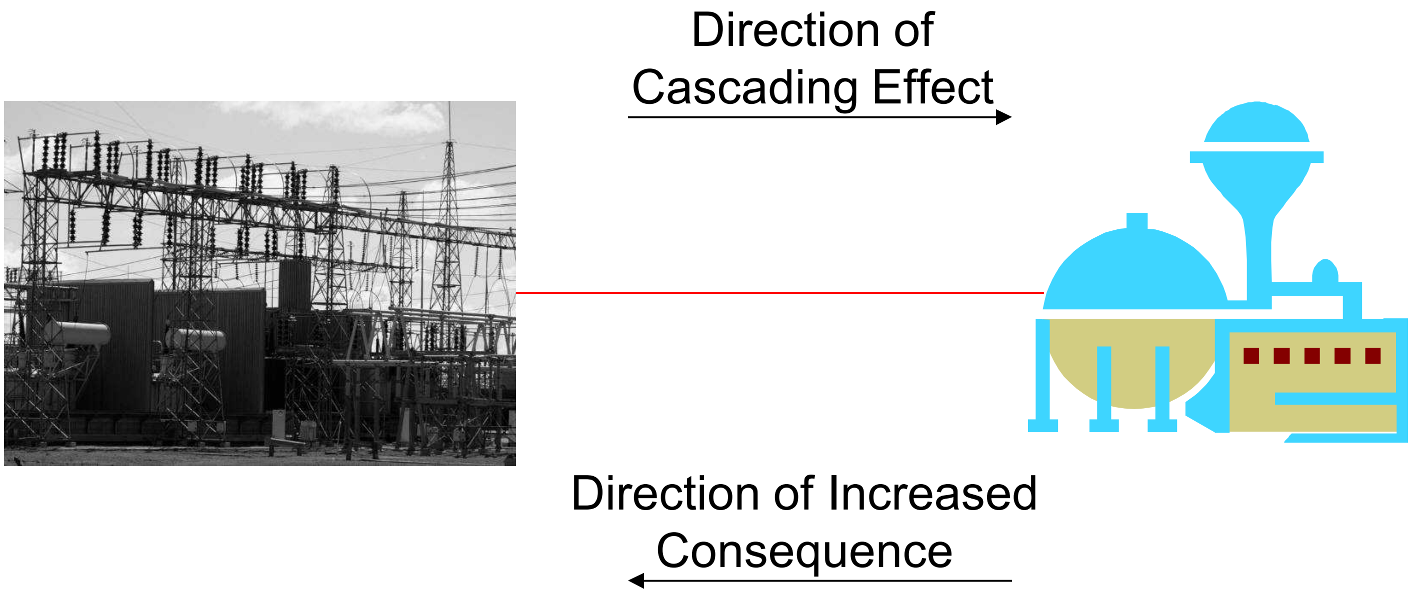
Interdependencies and Cascading Consequences

- **Certain parts of the infrastructure are dependent on other parts for their functioning, e.g.:**
  - Chemical plants can depend on the electrical distribution system for their continuing operation
  - Electrical generation facilities generally require large quantities of water for cooling
- **Loss of functionality in one infrastructure can trigger losses in functionality in downstream infrastructures**
- **Consequence assessment of infrastructure loss should include these downstream affects where significant**
- **This presentation focuses on a possible method to incorporate rough estimates of these affects in a practical manner**

Challenges for Inclusion of Interdependencies in Risk Assessment

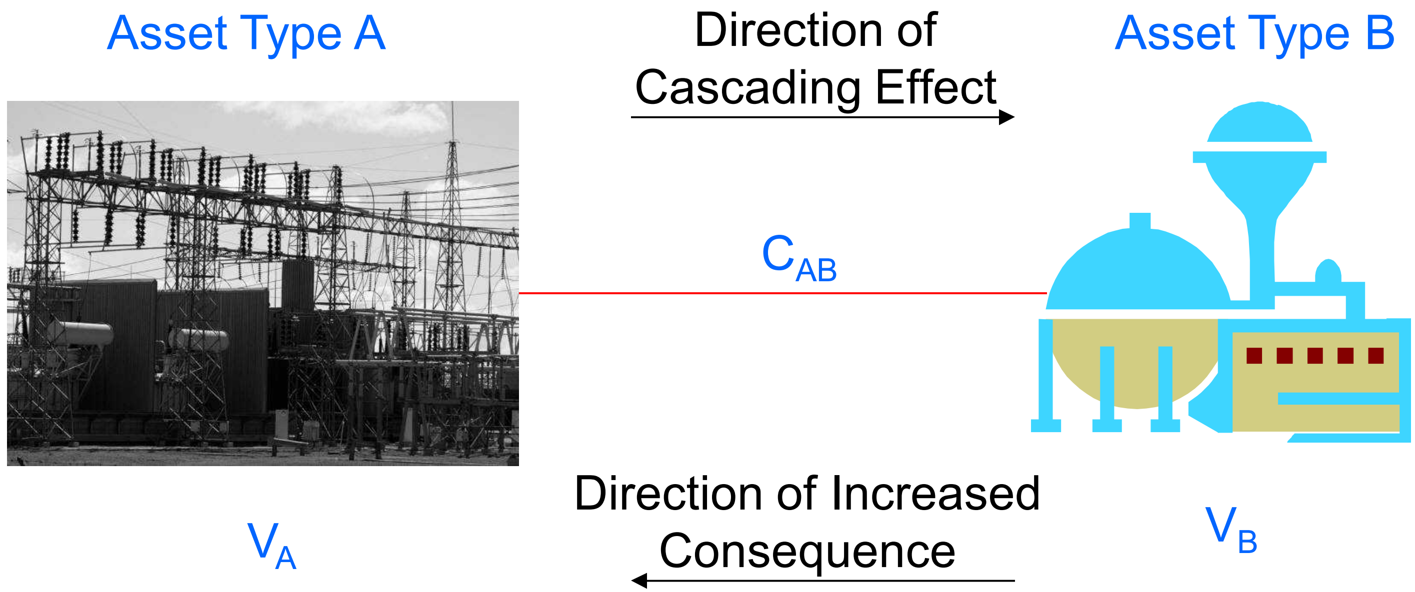
- **The resolution of the application may vary widely**
  - Asset/sector
  - Sector/subsector
  - Geographic resolution
  - Time
- **Interdependencies**
- **Scenario specification or lack thereof**
- **The example here is in support of a notional asset-type focused assessment**

Interdependencies



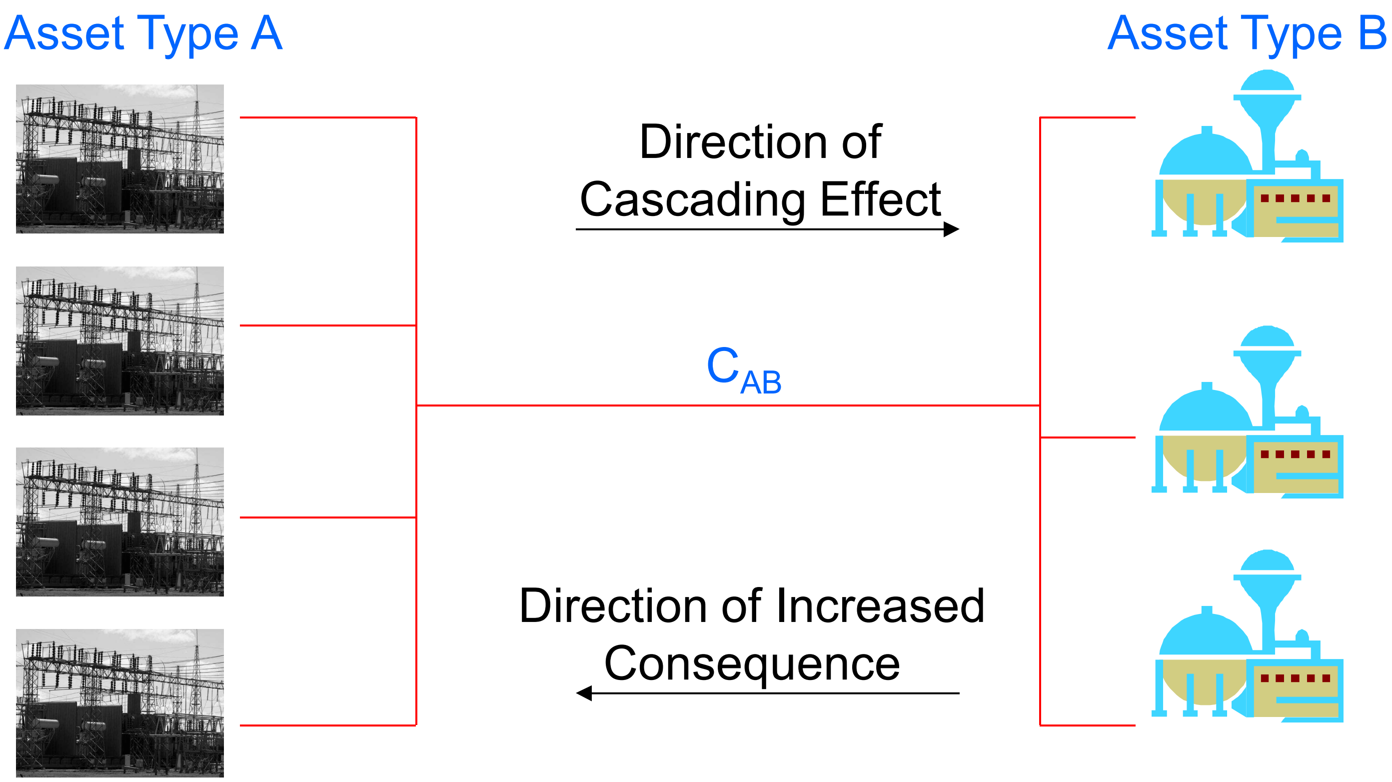
- **Chemical plant depends on substation**
- **Disruption to substation disrupts operation of plant**
- **Consequence of loss of substation increased by disruption to plant**

Interdependencies



- C_{AB} represents the fractional loss of plant value (B) as a result of losing substation (A)
- If V_A is the economic value of asset of type A without the cascading effect, the total value becomes $V_A + C_{AB} * V_B$
- C_{AB} represents the fractional loss of plant value (B) as a result of losing substation (A)

Interdependencies



- **Same logic is applied for interconnected systems**

Use of Interdependency Matrix

Impacted Infrastructure

Impacting Infrastructure

	A	B	C
A		0.2	0.1
B	0.3		0.3
C	0	0.1	

Sector level use of Matrix

$A = A_d + 0.2*B_d + 0.1*C_d$

$B = 0.3*A_d + B_d + 0.3*C_d$

$C = 0.1*B_d + C_d$

Asset level use of Matrix

$a = a_d + 0.2*B_d/|A| + 0.1*C_d/|A|$

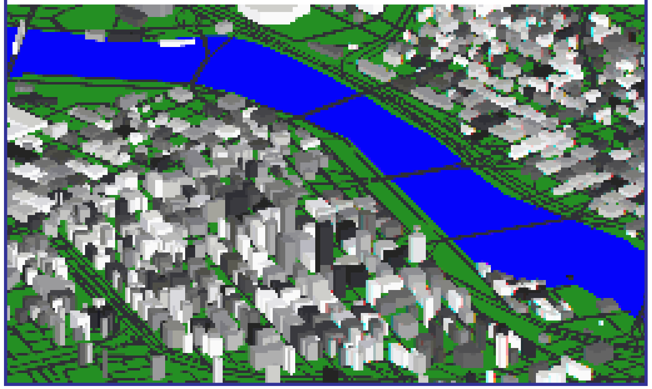
$b = 0.3*A_d/|B| + b_d + 0.3*C_d/|B|$

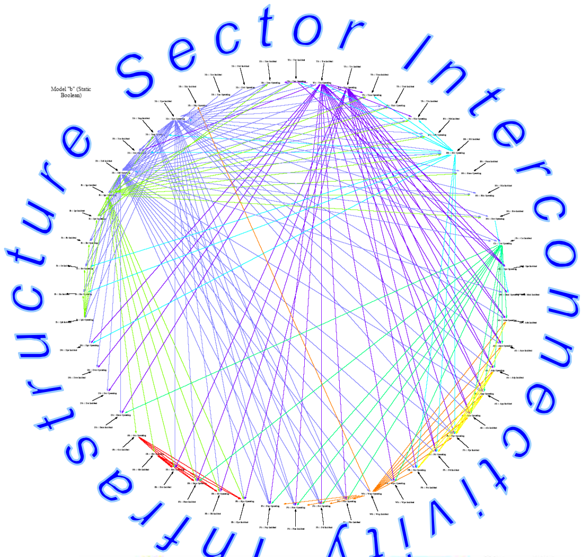
$c = 0.1*B_d/|C| + c_d$

CIPDSS Metropolitan Model Overview

- **Each infrastructure is represented by one or more sub-sectors**
- **Each sub-sector is a system of linked differential equations**
- **Infrastructure interactions between sectors A and B are represented by a variable in sector A being used in sector B**
- **Scenario models represent capabilities specific to the scenario and the linkages to infrastructure models**
  - Infectious disease
  - Chemical release
- **Generic city**
  - Infrastructures scaled to population
  - No representation of specific assets

Metropolitan Model





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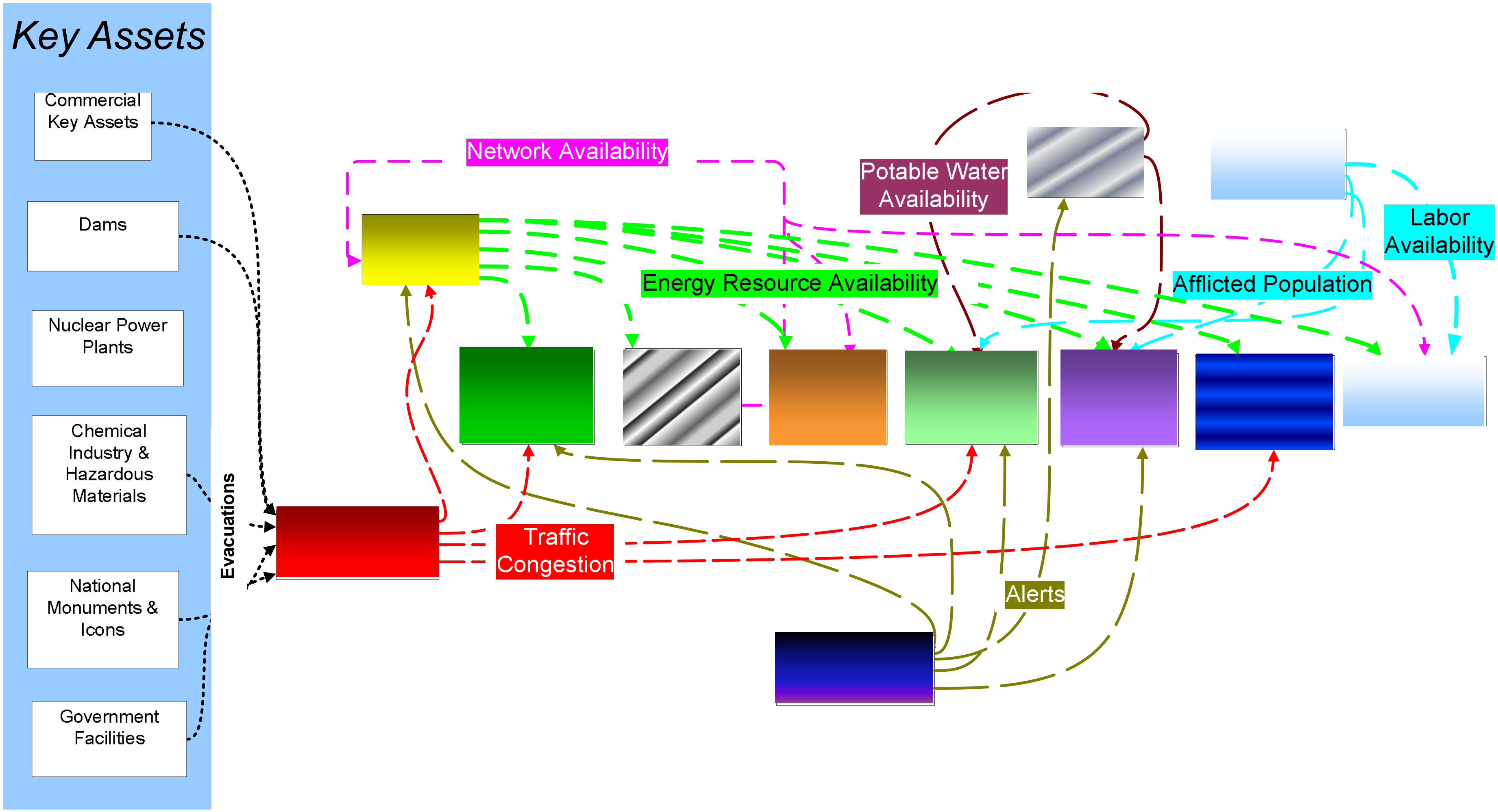
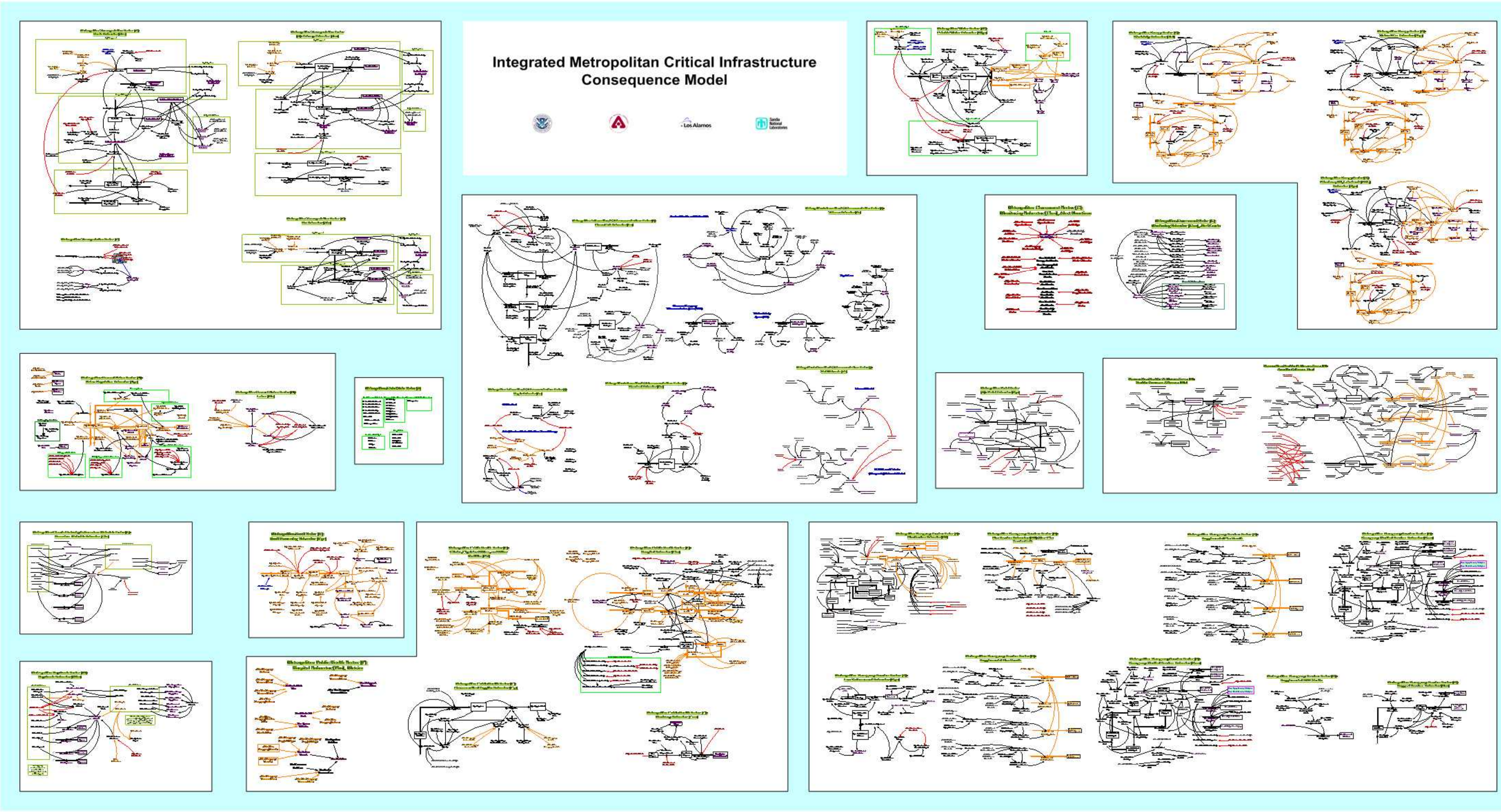
Metropolitan High Level Diagram



Interconnected Metropolitan CIP Sectors



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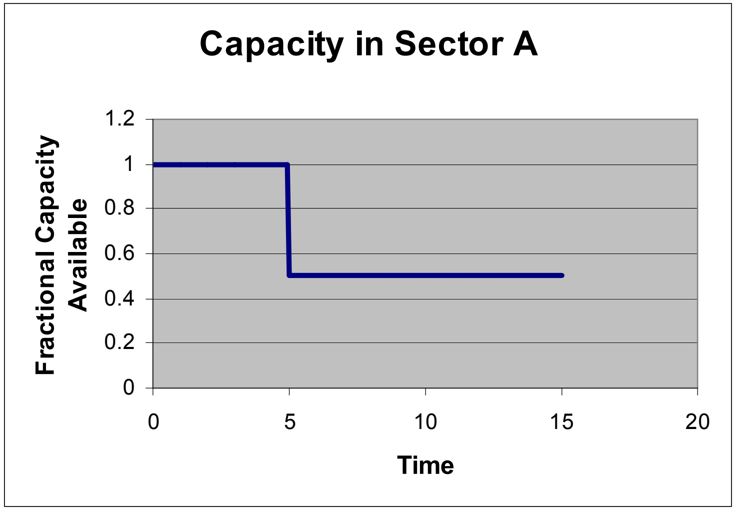
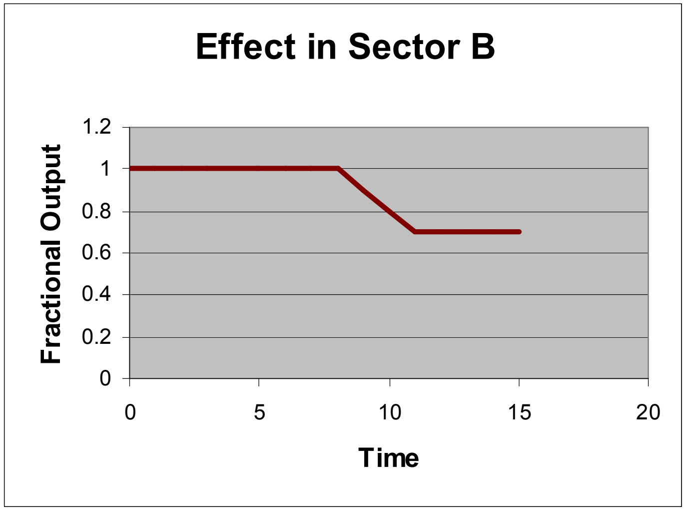
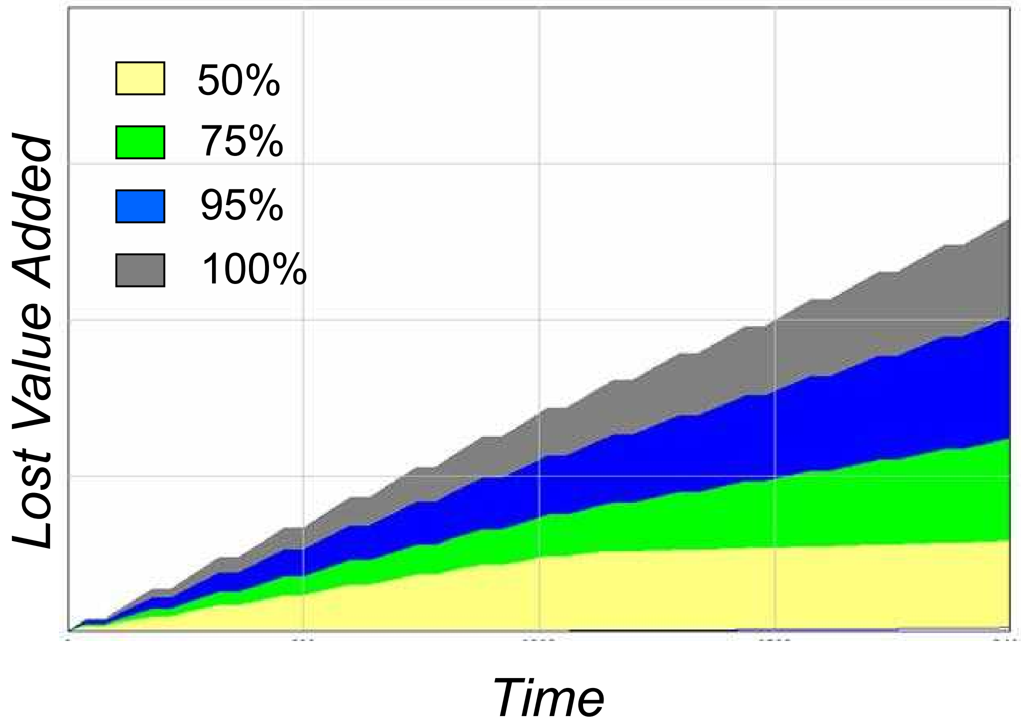
Estimating Cascading Effect Coefficients Using an Interdependency Model





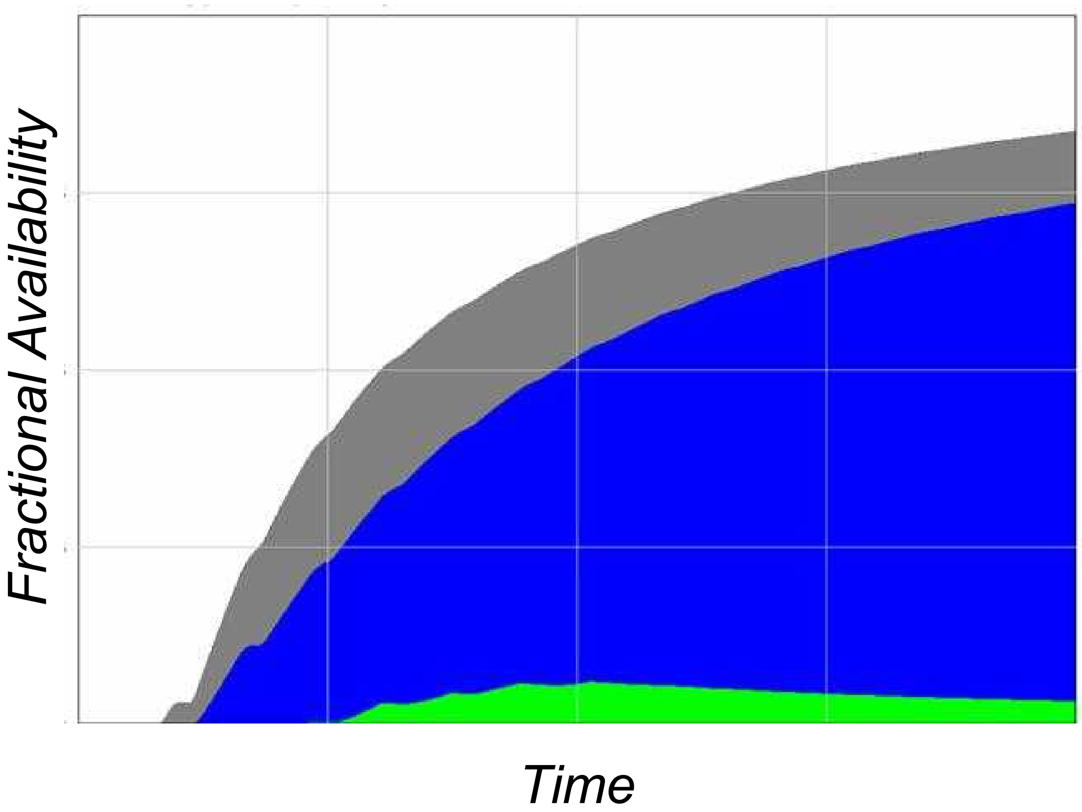
- **Used CIPDSS metro models to study direct and indirect effects of asset loss**
- **System capacity variables**
  - Capacity variables <u>induce</u> capacity loss
  - Lost asset is mapped to an appropriate capacity variable
- **System impact variables**
  - Impact variables <u>measure</u> capacity loss
  - Impact variables are used to measure sector dependencies
- **Caveats**
  - Functional, not physical interdependencies are modeled
- **Interpolation of catastrophic loss interactions**
  - Small losses of segment capacity do not interact in CIPDSS base models
  - Scenario-specific information is needed to completely determine partial loss interactions
  - Simulate 50% loss of capacity and interpolate to smaller losses as appropriate for specific assessment scope/resolution

Example of Impact Dependence on Scenario Severity



- **Example: Sensitivity of Economic Impact to Reduction in Available Electricity**
  - Sampled *Fraction Of Maximum Supply Rate Available* between .05 and .95 (20 samples)
- **No *modeled* economic impact (*Lost Value Added*) until electrical availability is reduced below 50%**
- **The context of the risk assessment is critical**
  - If asset focused, need to consider how to map asset loss to capacity
  - What scenarios lead to enough lost capacity to have an effect?

Temporal Effects: Residential Gas Availability



- **Exhaust local storage before shortages emerge**
  - Timing of shortage depends on severity of direct effect
- **When to measure impact?**
  - T = 0: Impact will not have propagated to adjacent sectors
  - Inappropriate to measure impact at T = inf
    - Capacity reduction won't be permanent
    - Many models do not have repair capabilities
- **Used a 5 to 45 day window for impact assessment**
  - Initial stabilization period of 5 days with no capacity reduction
  - Impact measured as maximum over total simulation time

Notional Interdependency Matrix (Portion)

	I1	I2	I3	I4	I5	I6	I7	F1
I6	0.18	0.01	0.00	0.83	0.02		0.00	0.72
I7	0.00	0.00	0.00	0.02	0.00	0.24		0.02
F1	0.13	0.03	0.00	0.53	0.49	0.42	0.00	
I8	0.06	0.00	0.00	0.06	0.00	0.70	0.04	0.06
I9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
I10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00

- **Impact measured at 50% reduction in capacity**
- **I – infrastructures; F – contributing factor (e.g., labor)**

Supplementing the Quantitative Assessment with Expert Judgment

- **Provides a check or vetting of the model results**
- **Catalog functional relationships**
- **Map asset types to infrastructures**
- **Collect sources of information**
- **Map the information to an asset type by asset type matrix**
  - Many asset types of concern do not have strong interdependency effects (e.g., hotels)
  - Infrastructures with strongest interdependencies often have significant resiliency
- **Combine the scores, with an emphasis on expert judgment and functional relationships.**

Identification of Causes of Interdependencies

	Electricity	Transportation	Telecommunications	Banking & Finance
Electricity	Unbalanced Load	Backlog & Delays	Sporadic Interruptions	Location Dependent Interruptions (eg New York)
Transportation (Air)	Interruptions in Fuel Delivery/Flow	Lower Level of Airline Industry Economic Activity	Increase of Remote Meetings (Telecommuting)	
Telecommunications	Uncoordinated load balance	Air Traffic Control Booking of Travel Coordination of Carriers	Increased Congestion in Unaffected Regions	Location Dependent Interruptions (eg New York)
Banking & Finance		Moderate Impact to Cash Flow / Payment System Issue		Major Impact to Cash Flow / Payment System Issue
Water & Sewage				
Public Health				
Food				
Economic Impact	Reduced Electricity Demand	Changes in Demand (Reduced Transportation Demand)	Changes in Demand	Changes in Demand (Economic Slow Down)

Example Infrastructure Analyst Assessment

#	Asset Type	1	2	3	4	5	6	7	8	9	10
1		0	0	0	0	0	0	0	0	0	0
2		1	1	1	1	1	1	0	1	0	1
3		0	0	0	0	0	0	0	0	0	0
4		0	0	0	1	1	0	0	0	0	0
5		1	0	0	0	1	0	0	0	0	1
6		0	0	0	0	0	0	0	0	0	0
7		0	0	0	0	0	0	0	0	0	0
8		3	2	2	3	3	3	0	2	3	2
9		2	1	1	2	2	2	0	1	2	2
10		0	0	0	0	0	0	0	0	0	0

BEA Input-Output Data

- Quantifies the direct and indirect effects of changes in final demand on the economy.
- The elements in the total requirements table could be used as a metric of how strong the linkage is between industries.

	Petroleum and coal products	Chemical products	Wholesale trade	Air transportation
Petroleum and coal products	1.1117	0.0575	0.008	0.1417
Chemical products	0.0366	1.2856	0.0096	0.0138
Wholesale trade	0.0655	0.0966	1.0382	0.0369
Air transportation	0.0029	0.0043	0.0036	1.0027

- Relative strength of dependencies could be categorized based on relative magnitude

	Petroleum and coal products	Chemical products	Wholesale trade	Air transportation
Petroleum and coal products	------	High	High	Medium
Chemical products	High	------	High	Low
Wholesale trade	High	High	------	Medium
Air transportation	High	High	High	------

Note that this data was used as an indicator not as a direct input – economic relationships are not functional relationships

Mapping the Sensitivity Study Matrix to the Asset Type Level

	S1	S2	S3	S4	S5	S6
S1		0.00	0.00	0.00	0.00	0.00
S2	0.00		0.00	0.00	0.00	0.00
S3	0.00	0.00		0.00	0.00	0.00
S4	0.00	0.00	0.00		0.00	0.00
S5	0.00	0.00	0.00	0.00		0.00
S6	0.19	0.17	0.00	0.83	0.12	

- *Asset interdependencies are drawn from the corresponding infrastructure interdependencies*
- *Because of sector-based modeling, we cannot analyze interdependencies between asset types from the same sector.*

#	Asset Type	1	2	3	4	5	6	7	8	9	10
1											
2						0.83			0	0	
3											
4											
5			0						0	0	
6											
7											
8			0.03			0.03					
9			0.03			0.03					
10											
11											

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Combining all of the information

The final matrix was scaled using the mapping below.

#	Asset Type	1	2	3	4	5	6	7	8	9	10
1			0	0	0	0	0	0	0	0	0
2		1		1	1	2	1	0	1	0	1
3		0	0		0	0	0	0	0	0	0
4		0	0	0		2	2	0	0	0	0
5		1	0	0	1		1	0	0	0	2
6		0	0	0	0	0		0	0	0	0
7		0	0	0	0	0	0		0	0	0
8		2	0	1	2	1	0	0		3	0
9		3	2	2	3	3	3	0	1		3
10		0	0	0	0	0	0	0	0	0	

#	Asset Type	1	2	3	4	5	6	7	8	9	10
1			0	0	0	0	0	0	0	0	0
2		0.1		0.1	0.1	0.2	0.1	0	0.1	0	0.1
3		0	0		0	0	0	0	0	0	0
4		0	0	0		0.2	0.2	0	0	0	0
5		0.1	0	0	0.1		0.1	0	0	0	0.2
6		0	0	0	0	0		0	0	0	0
7		0	0	0	0	0	0		0	0	0
8		0.2	0	0.1	0.2	0.1	0	0		0.4	0
9		0.4	0.2	0.2	0.4	0.4	0.4	0	0.1		0.4
10		0	0	0	0	0	0	0	0	0	

- Sensitivity analysis and historical data compared to qualitative approach and updated
- Rationale for final score noted.
- Mapping for final scoring:
  - 1 → 0.1
  - 2 → 0.2
  - 3 → 0.4

Common Issues

- Challenges in mapping to/from infrastructure types and sectors to model variables and BEA industries
- Temporal issues: impact duration, etc.
- Scenario neutral is somewhat arbitrary, scenario specific was impossible in needed timeframe
- Many strong assumption/approximations needed to apply available information for present application
- Some asset types have no appreciable interdependencies
- May need an adjustable parameter so that relative interdependence is calculated – absolute is harder
- Some numbers may be purely expert inference
- Combining it all is final challenge

Conclusions

- Aggregate interdependency modeling can inform risk assessment process
- Need to consider the context and scope very carefully
- Need to address uncertainty in outcome due to variability in initiating event, temporal considerations, etc.