Simulation of Infrastructure Interdependencies Dynamics for Disaster Response Coordination

UBC – I2Sim Team

JIIRP Canada Project

- PSEPC (Public Safety and Emergency Preparedness Canada)
- NSERC (Natural Sciences and Engineering Research Council of Canada)

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UBC's Partners

- British Columbia Transmission Corporation
- BC Hydro
- Telus Corporation
- Greater Vancouver Regional District
- Vancouver International Airport Authority

Collaborators

- David Grigg (UBC, Infrastructure & Services Planning, Assoc. Director)
- Gord Apperley (UBC Utilities, Director)
- John Manougian (UBC Hospital, Facilities Manager)
- Rick Critchlow (Fire Hall UBC)
- Sheena Vivian (BCHydro, Emergency Planning Manager)
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- Jeff Cornell (JIBC)
- David Zajdlik (UBC Health & Safety Committee)
- James Whyte (Regional Manager for B.C. PEP)
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- Kevin Molloy (YVR, Vice President & Chief Information Officer)
- Ivan Kusal (Telus, Director Corporate Business)

Our Mandate

"Develop innovative solutions to mitigate large disaster situations involving multiple infrastructure systems"

The Public Safety Problem

- Towns, municipalities and organizations are often not aware of the (hidden) interdependencies of their critical infrastructure.
- There is no mechanism to determine how their critical infrastructure system will react during an emergency, or what vulnerabilities exist in the system
- They do not have a way of validating and optimizing emergency response plans and decision making related to critical infrastructure

Result:

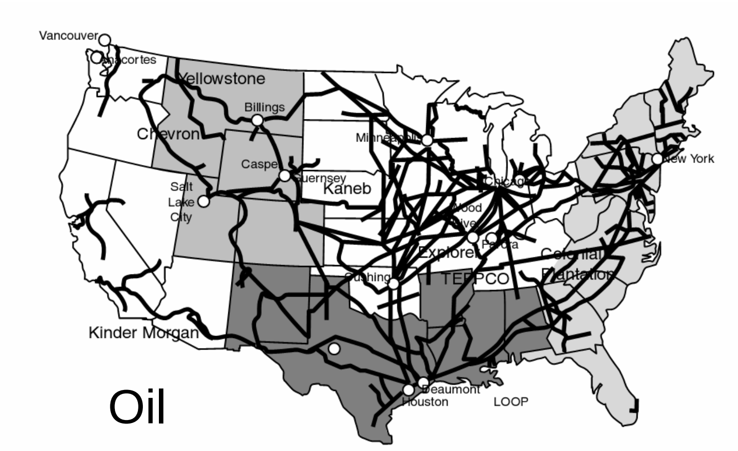
- *During an emergency or disaster, unexpected interdependencies appear that can cause emergency response plans to fail - sometimes catastrophically.*
- *Decisions are made that are not optimal. Ie. More lives may have been saved if better decisions had been made.*

Our Contribution: I2Sim – Critical Infrastructure Interdependencies Simulator

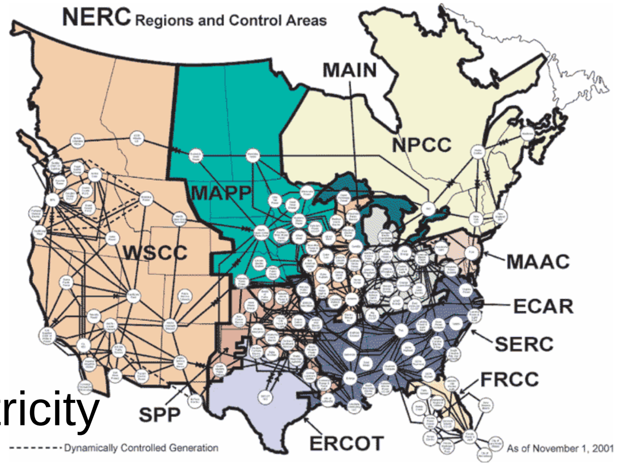
- I2Sim allows users to model the critical infrastructure and the associated interdependencies of a town, municipality or organization
- A emergency event can be simulated and a full simulation executed to see the effects on critical infrastructure
- The simulator can model the effect of decisions made by emergency management command and control
- Different scenarios can be executed in order to select the best course of action for emergency response planning or execution
- Simulations can be connected together to model interdependencies between larger entities (eg. All of BC, Canada)

- Result:
  - Municipalities and organizations can validate and test their critical infrastructure and optimize emergency response plans.
  - CI Simulations can be “grown” to provincial or national level.

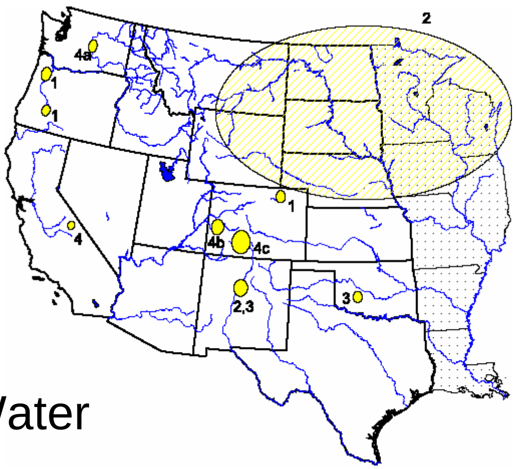
Complex Interdependent Multilayered Networks



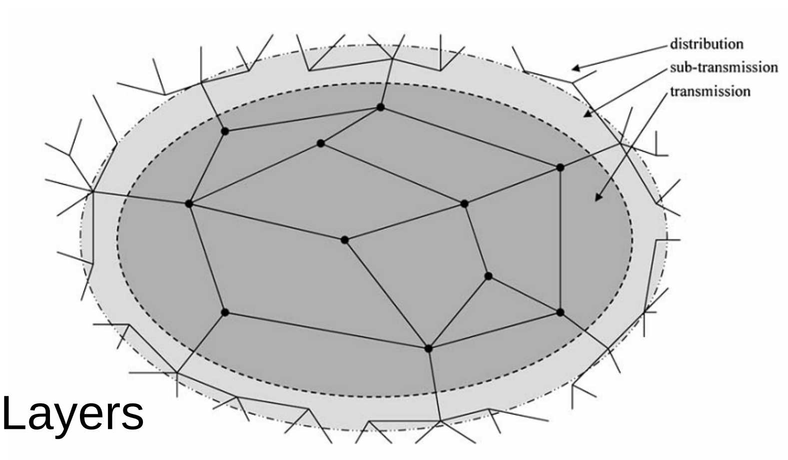
Oil



Electricity



Water



Layers

I2Sim Ontology

Ontology

- From Greek ??, genitive ??t??: of being (part. of e??a?: to be)
- Who are the objects in our world, where are they located, what do they look like at a given moment, how and why they change in time?

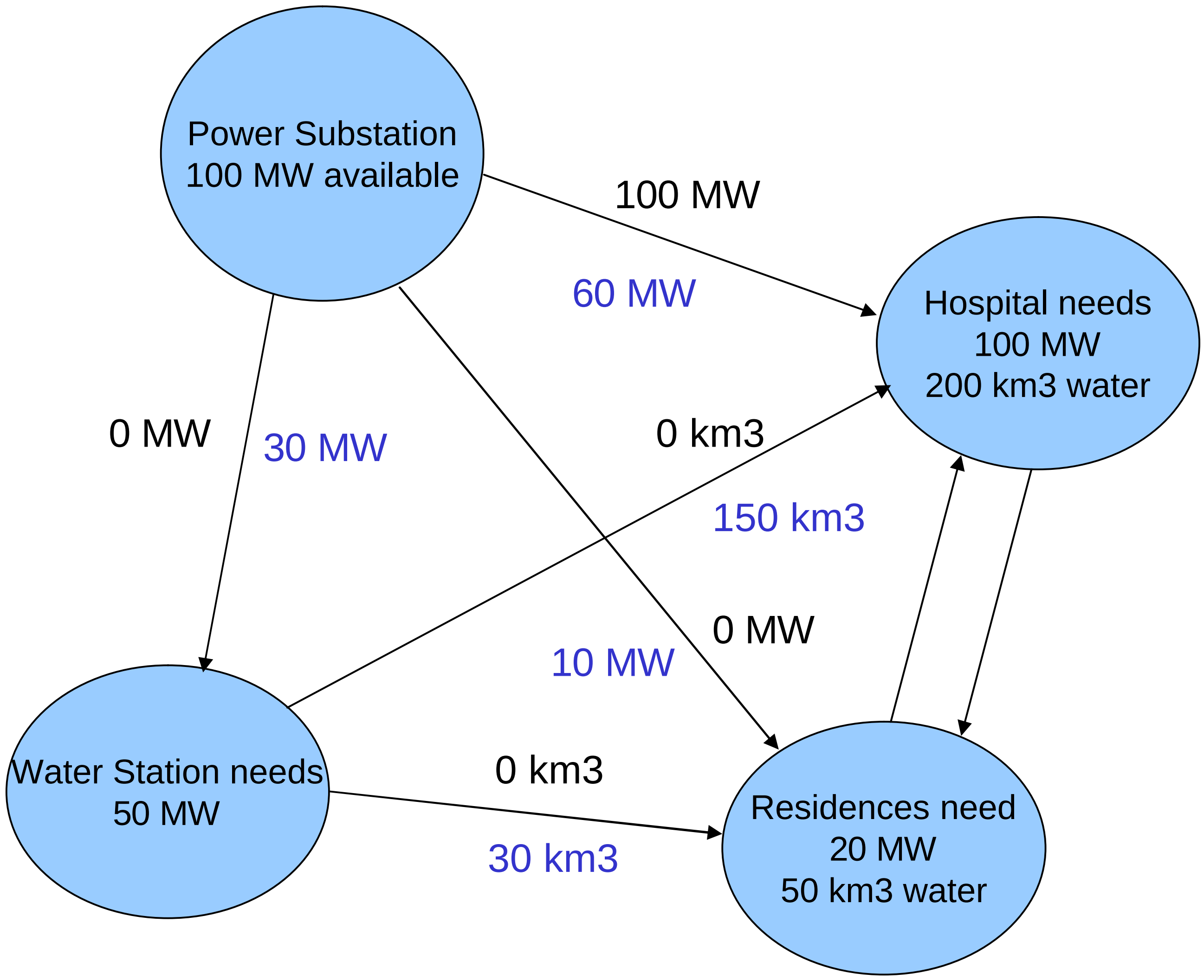
I2Sim Ontology

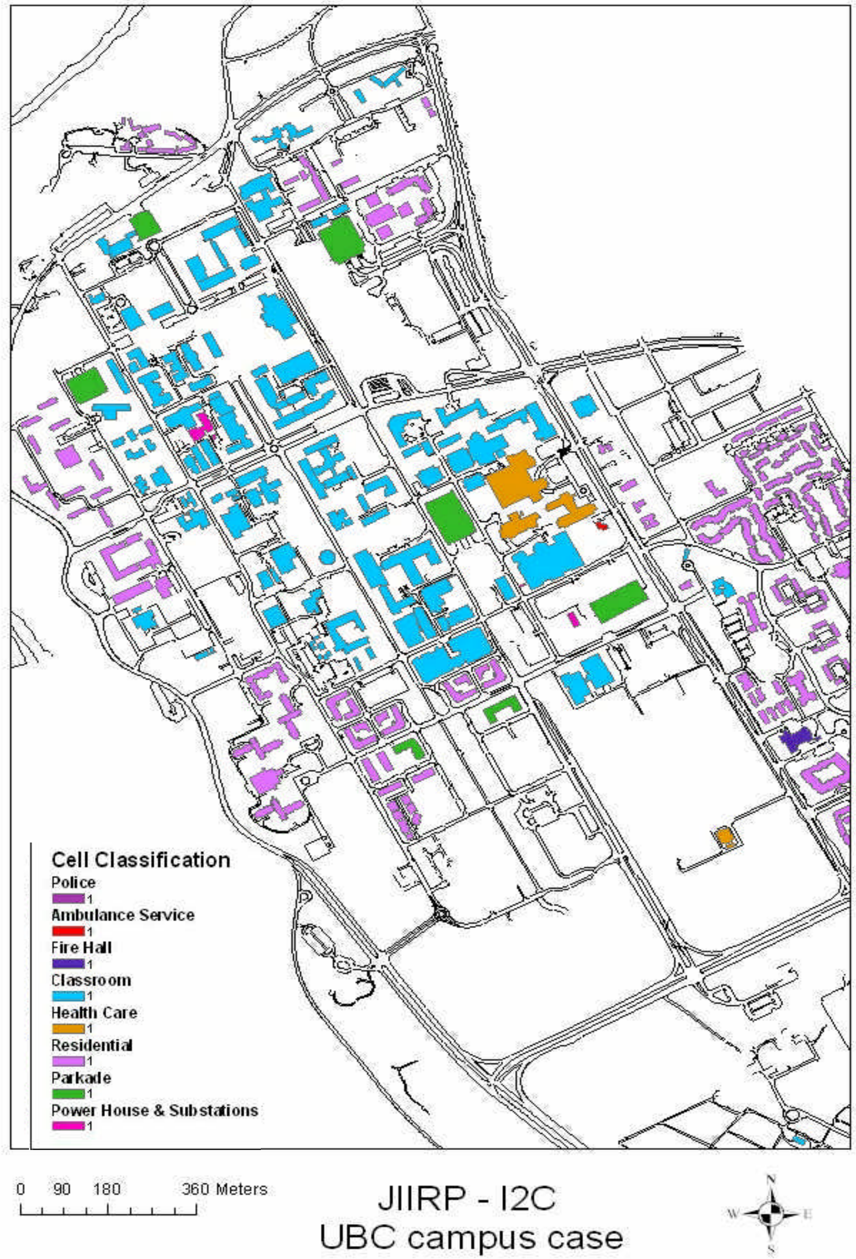
- Multiple dissimilar systems need to be solved simultaneously
- Only external representation is needed to coordinate decision making across multiple infrastructures

I2Sim Model

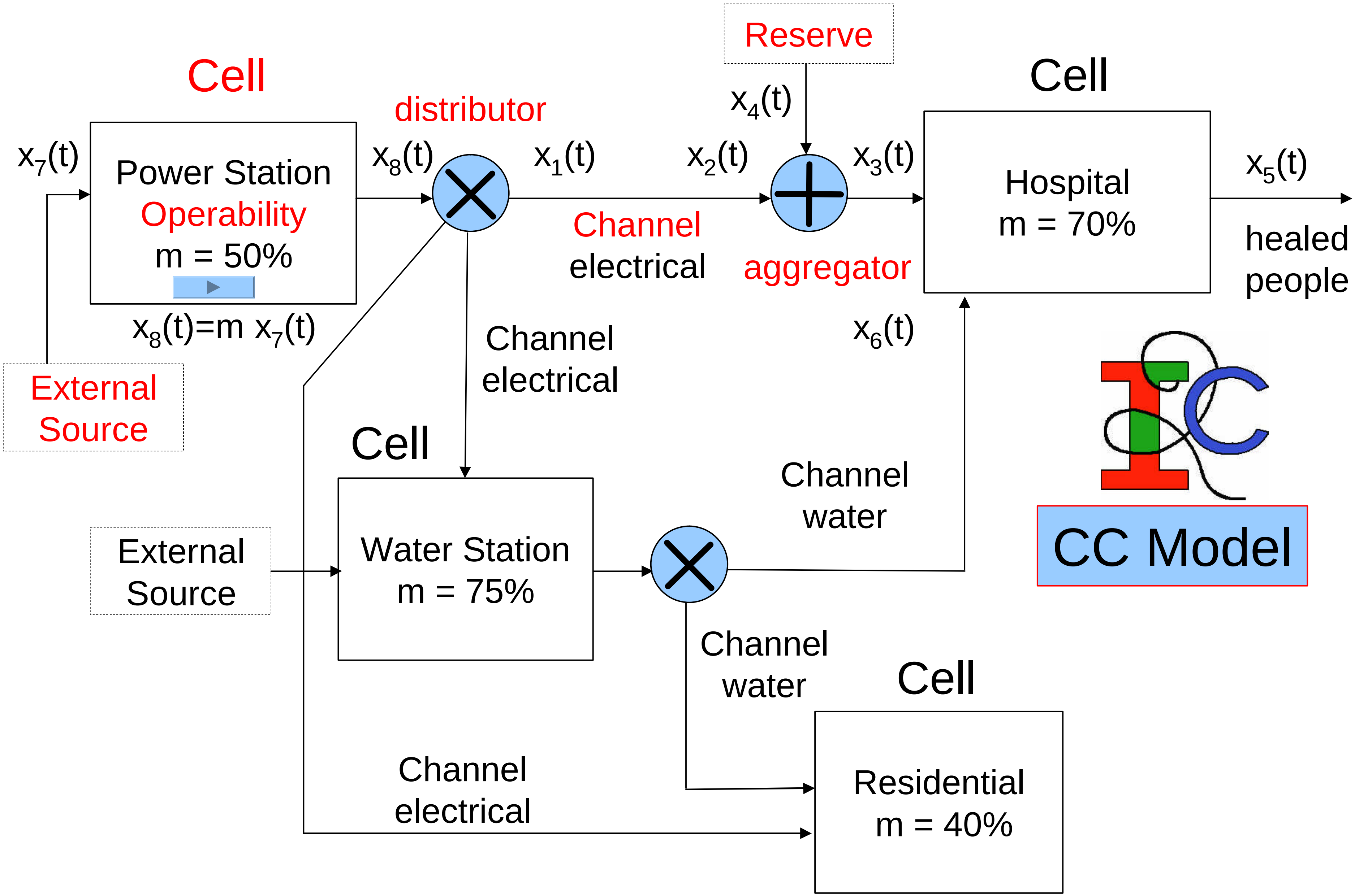
A complex infrastructure system is made up of basic components:

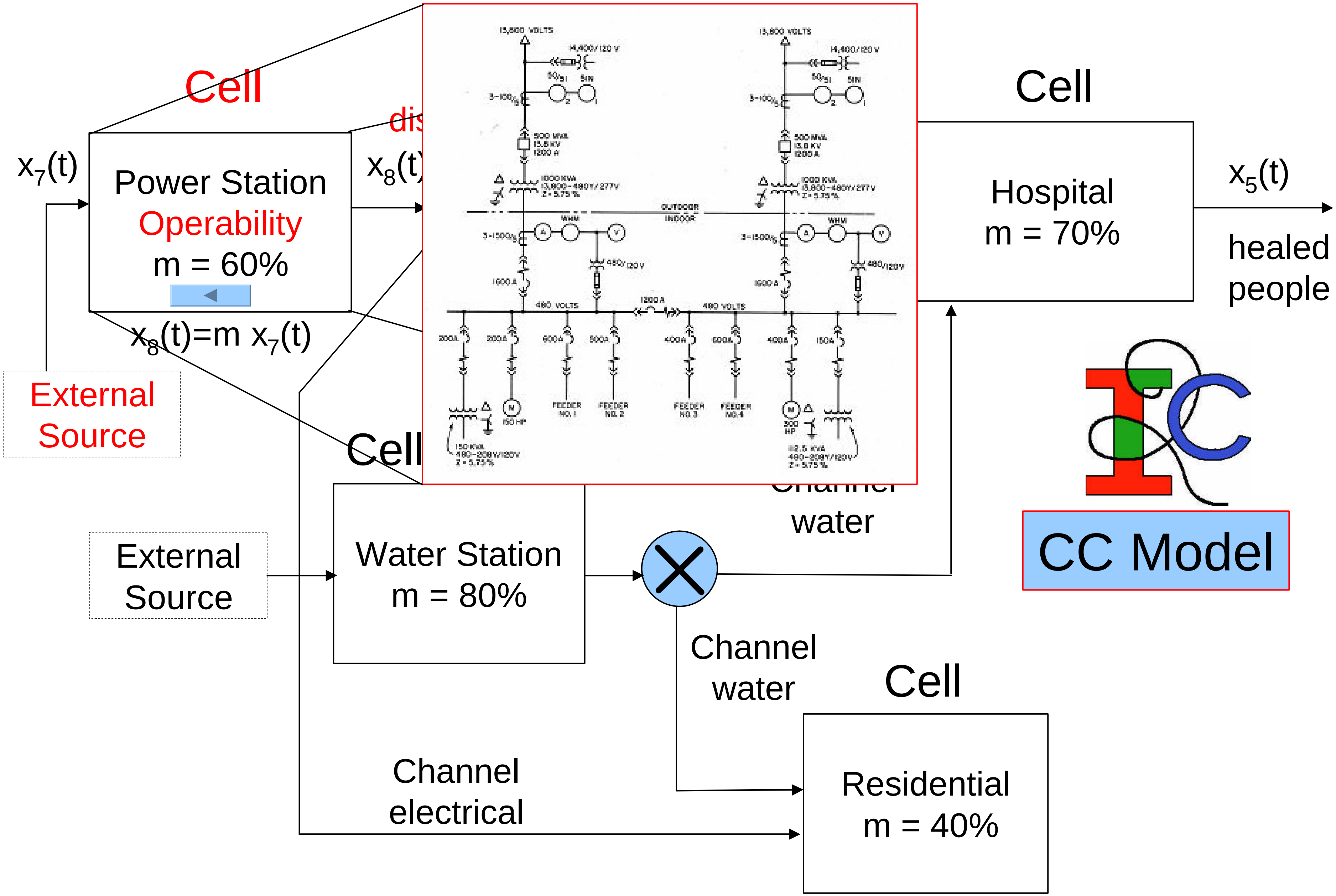
1. Cell (Production Component): For example, a hospital cell requires inputs: electricity, water, doctors, medicines, etc. and produces outputs: patients healed
2. Channel (Transportation Component): The electricity to the hospital is carried by wires, the water is carried by pipes, the doctors are carried by the transportation system
3. Dispatching (Decisions Component): Determines resource allocation during scarsity

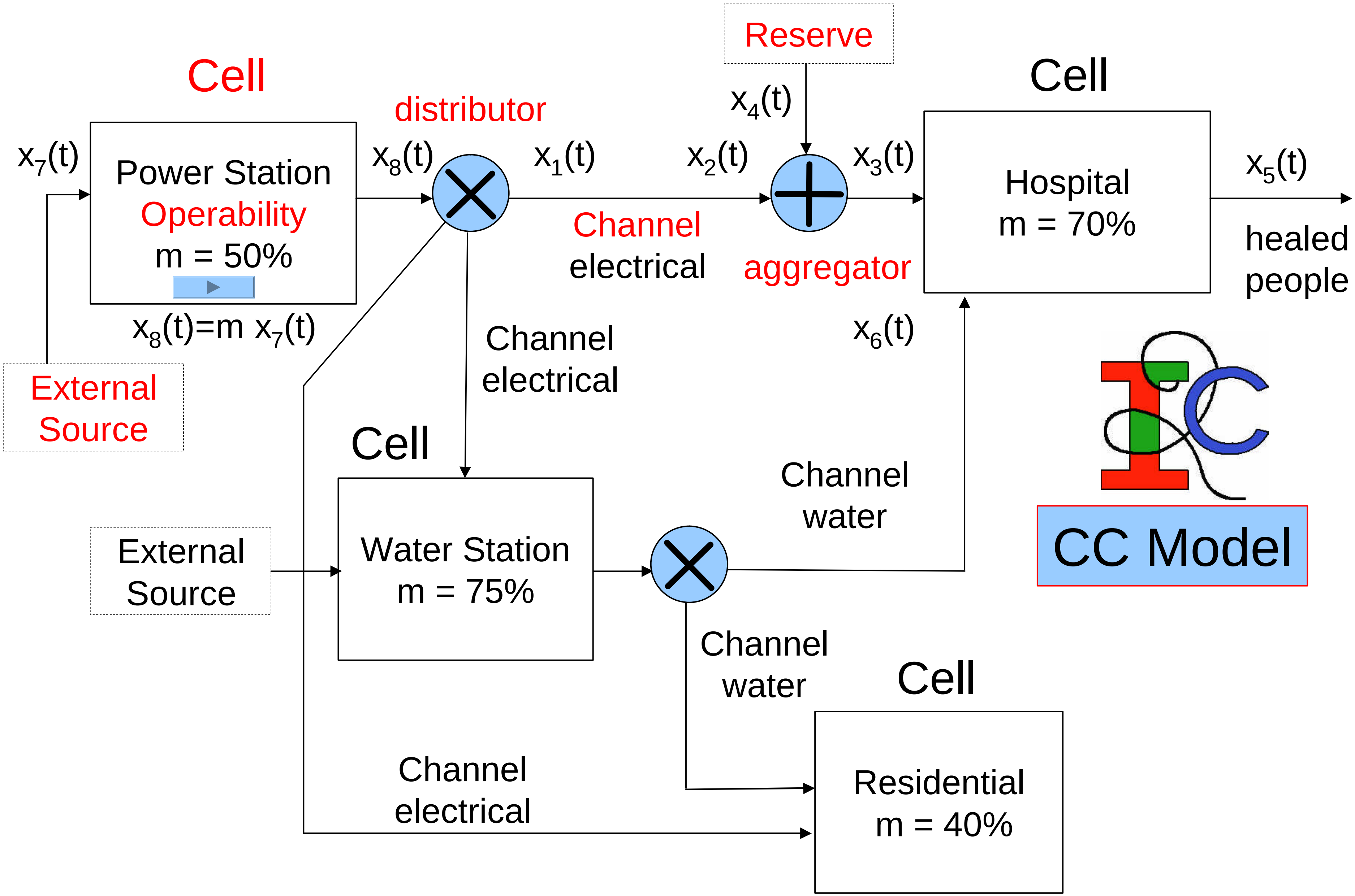

Power Substation
100 MW available
100 MW
60 MW
Hospital needs
100 MW
200 km3 water
0 MW
30 MW
0 km3
150 km3
0 MW
10 MW
Water Station needs
50 MW
0 km3
30 km3
Residences need
20 MW
50 km3 water



JIIRP - I2C
UBC campus case


Cell
Power Station
Operability
m = 50%
x7(t)
x8(t)=m x7(t)
External
Source
distributor
x8(t)
x1(t)
x2(t)
Channel
electrical
Reserve
x4(t)
aggregator
x3(t)
Cell
Hospital
m = 70%
x5(t)
healed
people
x6(t)
Channel
electrical
Cell
Water Station
m = 75%
External
Source
Channel
water
Channel
water
Cell
Residential
m = 40%
Channel
electrical
CC Model


Cell
dis
Power Station
Operability
m = 60%
$x_7(t)$
$x_8(t)$
$x_8(t)=m\ x_7(t)$
External
Source
Cell
Hospital
m = 70%
$x_5(t)$
healed
people
Cell
Water Station
m = 80%
External
Source
Channel
water
Channel
water
Cell
Residential
m = 40%
Channel
electrical
CC Model


Reserve
$x_4(t)$
Cell
distributor
Cell
$x_7(t)$
Power Station
Operability
m = 50%
$x_8(t)$
$x_1(t)$
$x_2(t)$
$x_3(t)$
Hospital
m = 70%
$x_5(t)$
healed people
Channel electrical
aggregator
$x_8(t)$=m $x_7(t)$
$x_6(t)$
External Source
Channel electrical
Cell
Channel water
CC Model
External Source
Water Station
m = 75%
Channel water
Cell
Channel electrical
Residential
m = 40%

Events that Change the System

- Disasters (e.g., earthquake) affect cell's m values and channel's a and Tau values. They also affect the external sources values
- Psychological Responses (e.g., panic) affect cell's m values and channel's a and Tau values
- Human Processes (e.g., bureaucratic red tape) affect cell's m values and channel's a and Tau values
- Human Decisions determine distributor ratios when resources are limited

Indices

- Operability ("m" factor): Assuming full inputs are available, a power substation designed to deliver an output of 200 MW but because of earthquake damage can only deliver 100 MW has m = 0.5
- Resource Availability ("r" factor): Reduced cell output which is not due to reduced cell's performance but to scarcity of resources. For example r = 0.7 means that due to lacking input or reserve resources the cell will only be able to produce 70% of its capacity even though m=1

Wellness

- Wellness ("w" factor): Capability of producing output:

  w = output_capable/output_rated

- Wellness can deteriorate by a reduction in m, a reduction in r, or a reduction in both

I2Sim Architecture

Water Station Cell
Human Readable Table (HRT)

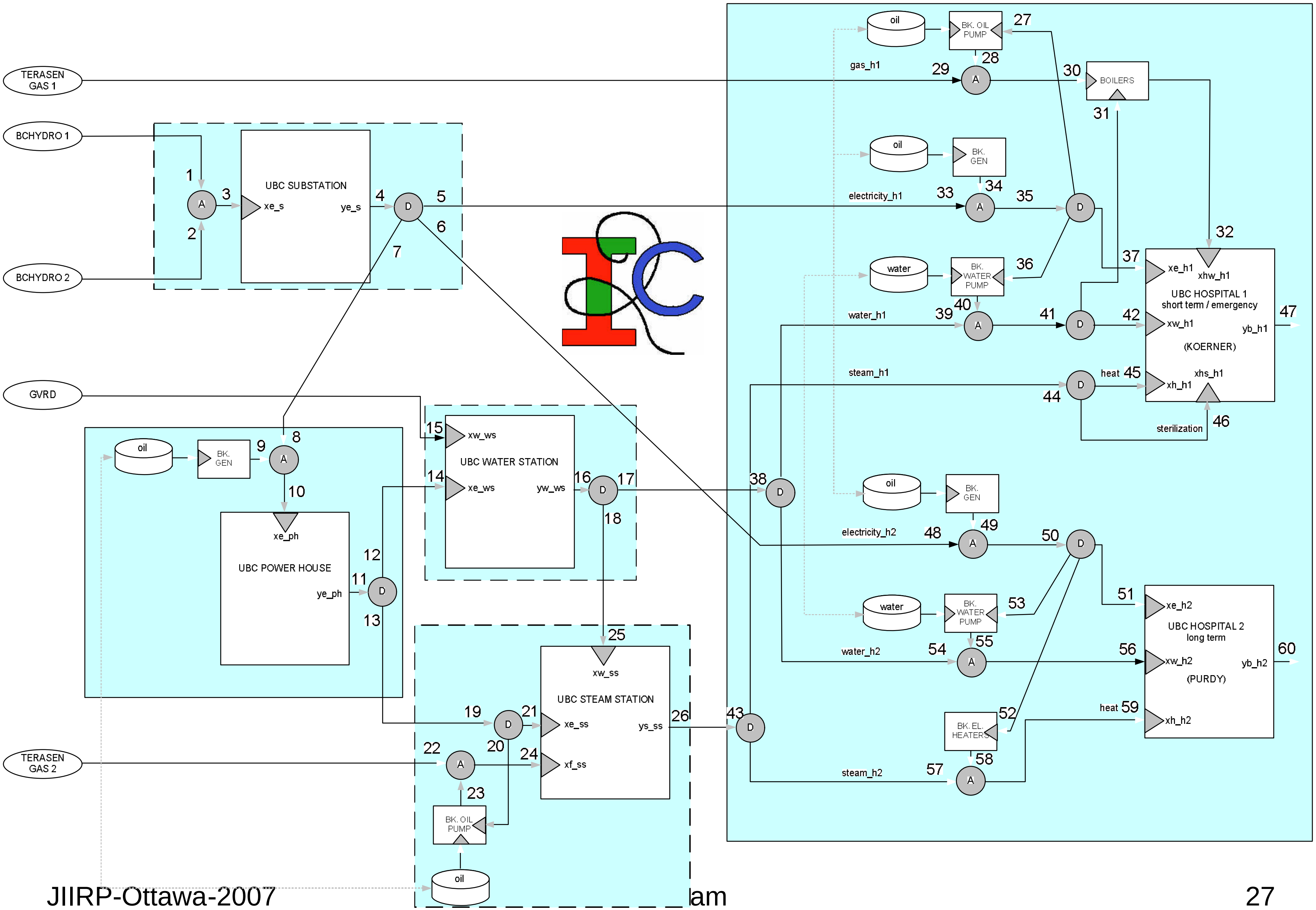
Input (x)		**Internal (m)**		**Output (y)**
Power	Water	Pumps	m	Water
100%	100%	2	1.0	100%
100%	100%	1	0.5	50%
50%	100%	2 or 1	0.5-1.0	50%
0%	100%	2 or 1	0.5-1.0	0%
100%	50%	2 or 1	0.5-1.0	50%
100%	0%	2 or 1	0.5-1.0	0%
0%	0%	2 or 1	0.5-1.0	0%

Hospital Cell in Winter HRT

Input										output		
xw1	xe1	xs1	xh1	xe2	xs2	doctor s	nurse s	meds	patien ts	Long	Short	Emer gency
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%
100%	0%	100%	100%	0%	100%	100%	100%	100%	100%	0%	0%	0%
100%	100%	0%	100%	100%	0%	100%	100%	100%	100%	0%	80%	80%
100%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%	90%	0%
100%	100%	100%	100%	100%	100%	0%	100%	100%	100%	0%	0%	0%
100%	100%	100%	100%	100%	100%	100%	0%	100%	100%	0%	0%	0%
100%	100%	100%	100%	100%	100%	100%	100%	0%	100%	0%	0%	0%
100%	100%	100%	100%	100%	100%	100%	100%	100%	0%	0%	0%	0%

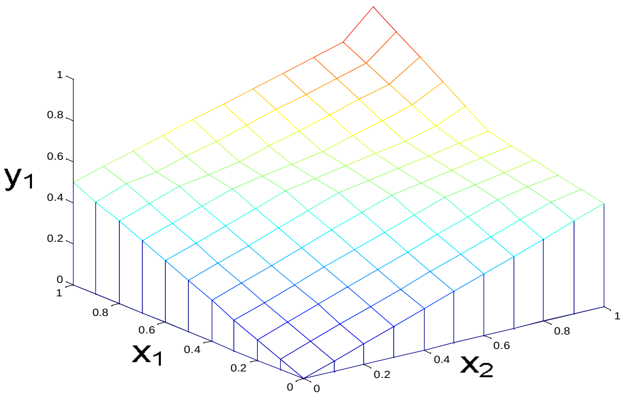
xw1 = water from the powerhouse to the hospital	xh1 = steam for sterilization of the surgery equipment surgery
xe1 = power for the Koerner building	xe2 = power for the Purdy building
xs1 = heating for the Koerner building	xs2 = heating for the Purdy building

I2Sim Cell/Channel (CC) Model from HRT



I2Sim Linearized Cell Model

- Four-region approximation and corresponding table of input/output relationship:



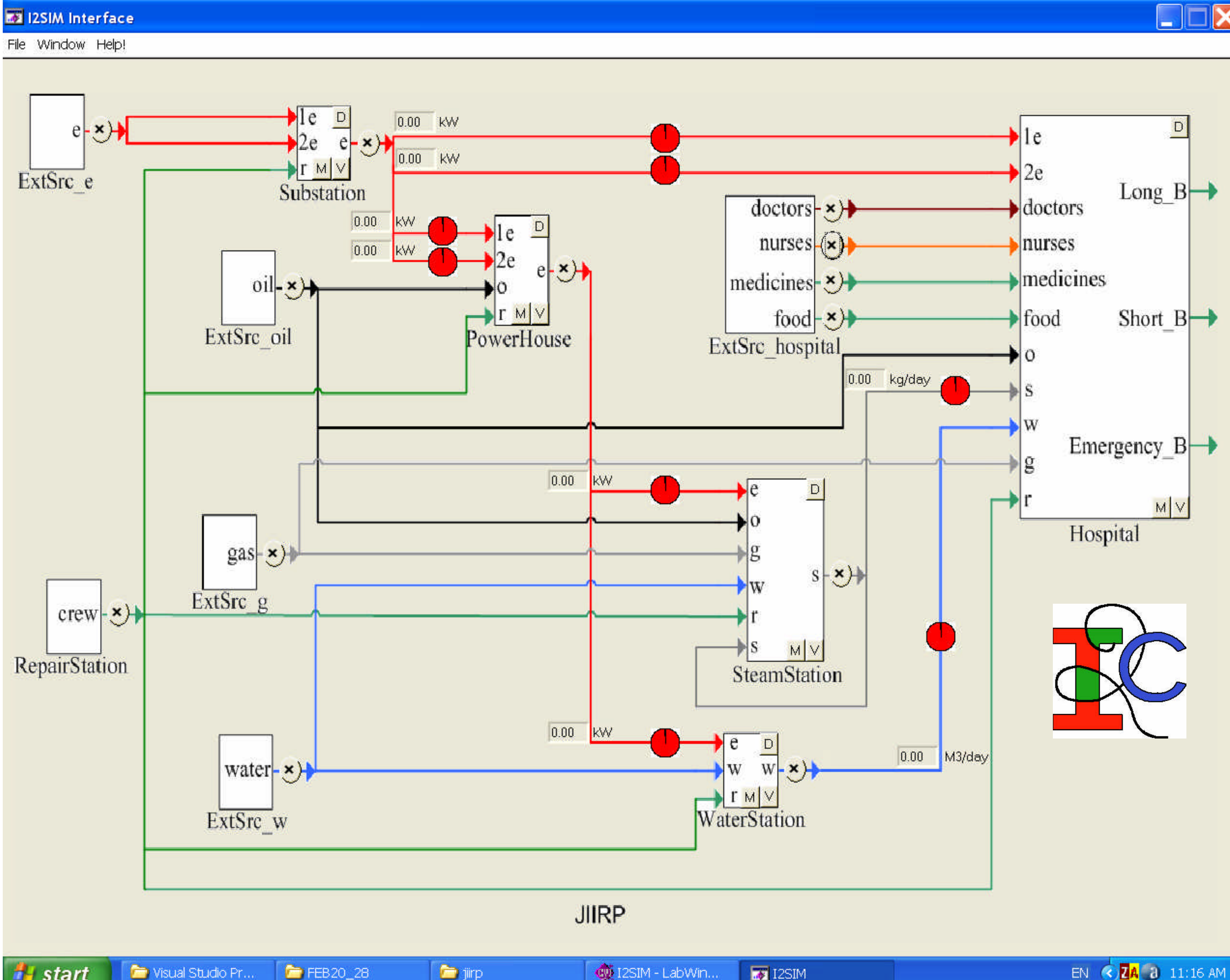
(I) $0.5x_1 + 0.5x_2 = y_1$

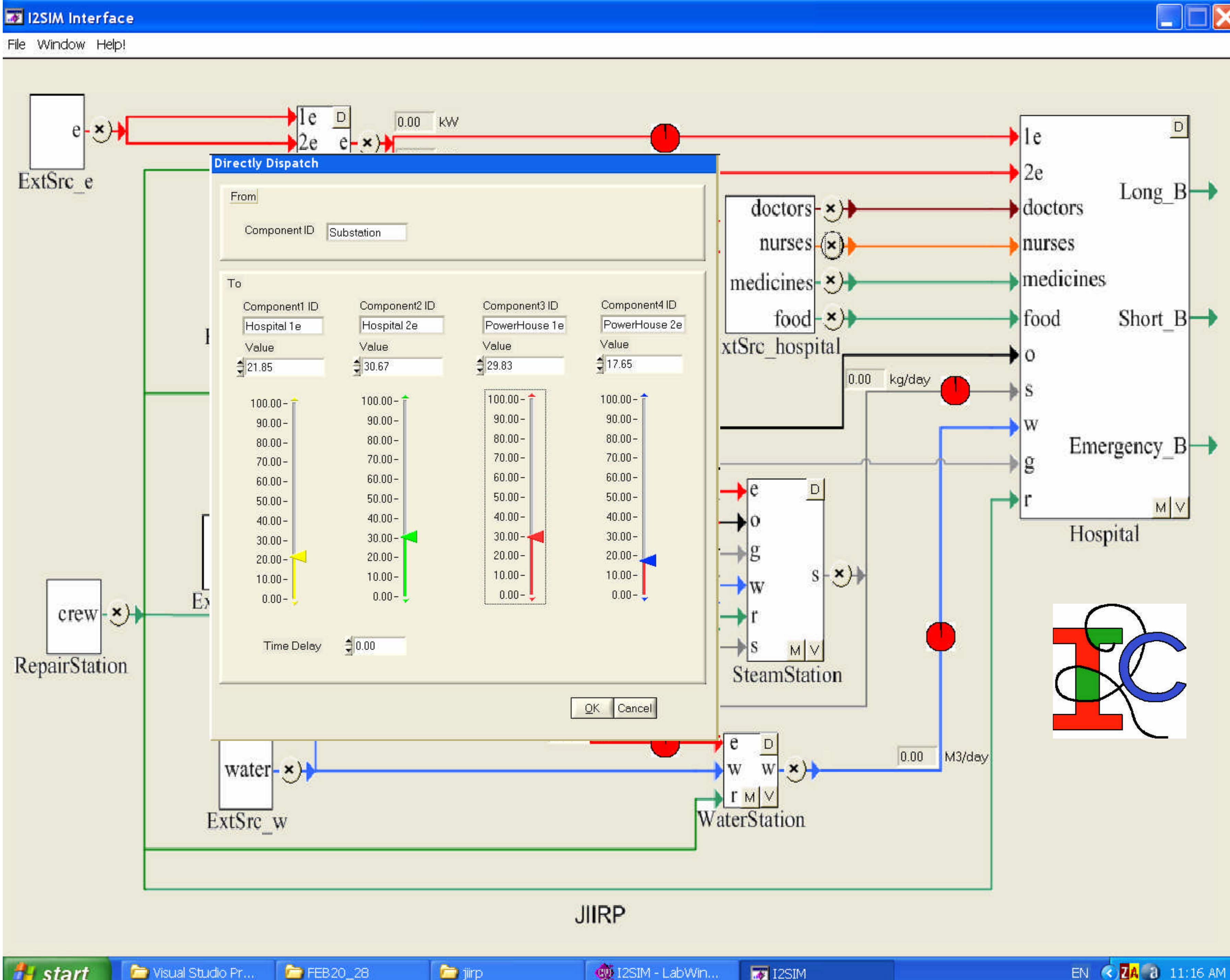
(II) $0.25x_1 + 0.25x_2 = y_1 - 0.25$

(III) $0.40x_1 + 0.56x_2 = y_1 + 0.06$

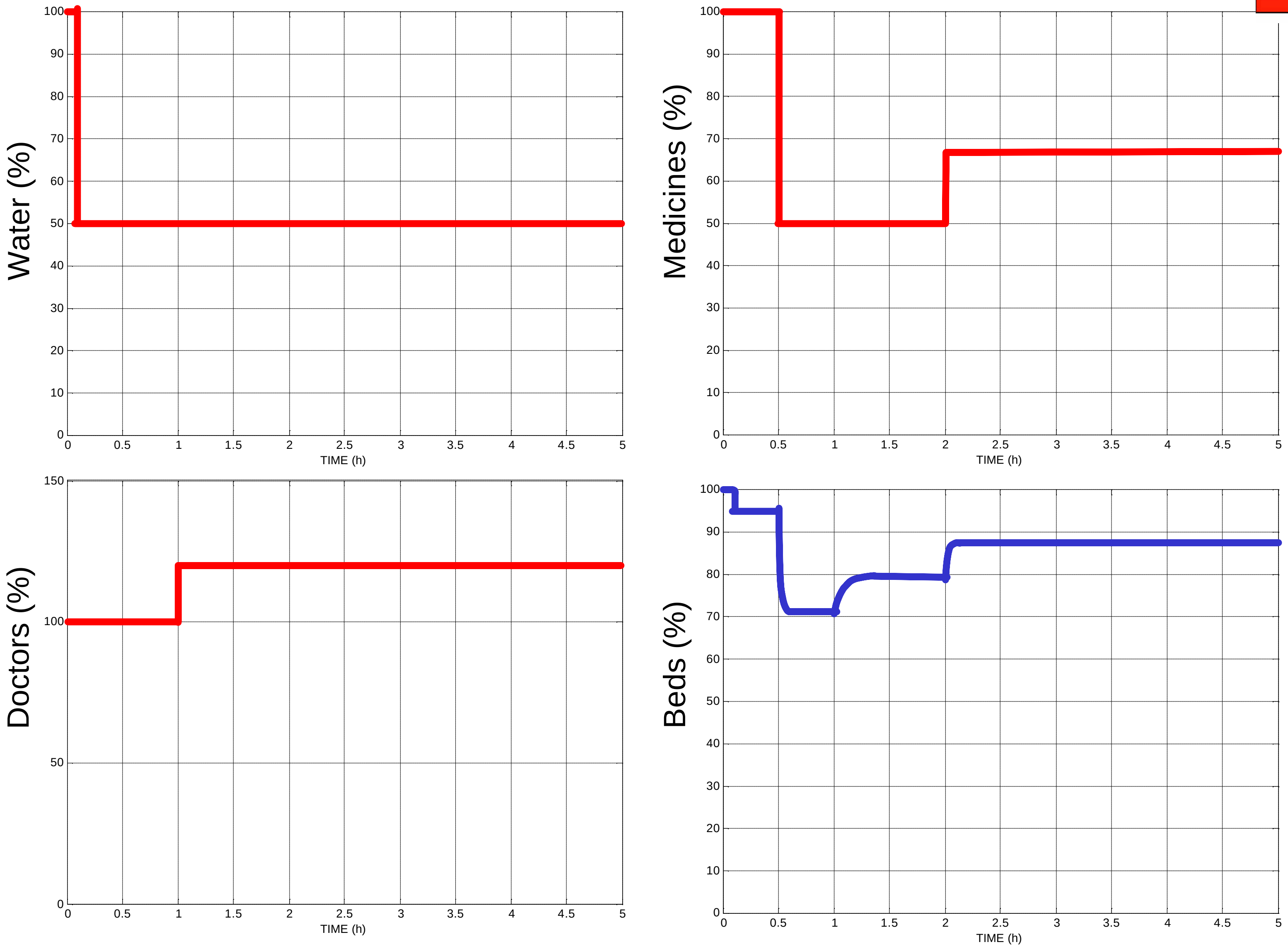
(IV) $1.355x_1 + 0.75x_2 = y_1 + 1.105$

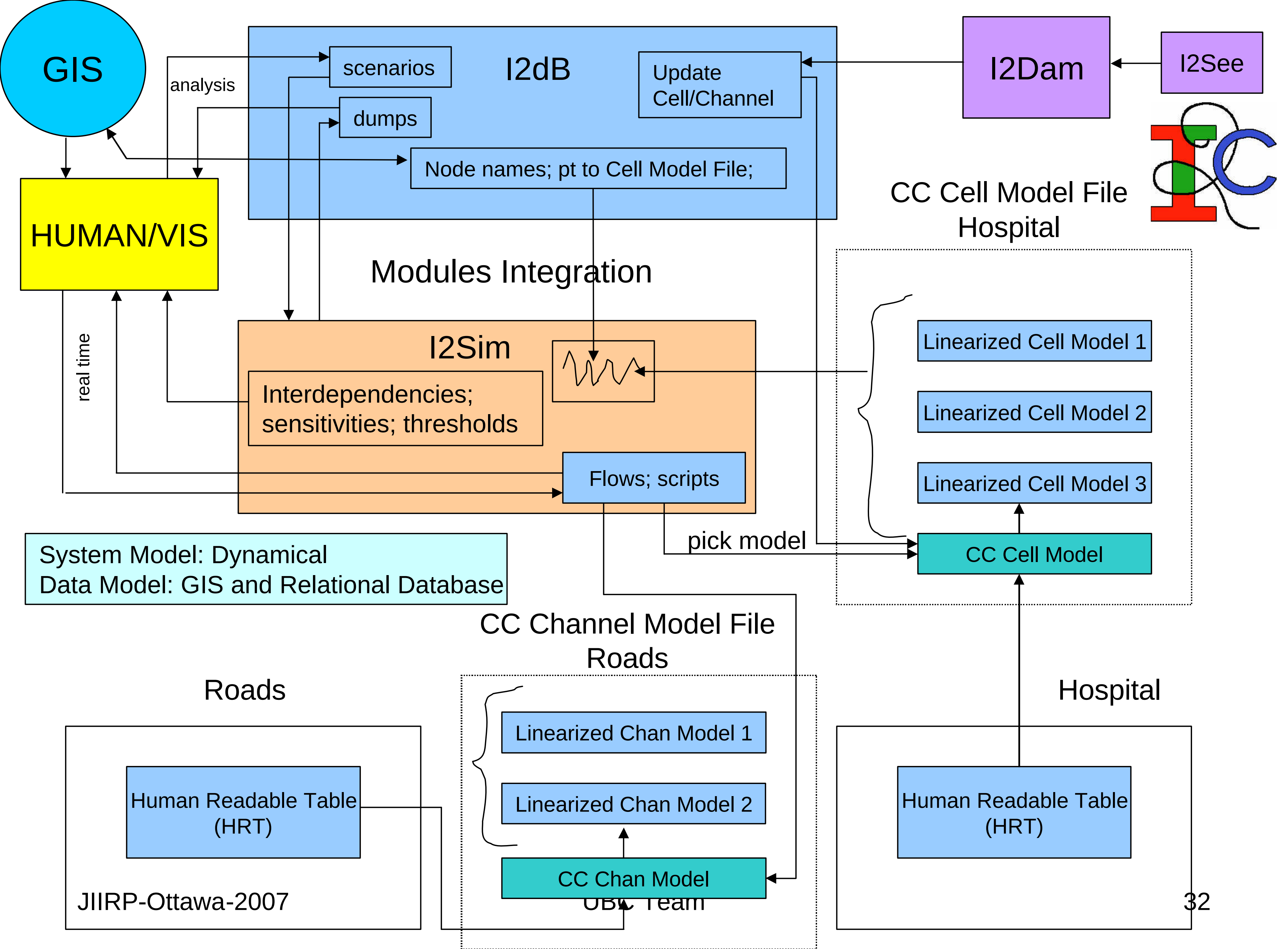
x1	x2	y1
100%	100%	100%
90%	100%	86%
50%	100%	63%
0%	100%	50%
100%	0%	50%
0%	0%	0%


I2SIM Interface
File Window Help!
ExtSrc_e
Substation
ExtSrc_oil
PowerHouse
ExtSrc_hospital
doctors
nurses
medicines
food
Hospital
Long_B
Short_B
Emergency_B
ExtSrc_g
RepairStation
crew
SteamStation
ExtSrc_w
water
WaterStation
0.00 kW
0.00 kg/day
0.00 M3/day
JIIRP
start
Visual Studio Pr...
FEB20_28
jiirp
I2SIM - LabWin...
I2SIM
EN
11:16 AM


I2SIM Interface
File Window Help!
ExtSrc_e
1e
2e
0.00 kW
Directly Dispatch
From
Component ID Substation
To
Component1 ID Hospital 1e
Value 21.85
Component2 ID Hospital 2e
Value 30.67
Component3 ID PowerHouse 1e
Value 29.83
Component4 ID PowerHouse 2e
Value 17.65
Time Delay 0.00
OK Cancel
doctors
nurses
medicines
food
xtSrc_hospital
0.00 kg/day
Long_B
Short_B
Emergency_B
Hospital
SteamStation
crew
RepairStation
water
ExtSrc_w
0.00 M3/day
WaterStation
JIIRP
start
Visual Studio Pr...
FEB20_28
jiirp
I2SIM - LabWin...
I2SIM
11:16 AM

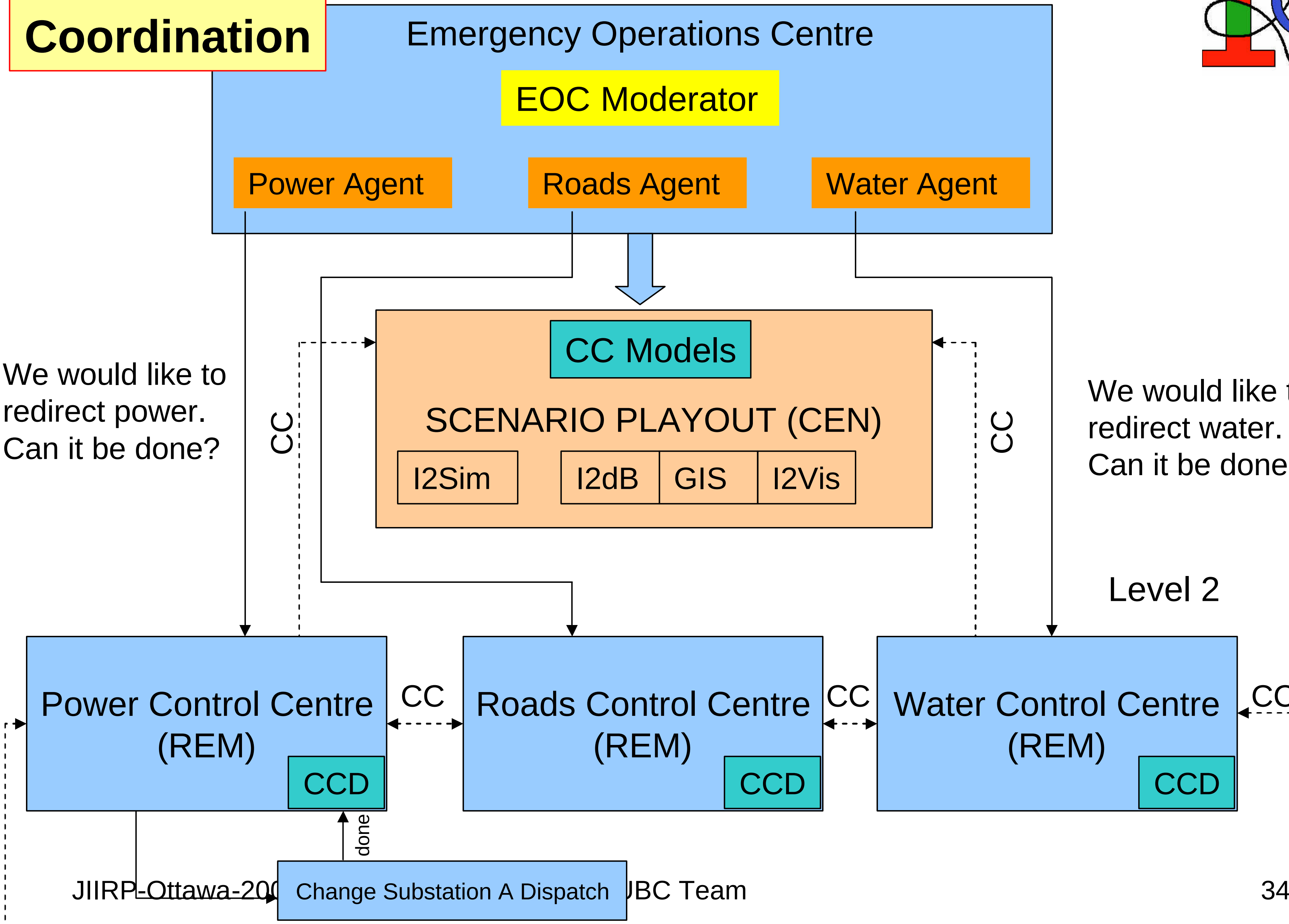
States


Water (%)
Medicines (%)
Doctors (%)
Beds (%)
TIME (h)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
150

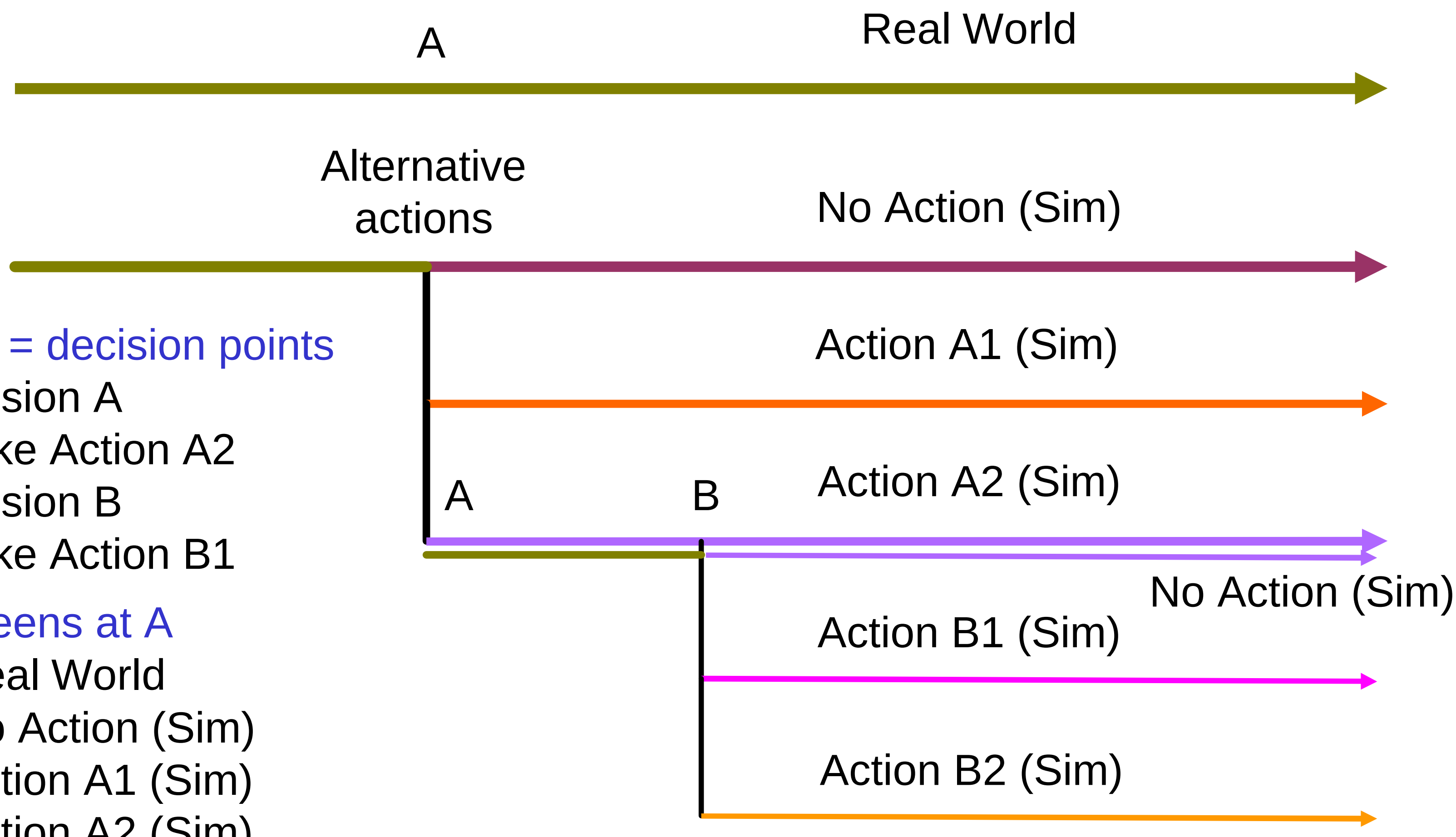

GIS
I2dB
scenarios
analysis
dumps
Update Cell/Channel
Node names; pt to Cell Model File;
I2Dam
I2See
HUMAN/VIS
CC Cell Model File
Hospital
Modules Integration
real time
I2Sim
Interdependencies; sensitivities; thresholds
Flows; scripts
Linearized Cell Model 1
Linearized Cell Model 2
Linearized Cell Model 3
pick model
CC Cell Model
System Model: Dynamical
Data Model: GIS and Relational Database
CC Channel Model File
Roads
Roads
Hospital
Linearized Chan Model 1
Linearized Chan Model 2
CC Chan Model
Human Readable Table (HRT)
Human Readable Table (HRT)

I2Sim
Scenario Play Out

Level 1 Coordination



Decision Making Scenario Level 1



A, B = decision points

Decision A

- Take Action A2

Decision B

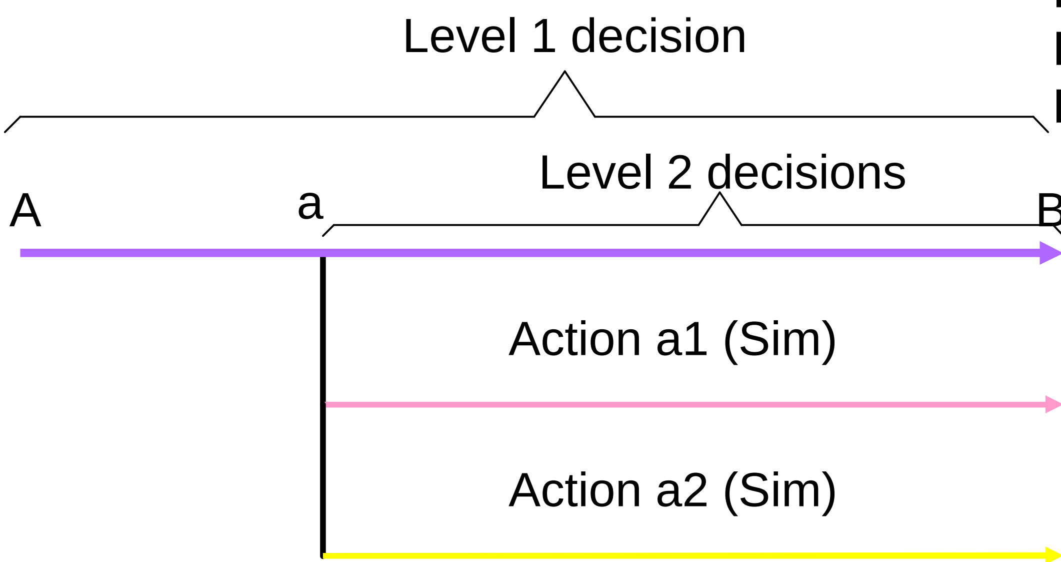
- Take Action B1

Screens at A

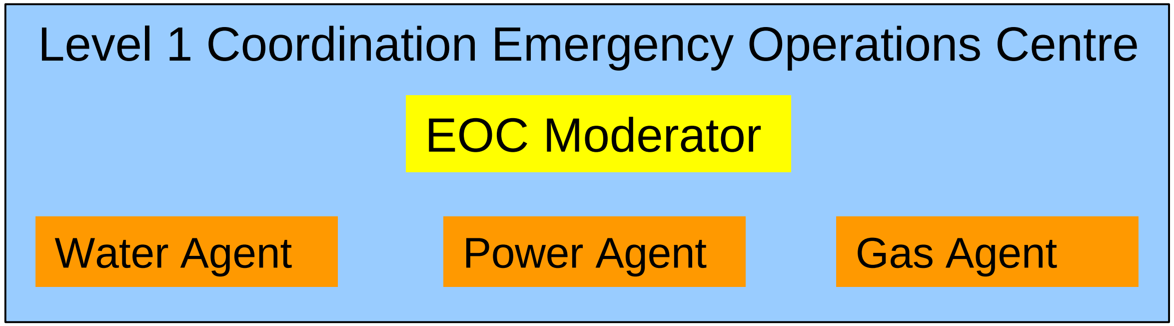
- Real World
- No Action (Sim)
- Action A1 (Sim)
- Action A2 (Sim)

Decision Making Scenario Level 2

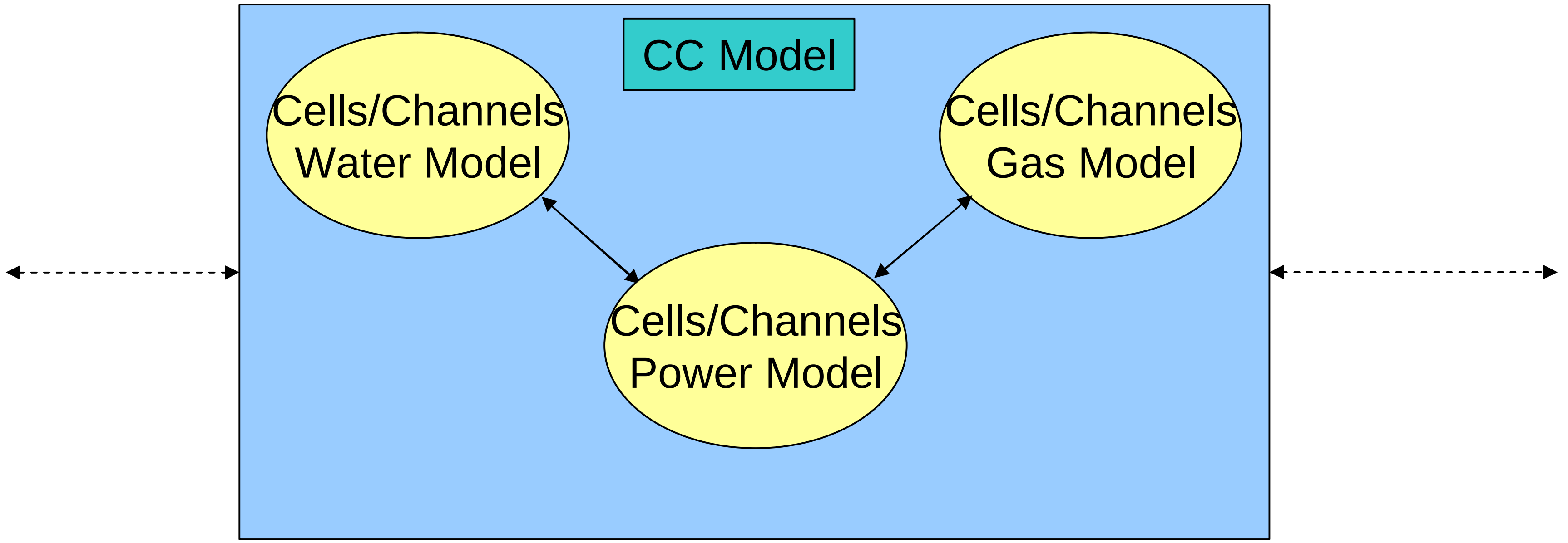
Level 1 decisions: A, B, …
Level 2 decisions: a, b, …
Level 3 decisions: i, ii, …



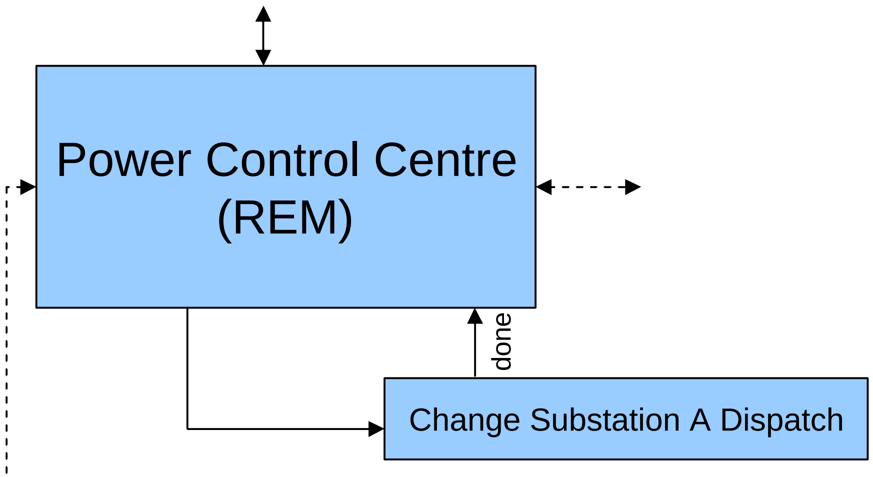
For Level 2, Level 1decision A has already been taken and Level 2 proceeds from there. The combined results of multiple Level 2 decisions will create a new real-world picture which will prompt Level 1 decision B. Level 2 decisions will be the starting point for Level 3 decisions, etc.



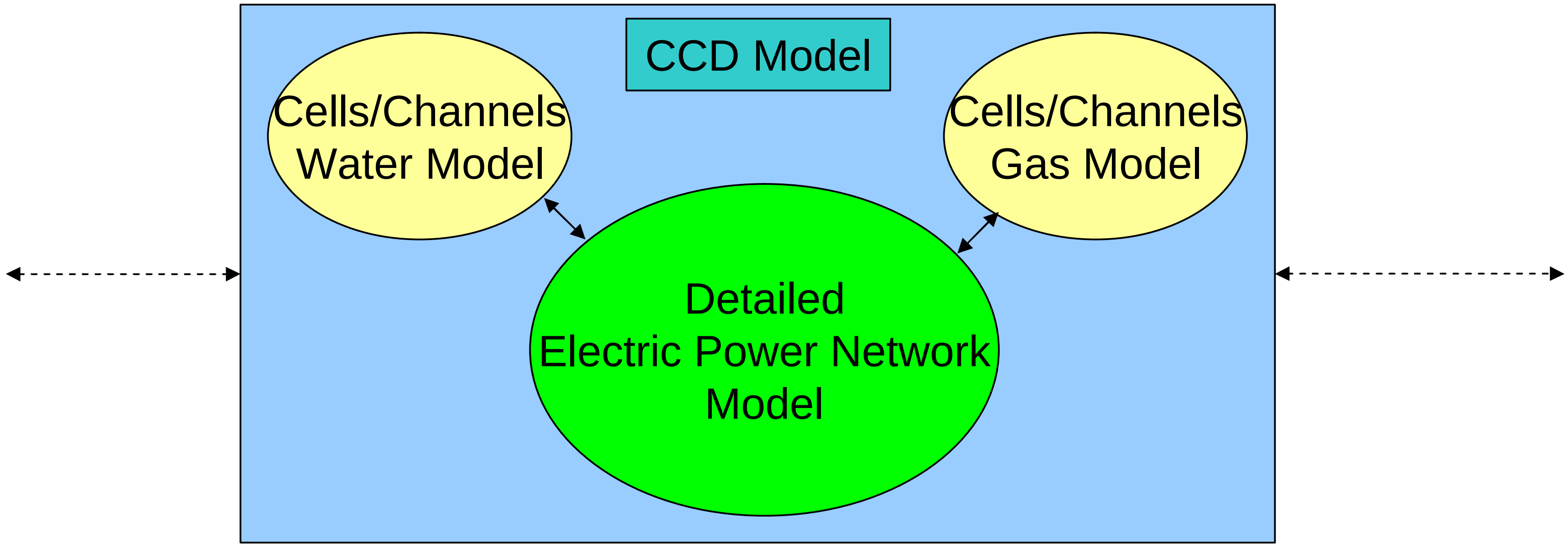
System of Systems



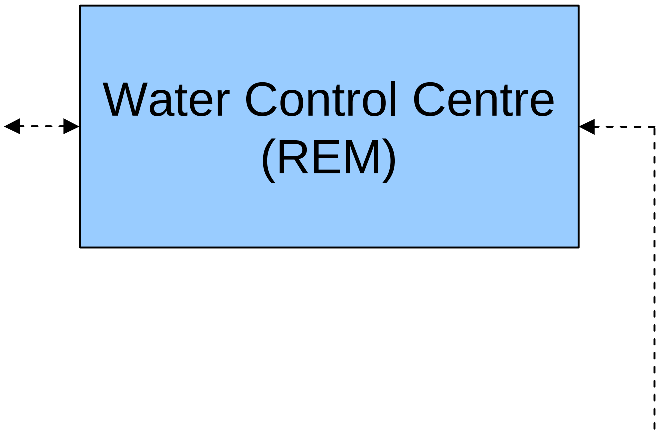
Level 2 Coordination Power System Control Centre



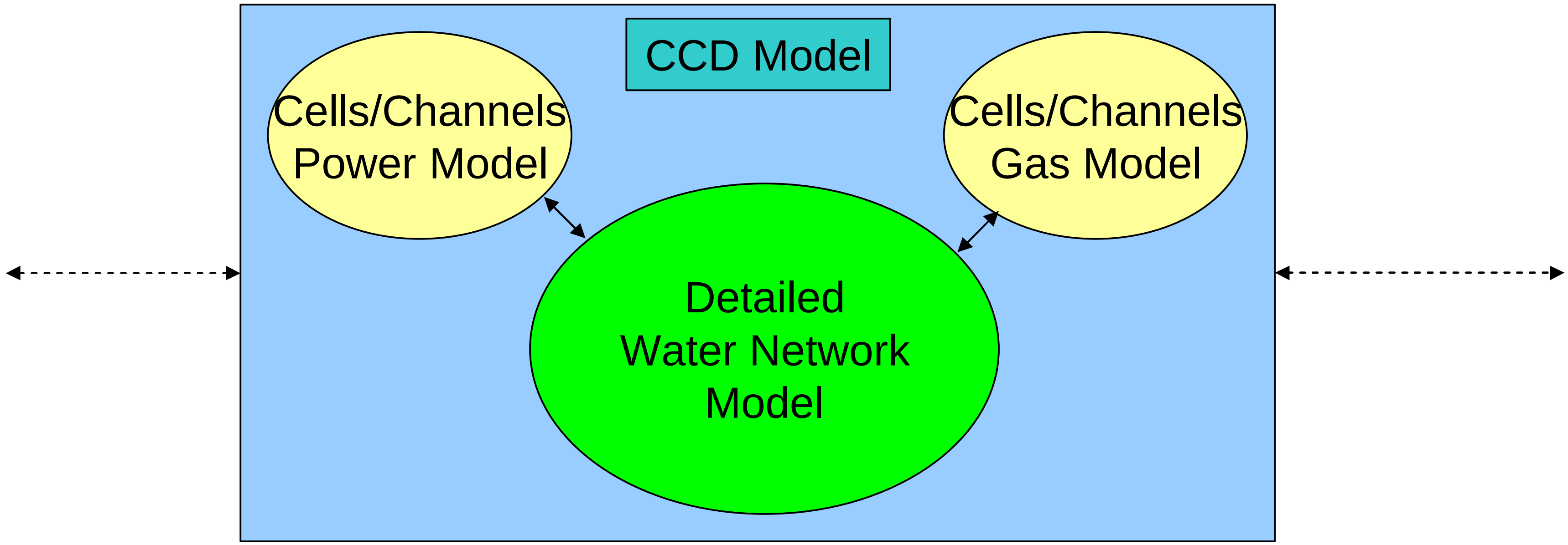
Power System Control Centre



Level 2 Coordination Water System Control Centre



Water System Control Centre

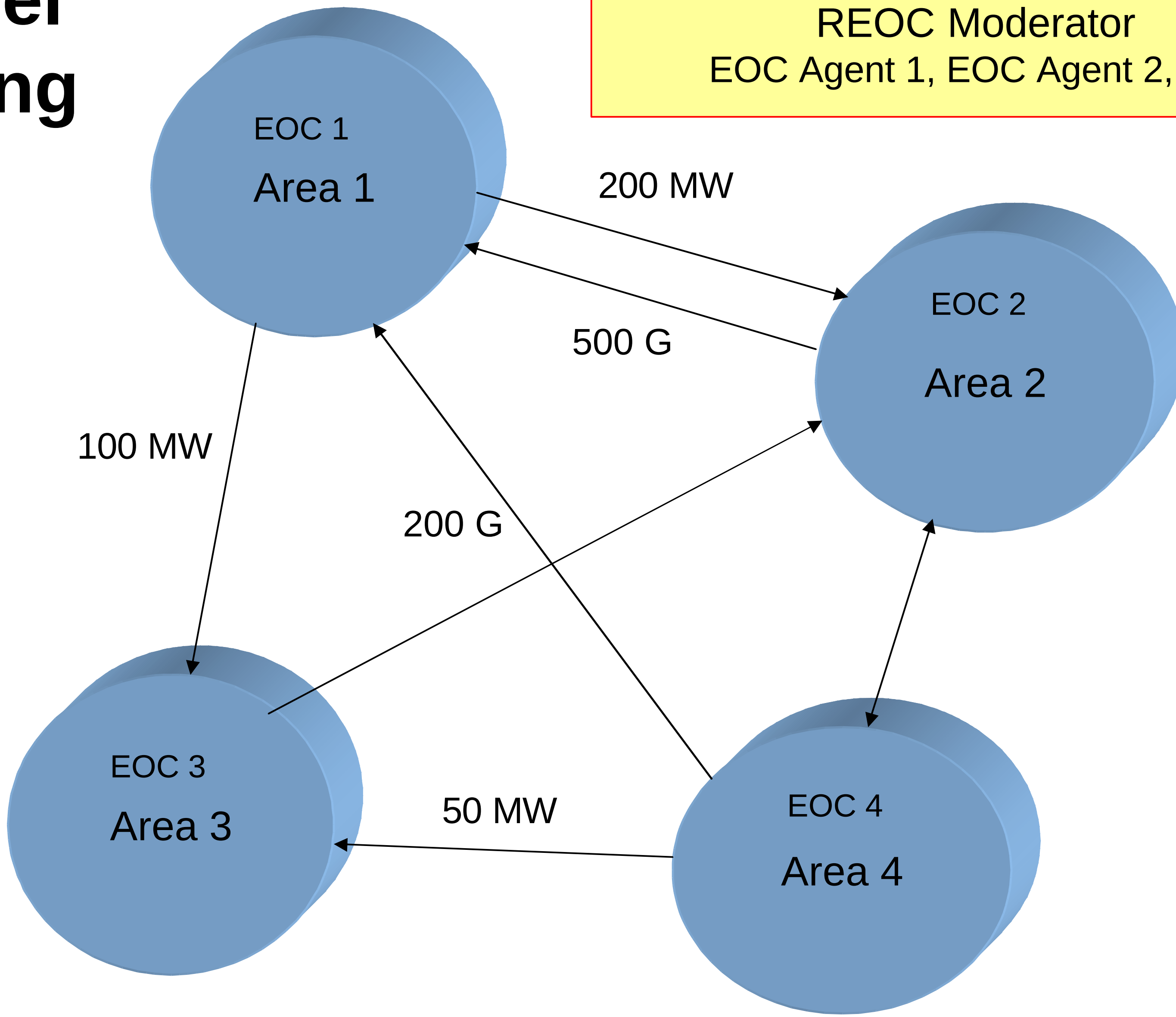


Simulation vs Reality

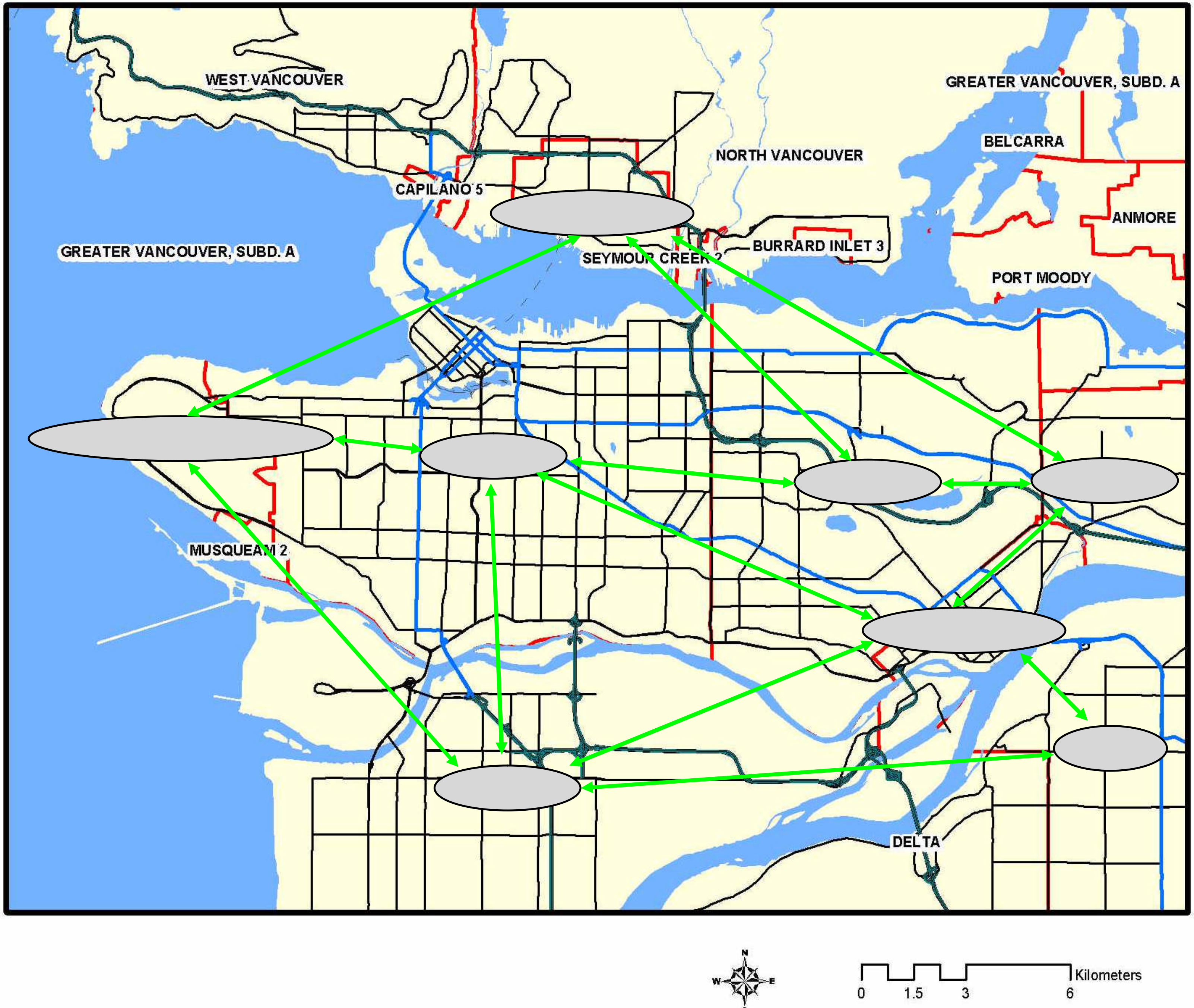
- “Before the battle is joined, plans are everything, but once the shooting begins, plans are worthless.” (Dwight D. Eisenhower during WWII)
- I2Sim merges together planed scenarios, simulation, and reality in a very fast real-time platform

Up Level Islanding

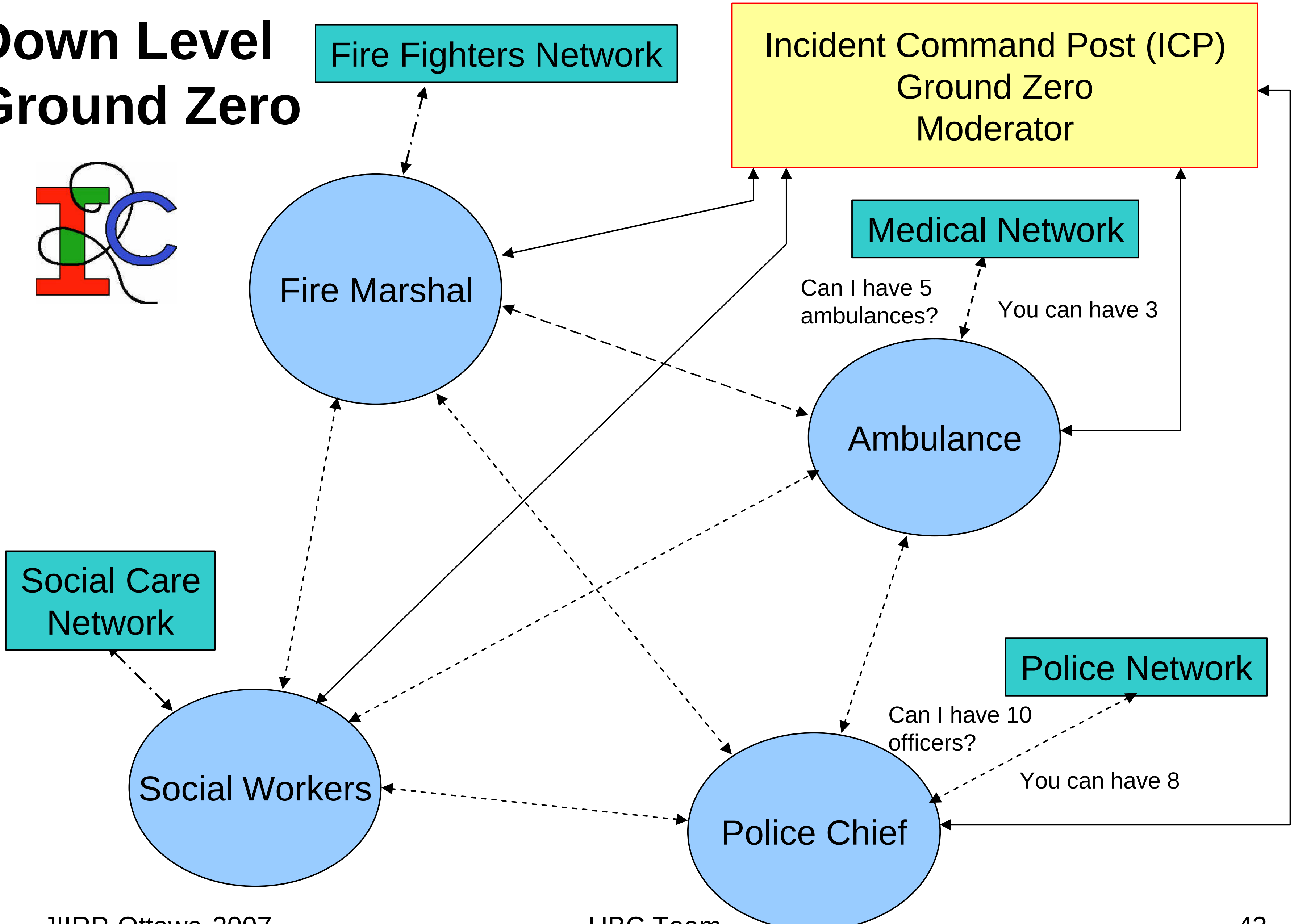
Regional Emergency Operations Centre
REOC Moderator
EOC Agent 1, EOC Agent 2, etc.



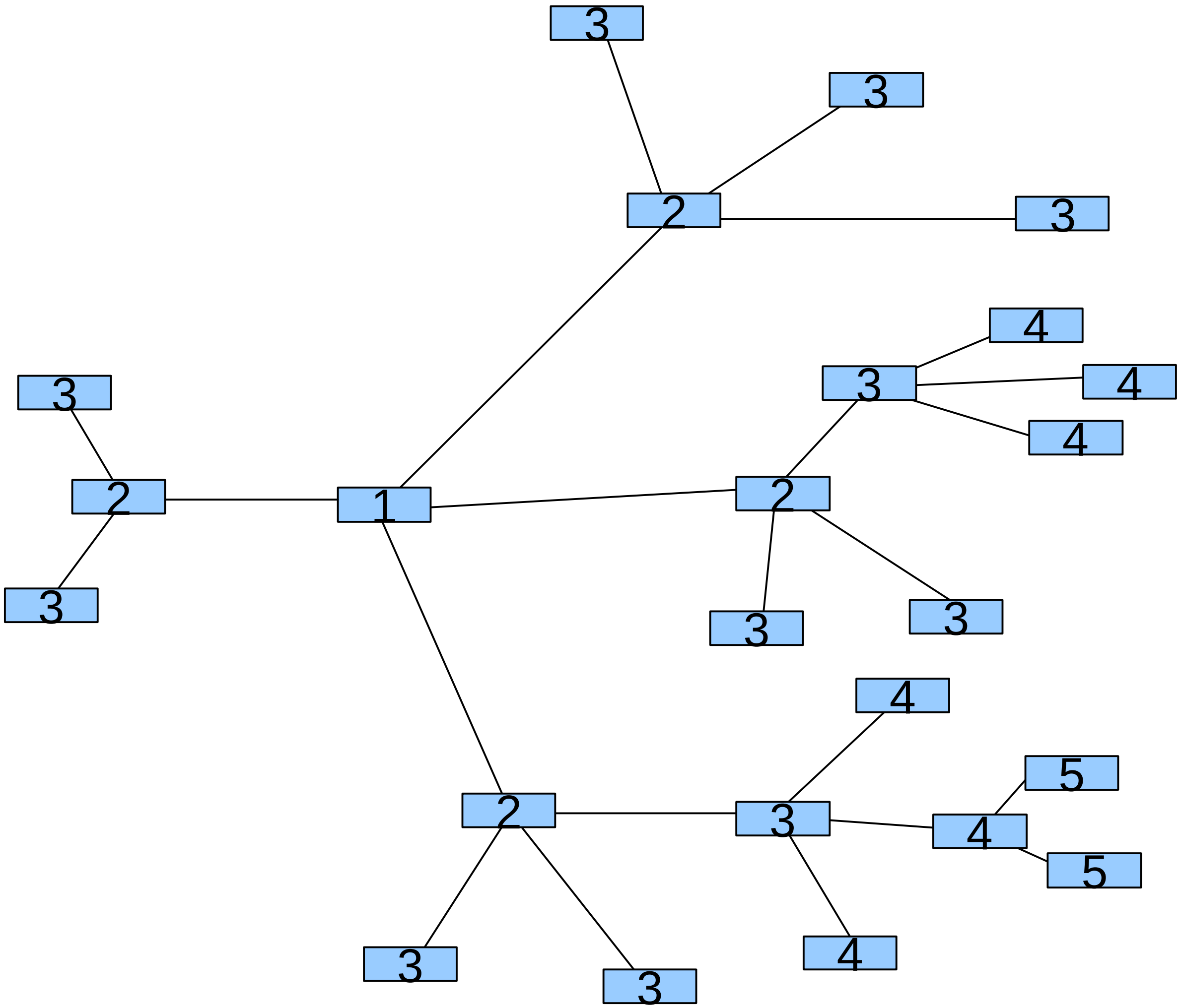
Jurisdictions



Down Level Ground Zero



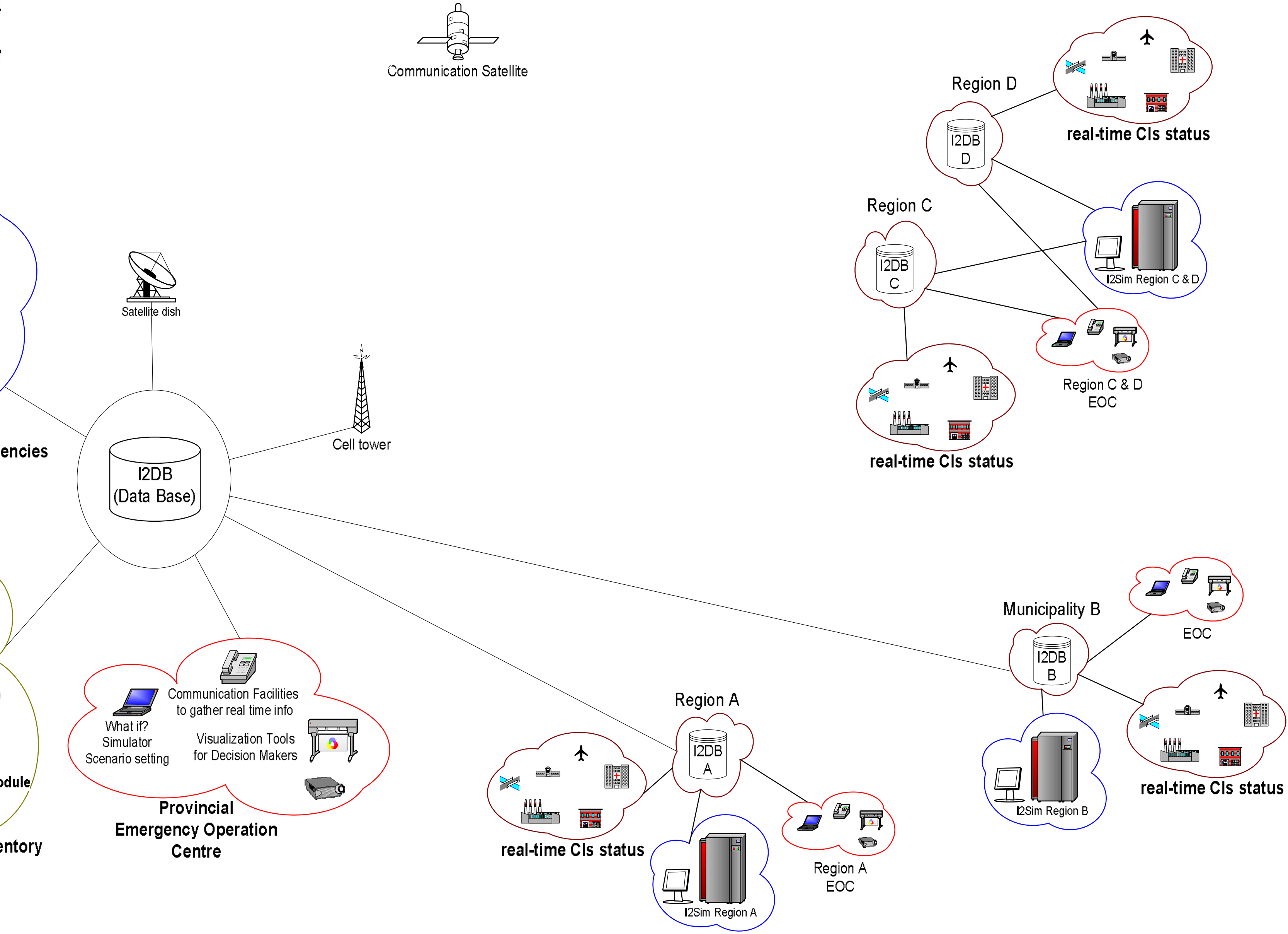
Global CC Models Sharing



Internet Based
CC Models Database
Hosting: Akamai, VeriSign

2 CP2 = Coordinating Post Level 2

Each post has access to global CC data zoomed on his area of operation (like a GPS car navigator)


Communication Satellite
Satellite dish
Cell tower
Simulator Visual Output
I2SIM Simulator Cluster
Provincial I2SIM Infrastructure Interdependencies Simulator
I2DB (Data Base)
Scenario Analysis Module
Damage Assessment Module I2DAM
Infrastructure Asset Inventory I2ASSET
Communication Facilities to gather real time info
What if? Simulator Scenario setting
Visualization Tools for Decision Makers
Provincial Emergency Operation Centre
Region D
I2DB D
real-time CIs status
Region C
I2DB C
I2Sim Region C & D
Region C & D EOC
real-time CIs status
Municipality B
I2DB B
EOC
real-time CIs status
I2Sim Region B
Region A
I2DB A
real-time CIs status
I2Sim Region A
Region A EOC

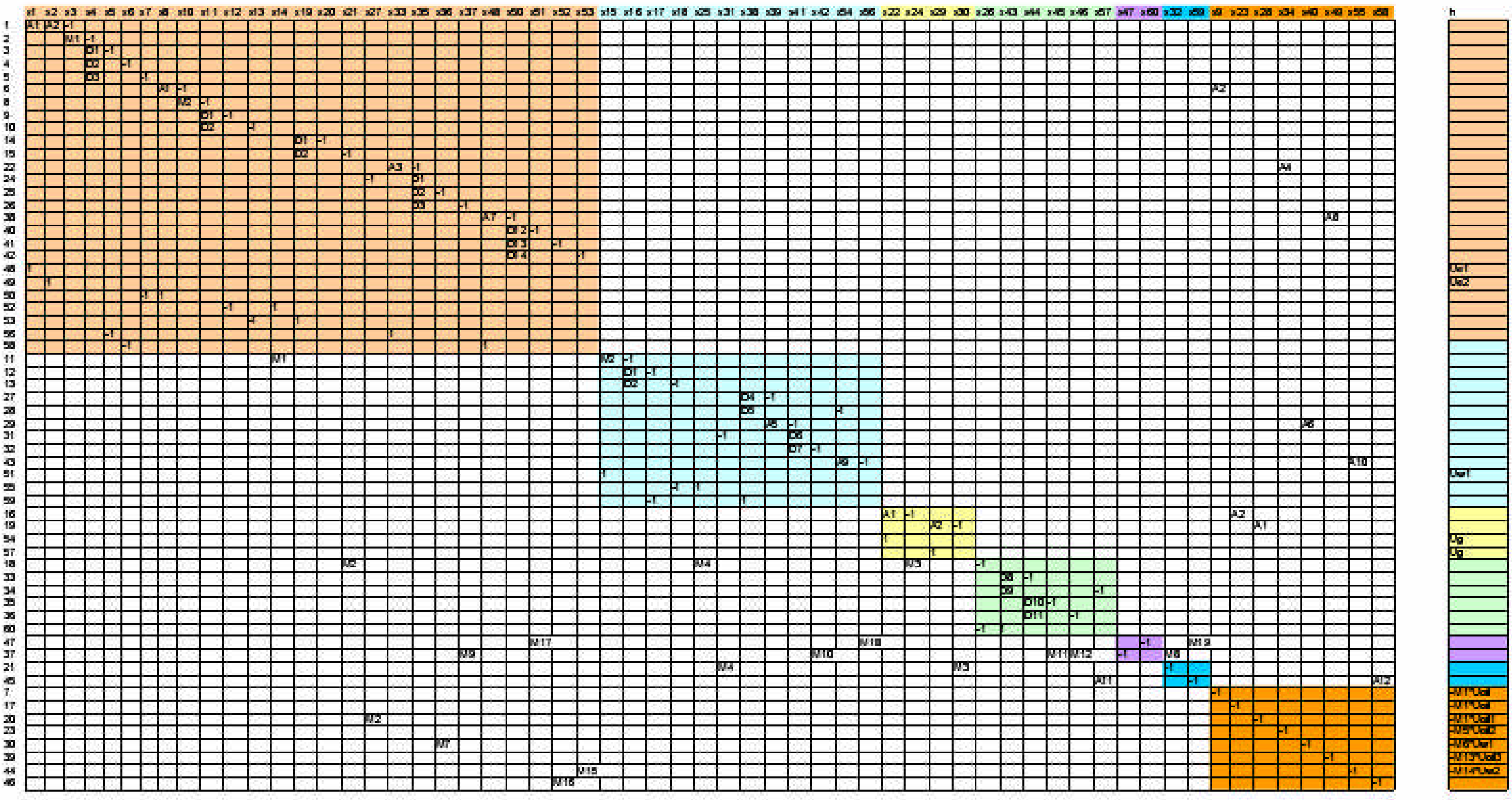
I2Sim
Mathematical Solution

Interdependencies Matrix

$$[\mathbf{T}][\mathbf{x}] = [\mathbf{w}]$$

- [x] = resources; [w] = sources
- [T] = Interdependencies Matrix; built from cell's m factors and channel's (a, Tau) factors
- Interdependencies Analysis
- Sensitivity Analysis
- Dynamic Trajectories Analysis

Interdependencies Matrix
UBC Campus Case



Real-Time Performance

- I2Sim solves a piece-wise linear system between Delta-t steps. This allows for solution speeds 1,000 to 10,000 times faster than standard (non-linear) simulators
- I2Sim can solve a system of 3,000 cells with 15 inputs/outputs per cell (45,000 state variables) for a 10 hr scenario with Delta-t = 5 minutes in less than a second of computer time
- Interactive scenario playing is basically instantaneous
- Linear speedup in PC-Clusters (e.g., a cluster with 10 processors makes the solution 10 times faster)

The Human Layer
Psychological Issues
I2Psy

Psychological issues Linked to the Physical Layer: Using our Simulator

- Simulator effectiveness relies on its ability to identify:
  - Infrastructure weaknesses and interdependencies
  - Relief weaknesses and interdependencies
  - Resource allocation
- because these issues predict collective efficacy across social geography they support human capacity to cope and act during disaster

We Look First at Population-Related Issues

- Large-scale psychological issues
- Those “victimized” by the disaster
- Varying in
  - – Vulnerability
    - Access to disaster support and services
    - Beliefs regarding consequences and probability
  - – Psychological characteristics

For Later Consideration

- First Responders
  - Health care professionals
  - Police
  - Firefighters
  - Community workers
  - Volunteers

Some Psychological Issues

- Coping with serious illness as an analogy
- Analytical Focal Points
  - Key psychological factors that correlate with coping and outcome that
    - Can be operationalized
    - Can be quantified?

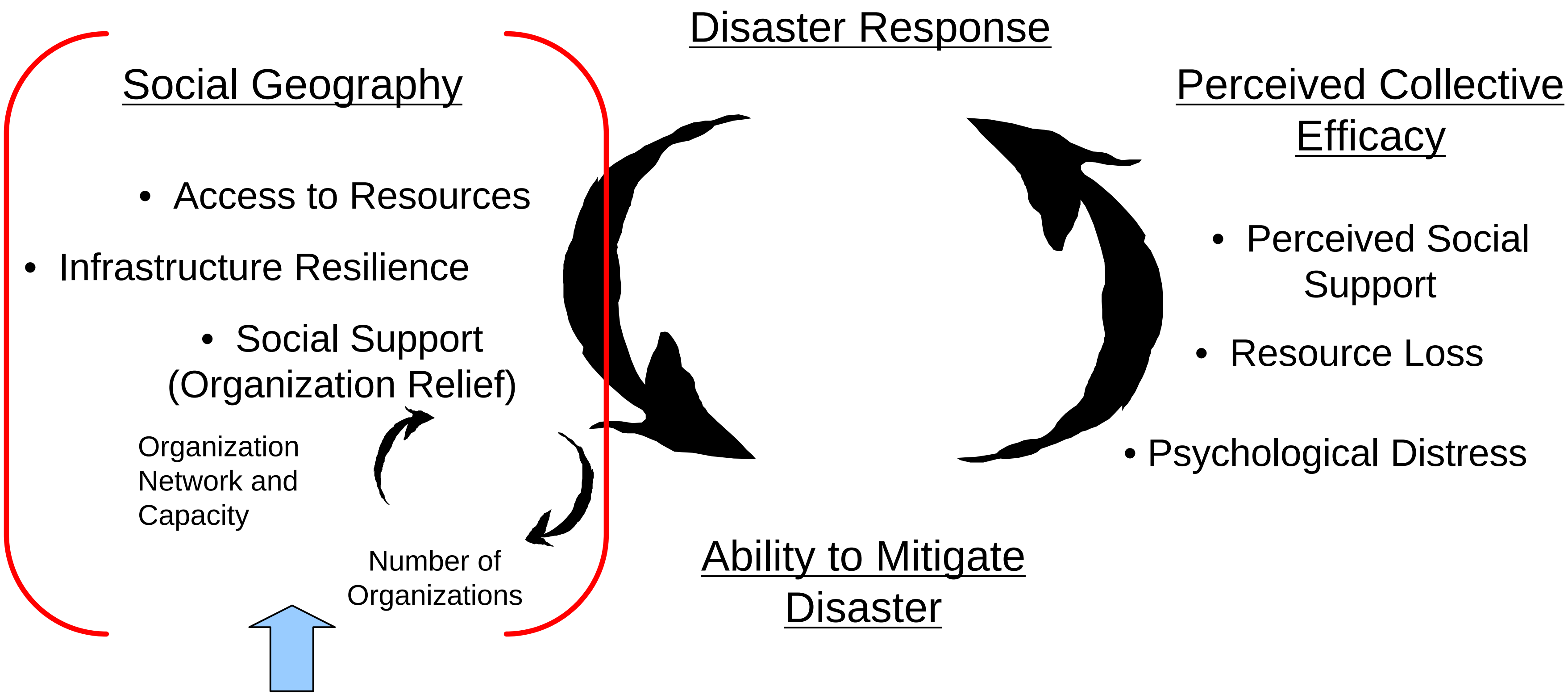
Perceived Vulnerability

- “Imaginability”
- “…it is necessary to examine the assumptions of everyday life and the effects of having these assumptions shattered” (Brown & Neal, 2001)

Collective Efficacy

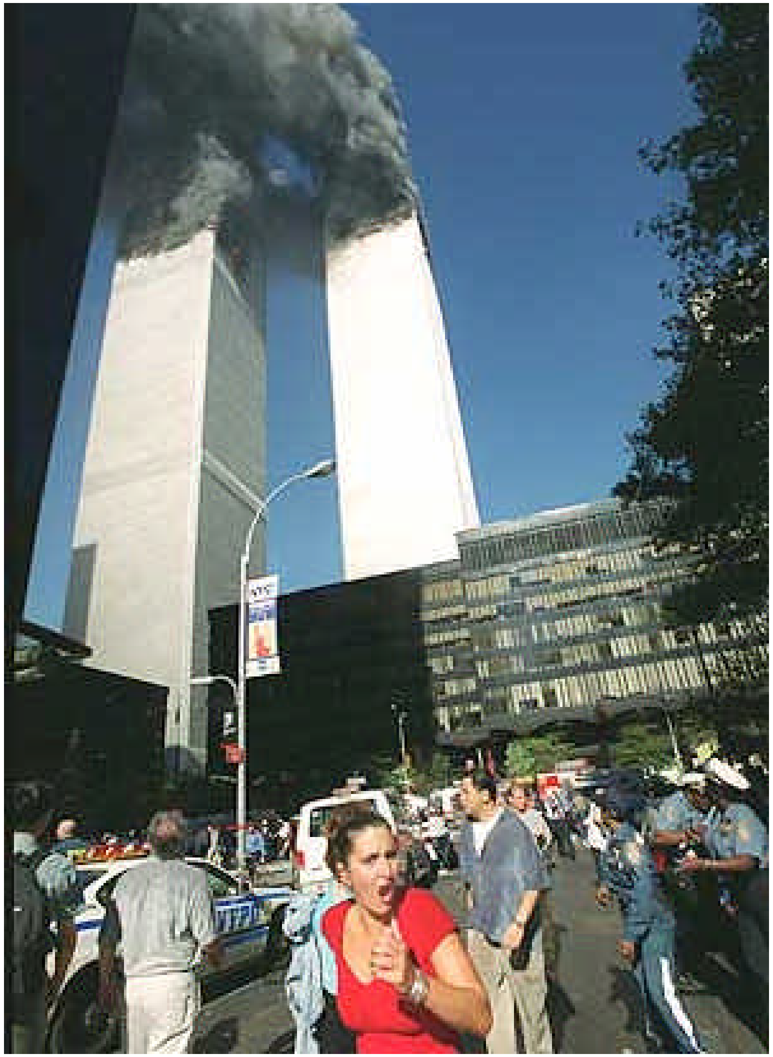
- The "shared belief that a group can effectively meet environmental demands and improve their lives through concerted effort" (Benight, 2004)
  - *Communitas* – the momentary upsurge in collective unity and spirit associated with certain ritual events and social crises

Vulnerable Populations Loop



The Simulator works here

The Psychology of Evacuation



Panic as a Social Phenomenon

- Elevated by a lack of familiarity with place — exacerbating contagion
- Reduced by support — given and received
  - If you can’t find loved ones, find someone
    - Called the “convergence effect”
      - To help others
      - Evidence of being alive and unaffected
      - Social comparison

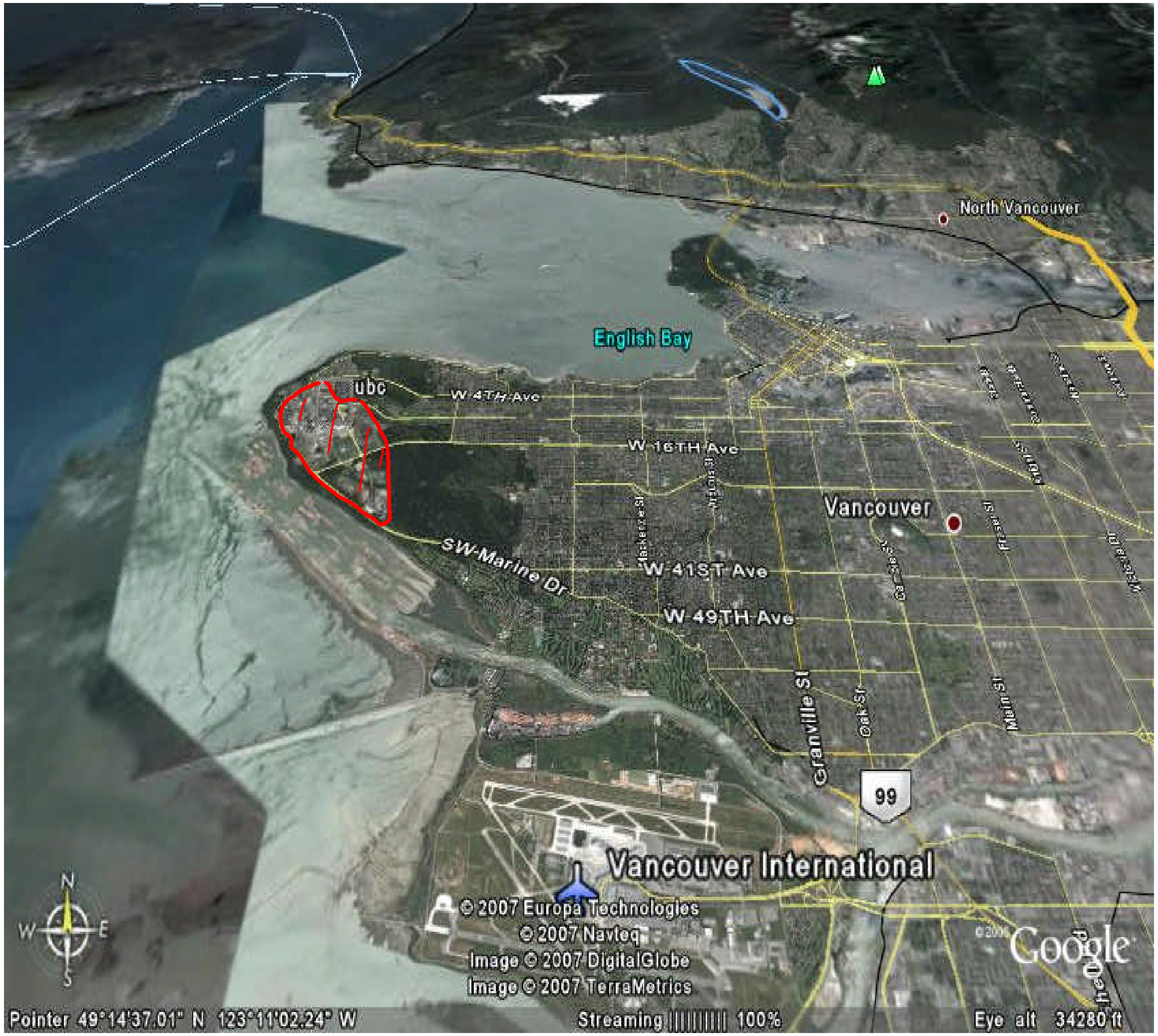
Panic and Affiliation: A Social Attachment Model

- Classic conception: Panic = perceived imminent danger + limited escape options
- Newer conception: location of attachment figures more important than escape options

	Affiliation Present	Affiliation Absent
Threat Low	•Increased attachment	•Low intensity avoidance of threat
Threat High	•Increased attachment •Orderly flight/evacuation •Occasional panic	•Mass panic — toward the familiar, not always away from danger

UBC Campus Case Study

UBC Campus Case Study



Why modeling UBC campus?

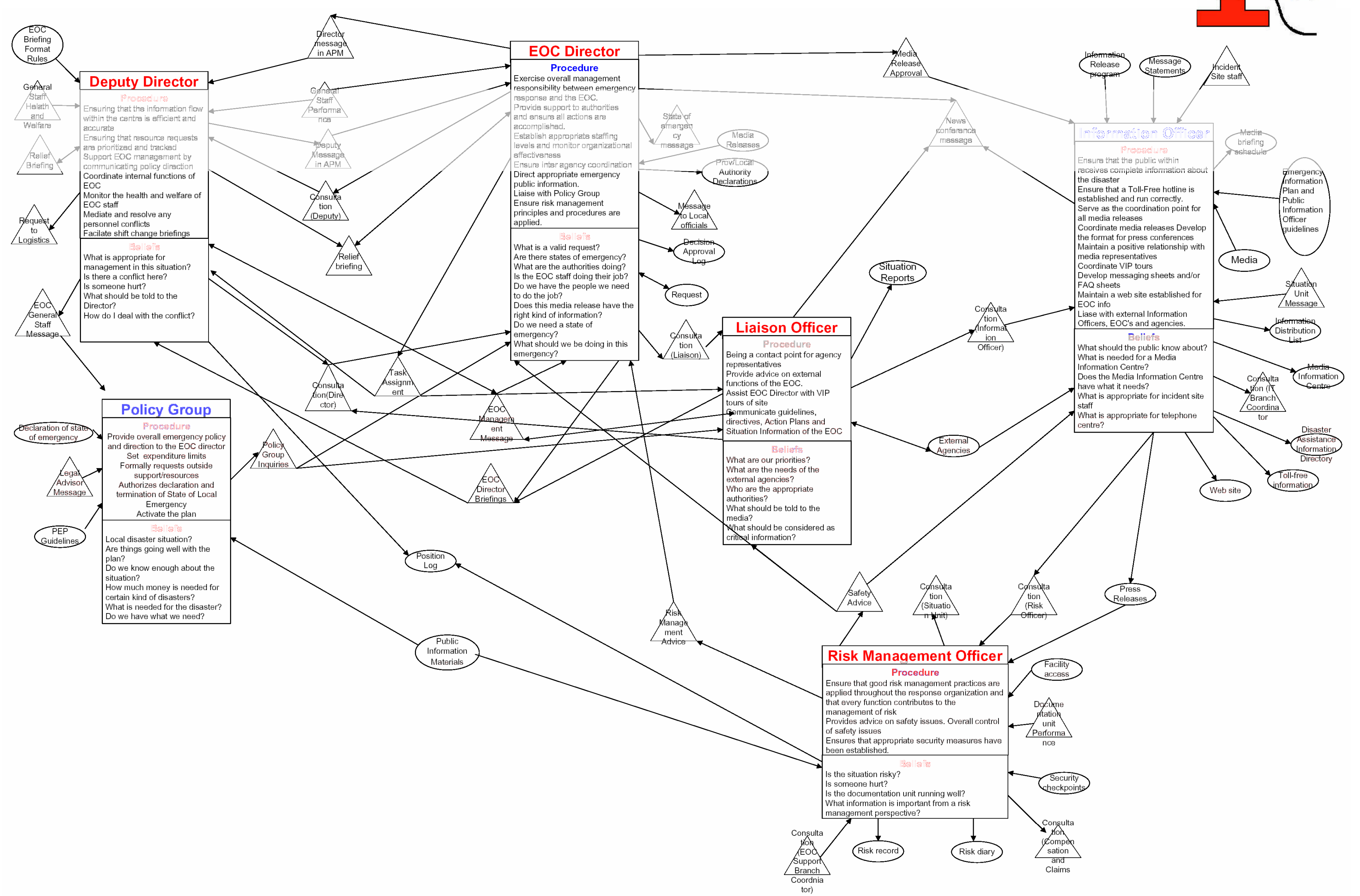
- The UBC campus shares many attributes of a small city
  - 47000 daily transitory occupants
  - 10000 full time residents
  - own utilities providers
- Information accessibility
- Good starting point before modeling larger area, such as GVRD

JIIRP-I2C Team Goals

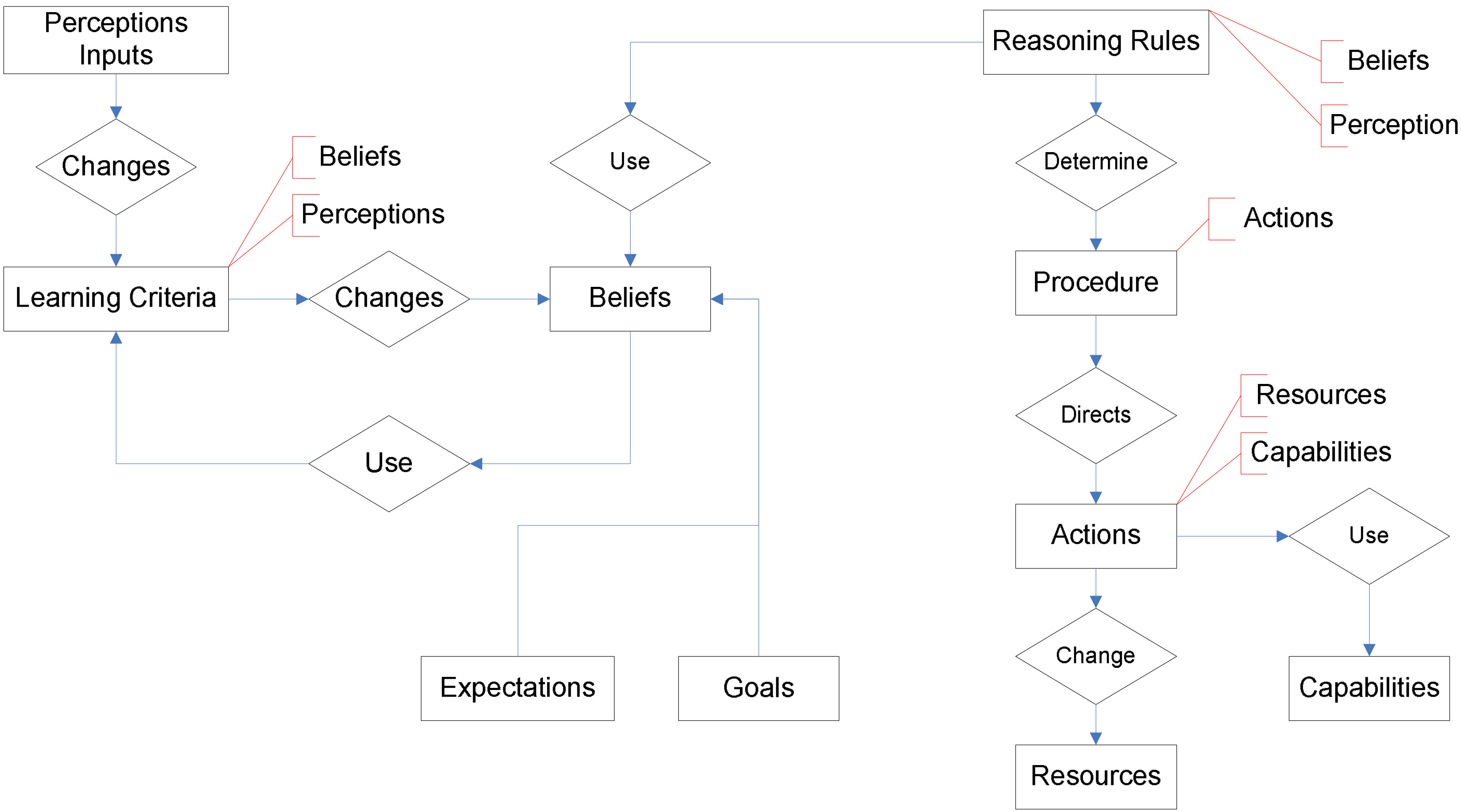
- Analysis of interdependencies among critical infrastructures
- Develop methodologies of analysis
- Concentrate UBC's infrastructure information in a GIS
- Analyze infrastructure interdependencies
- Contribute to evolve from a *culture of reaction* into a *culture of preparedness*

The Human Layer: Policy Interdependencies Simulation

Policy Coordination



Policy Coordination Simulation

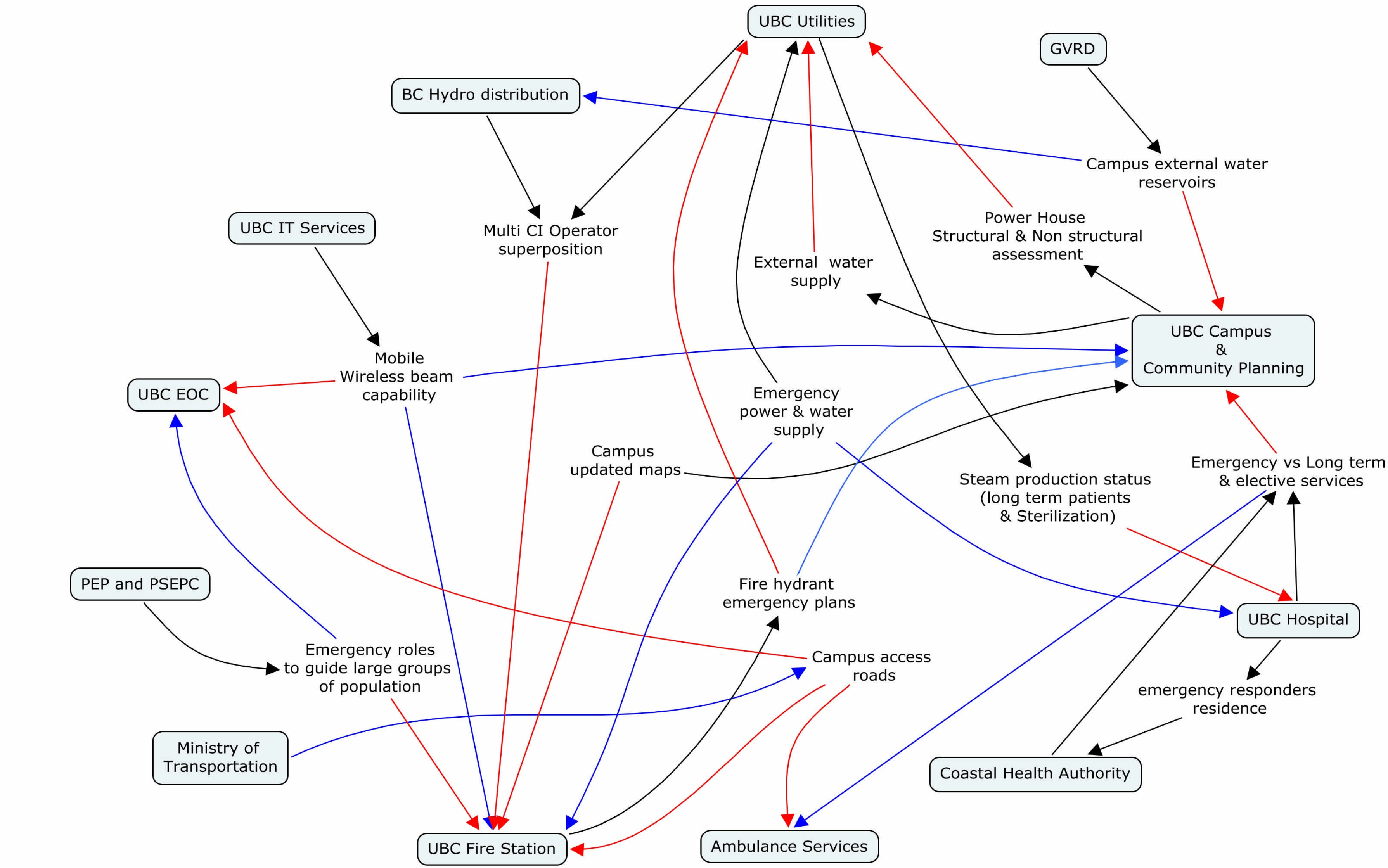


Policy Making Based on Knowledge: Interdependencies Analysis

Critical missing information

Important missing information

Information origin



Policy Creation Based on Simulation

Useful to identify

- weakly coupled inter-agencies policies
- hidden knowledge
- unused resources

Help to preserve

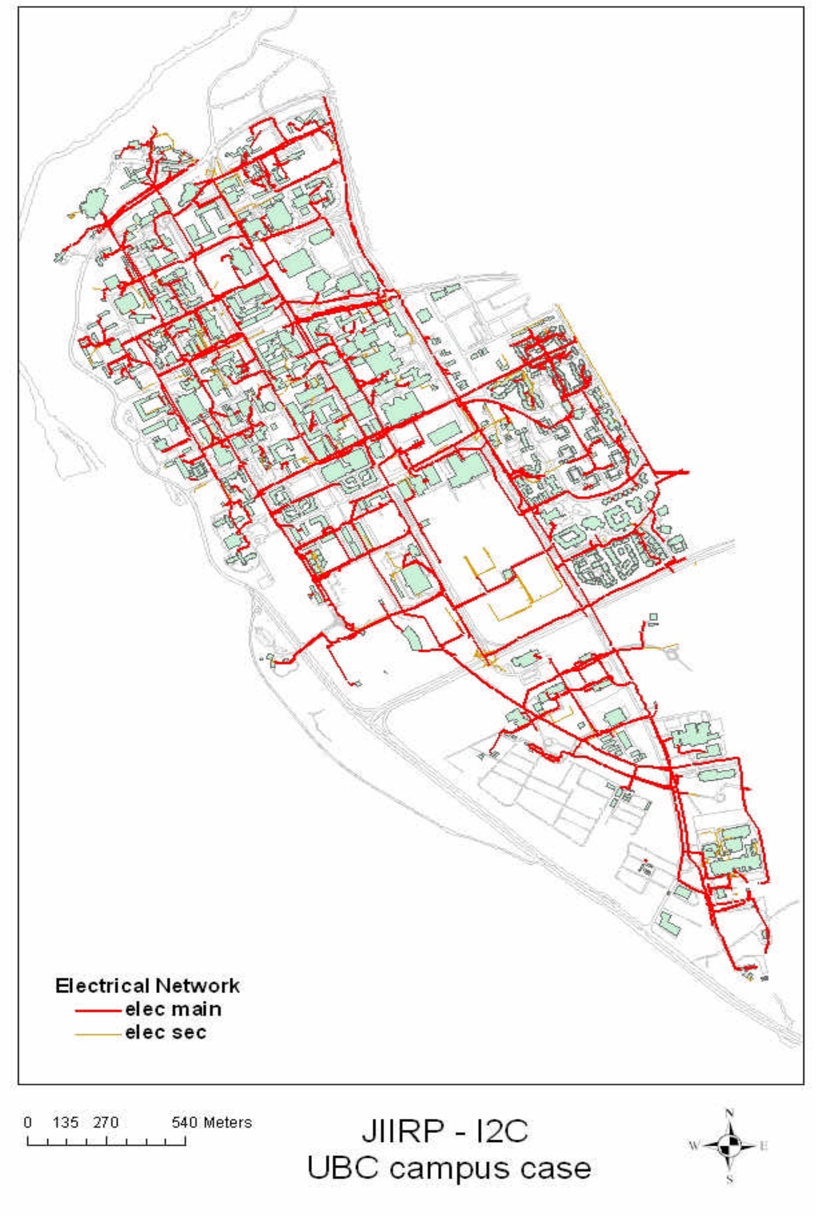
- institutional memory

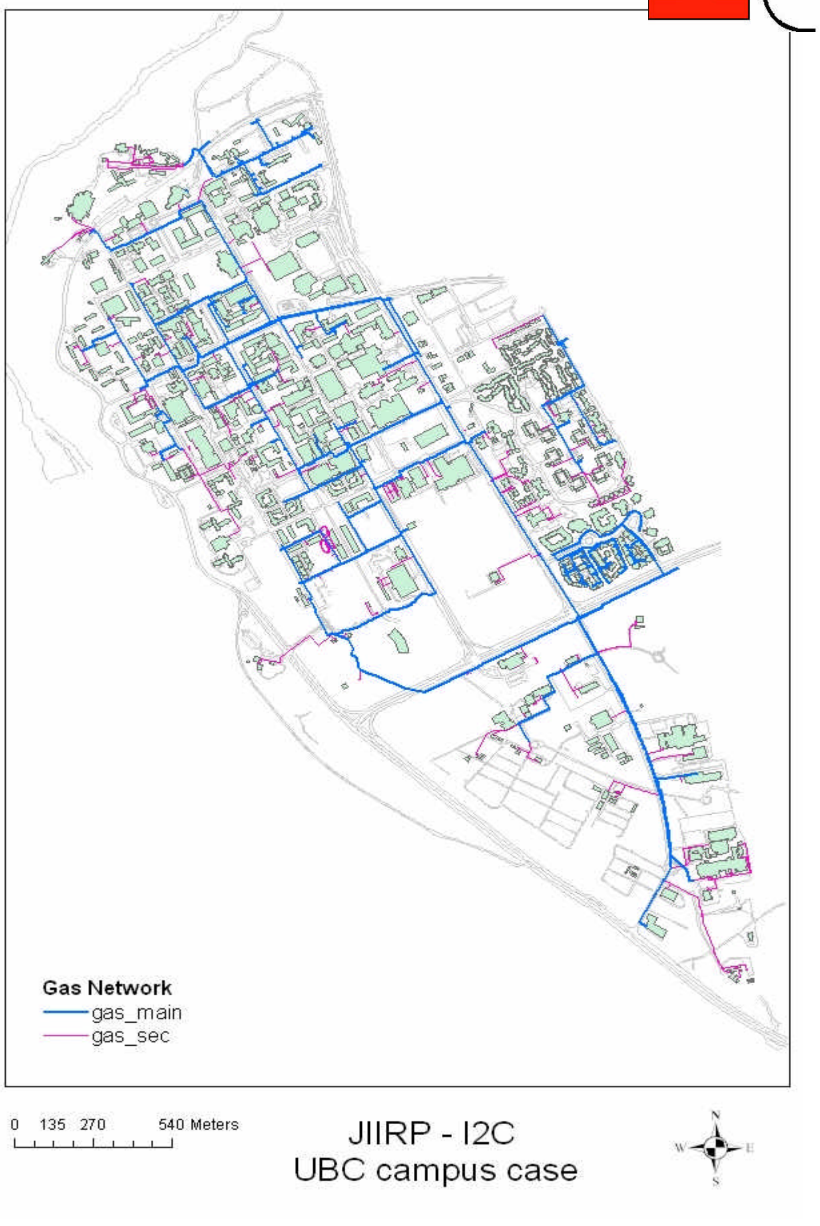
Interdependencies Visualization I2V

Visualizing Infrastructure Interdependencies in Emergencies

- GIS tools
  - Excellent to visualize snapshots of evolving events
- New Collaborative Visualization tools
  - "What if" scenario playing
  - Time/state
  - (un)certainty of data
  - Novel display environments

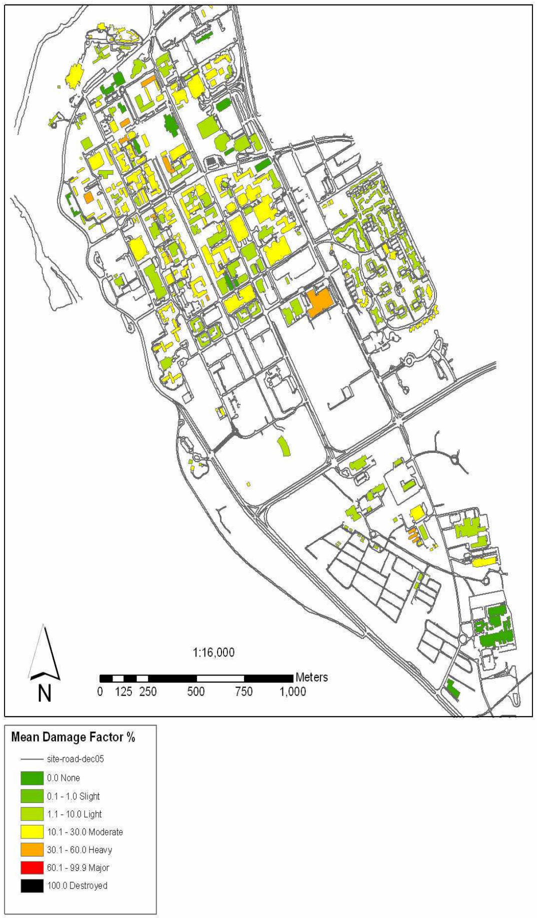
Campus Networks: GIS



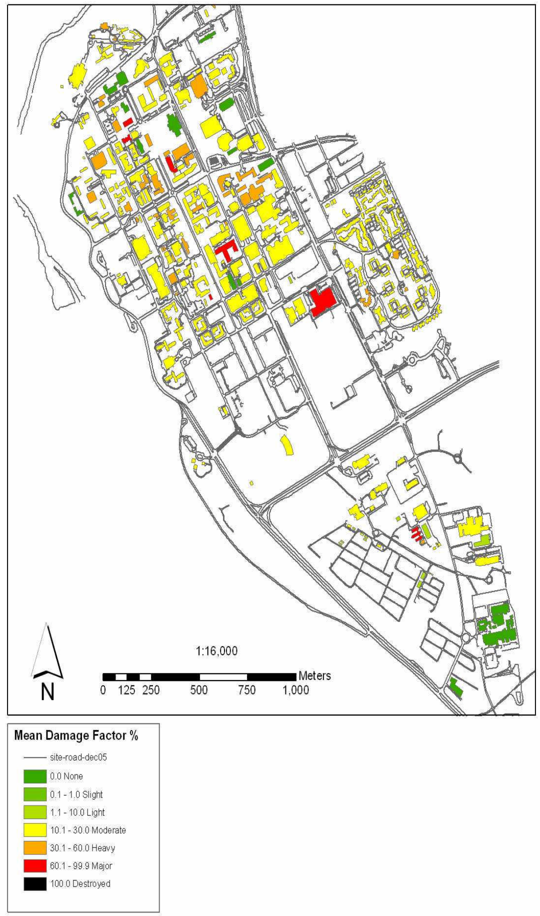


UBC Earthquake Damage Assessment

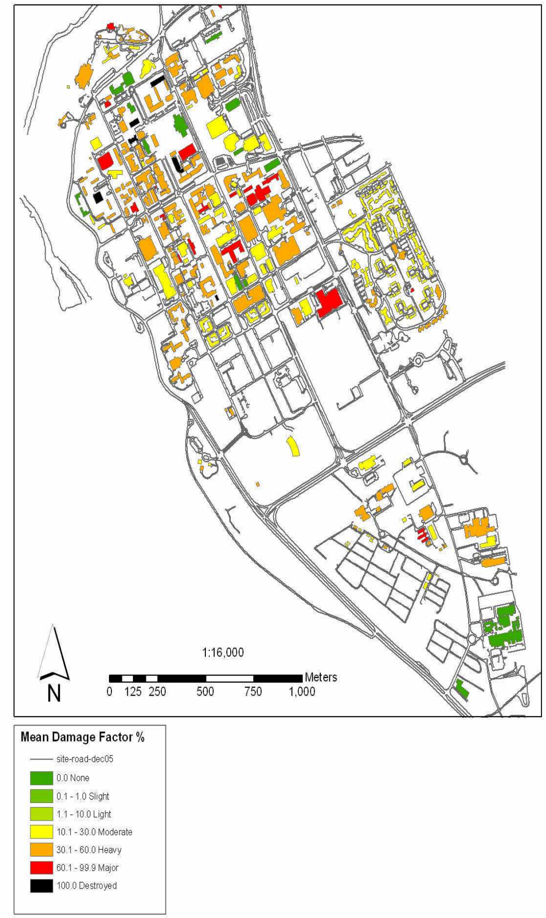
BC31 Mean Damage Factors with Modifiers
Intensity VIII - UBC Campus



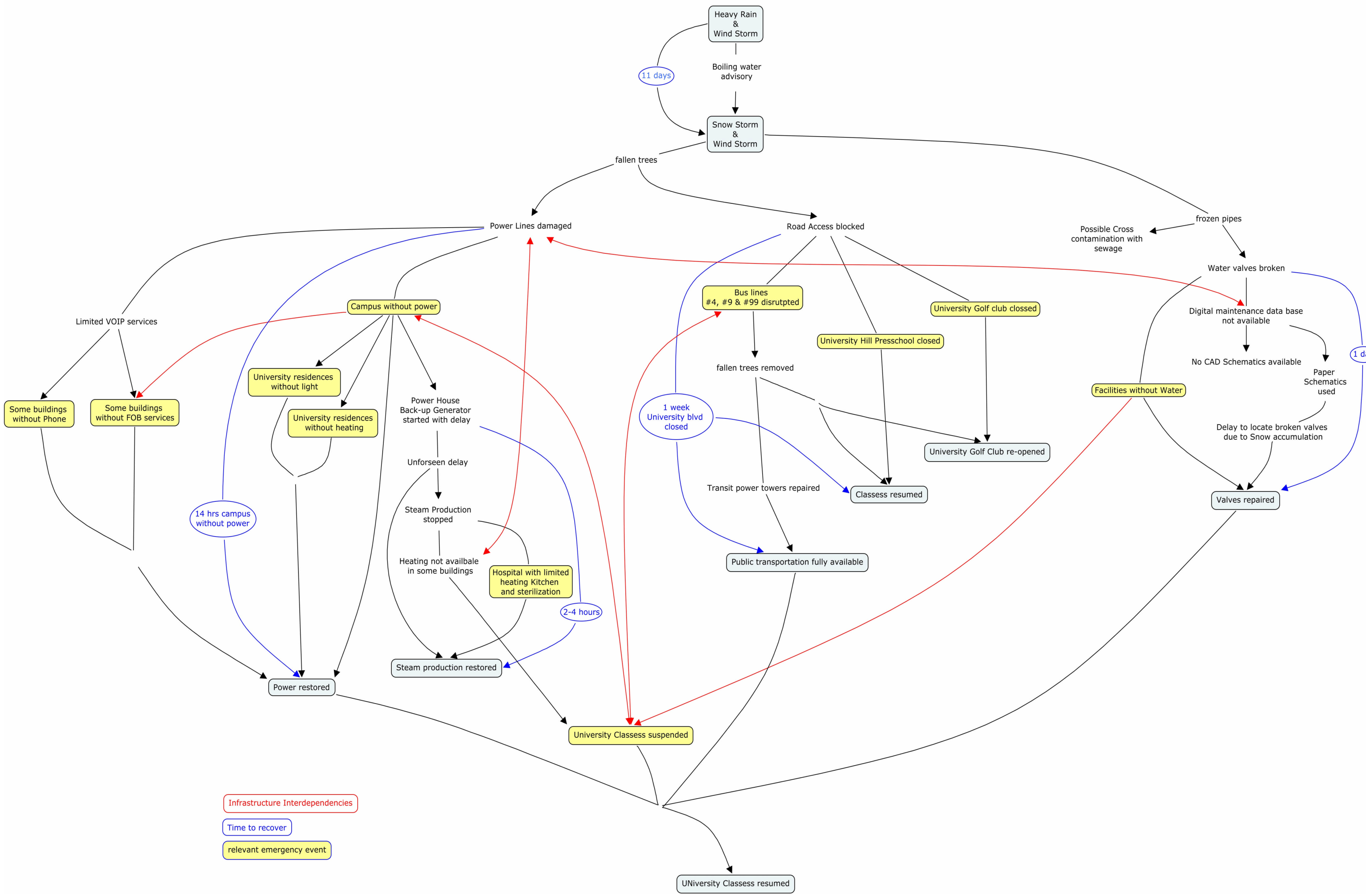
BC31 Mean Damage Factors with Modifiers
Intensity IX - UBC Campus

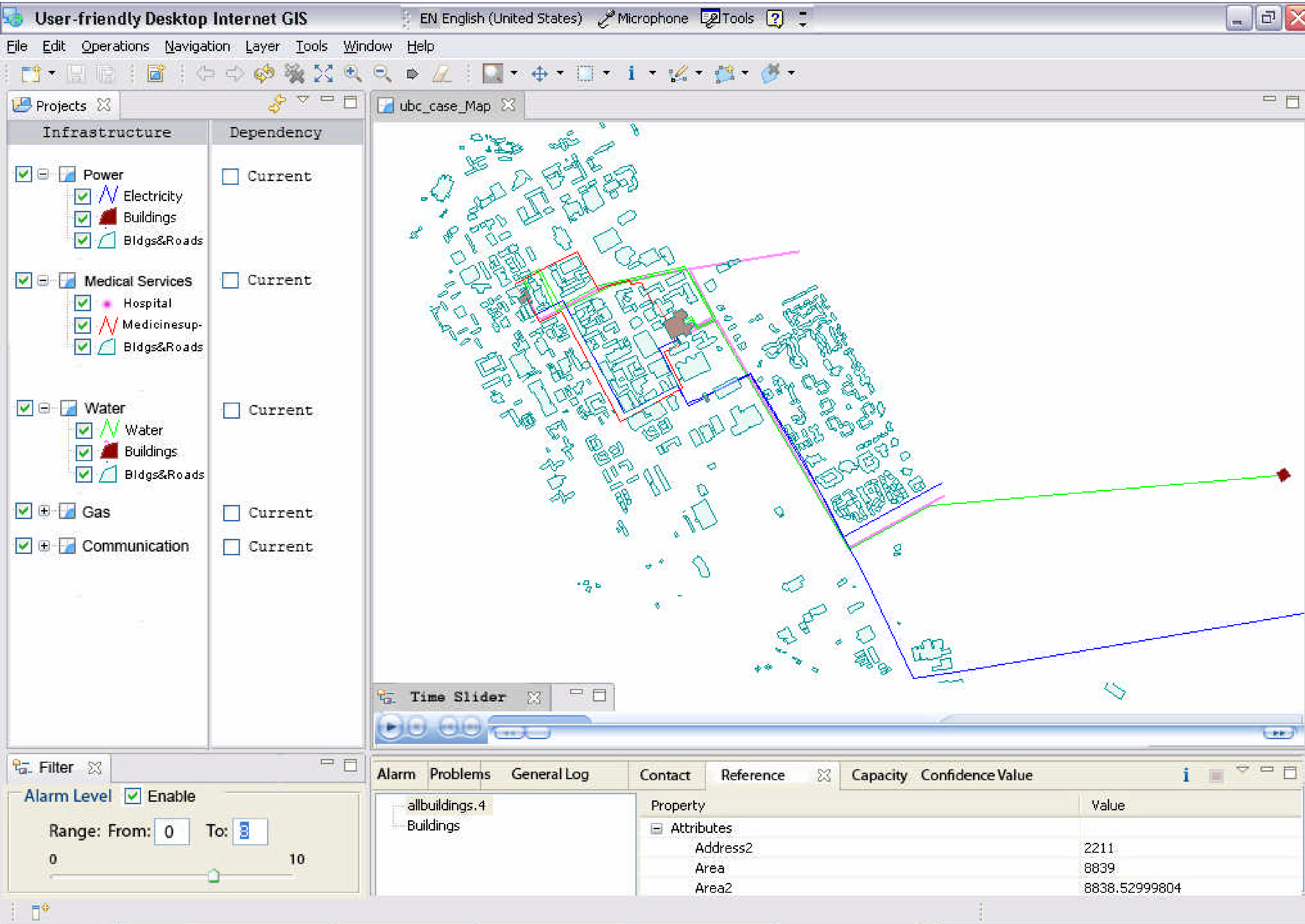


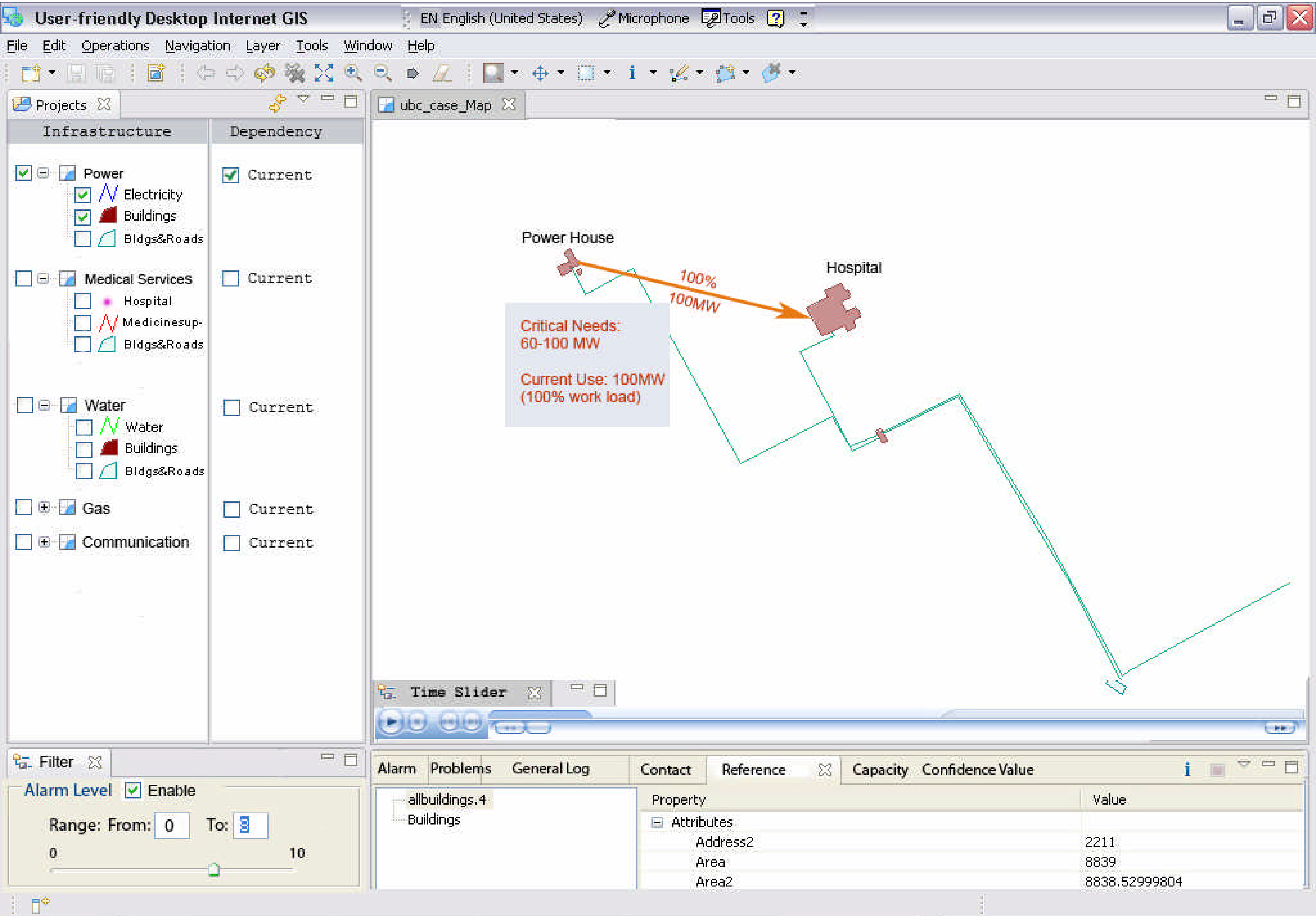
BC31 Mean Damage Factors with Modifiers
Intensity X - UBC Campus



Internet-based collaborative scenario analysis




User-friendly Desktop Internet GIS
EN English (United States)
Microphone
Tools
File
Edit
Operations
Navigation
Layer
Tools
Window
Help
Projects
Infrastructure
Dependency
Power
Electricity
Buildings
Bldgs&Roads
Medical Services
Hospital
Medicinesup-
Bldgs&Roads
Water
Water
Buildings
Bldgs&Roads
Gas
Communication
Current
Current
Current
Current
Current
ubc_case_Map
Time Slider
Filter
Alarm Level
Enable
Range: From: 0
To: 3
0
10
Alarm
Problems
General Log
Contact
Reference
Capacity
Confidence Value
allbuildings.4
Buildings
Property
Value
Attributes
Address2
2211
Area
8839
Area2
8838.52999804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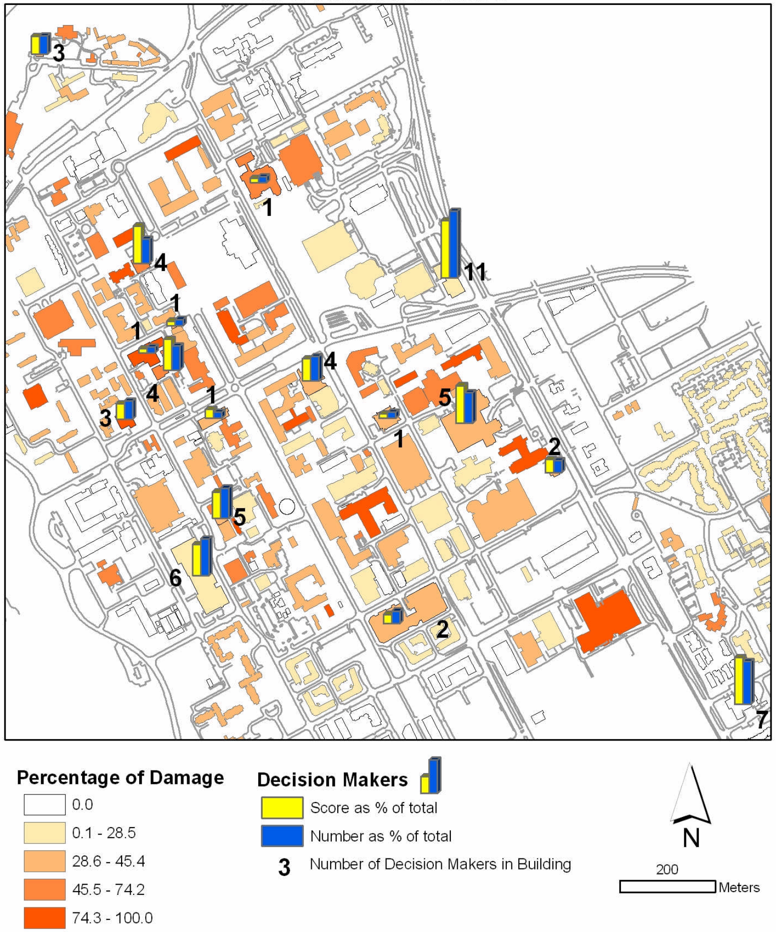
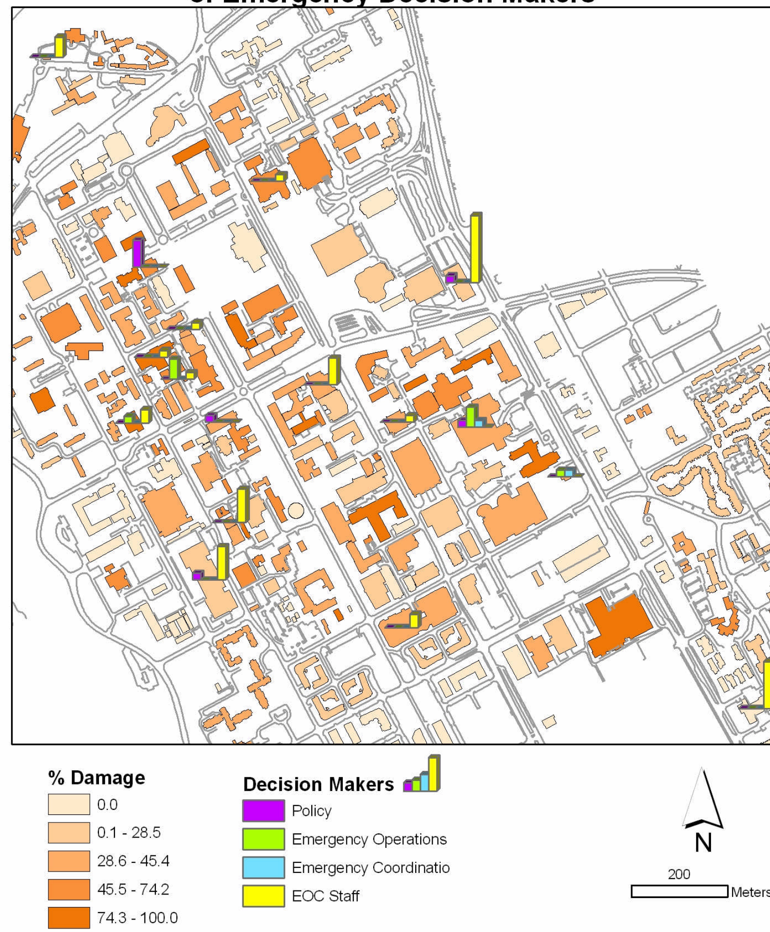
Water
Water
Buildings
Bldgs&Roads
Current
Gas
Current
Communication
Current
Power House
Hospital
100%
100MW
Critical Needs:
60-100 MW
Current Use: 100MW
(100% work load)
Time Slider
Filter
Alarm Level
Enable
Range: From: 0
To: 3
0
10
Alarm
Problems
General Log
Contact
Reference
Capacity
Confidence Value
allbuildings.4
Buildings
Property
Value
Attributes
Address2
2211
Area
8839
Area2
8838.52999804

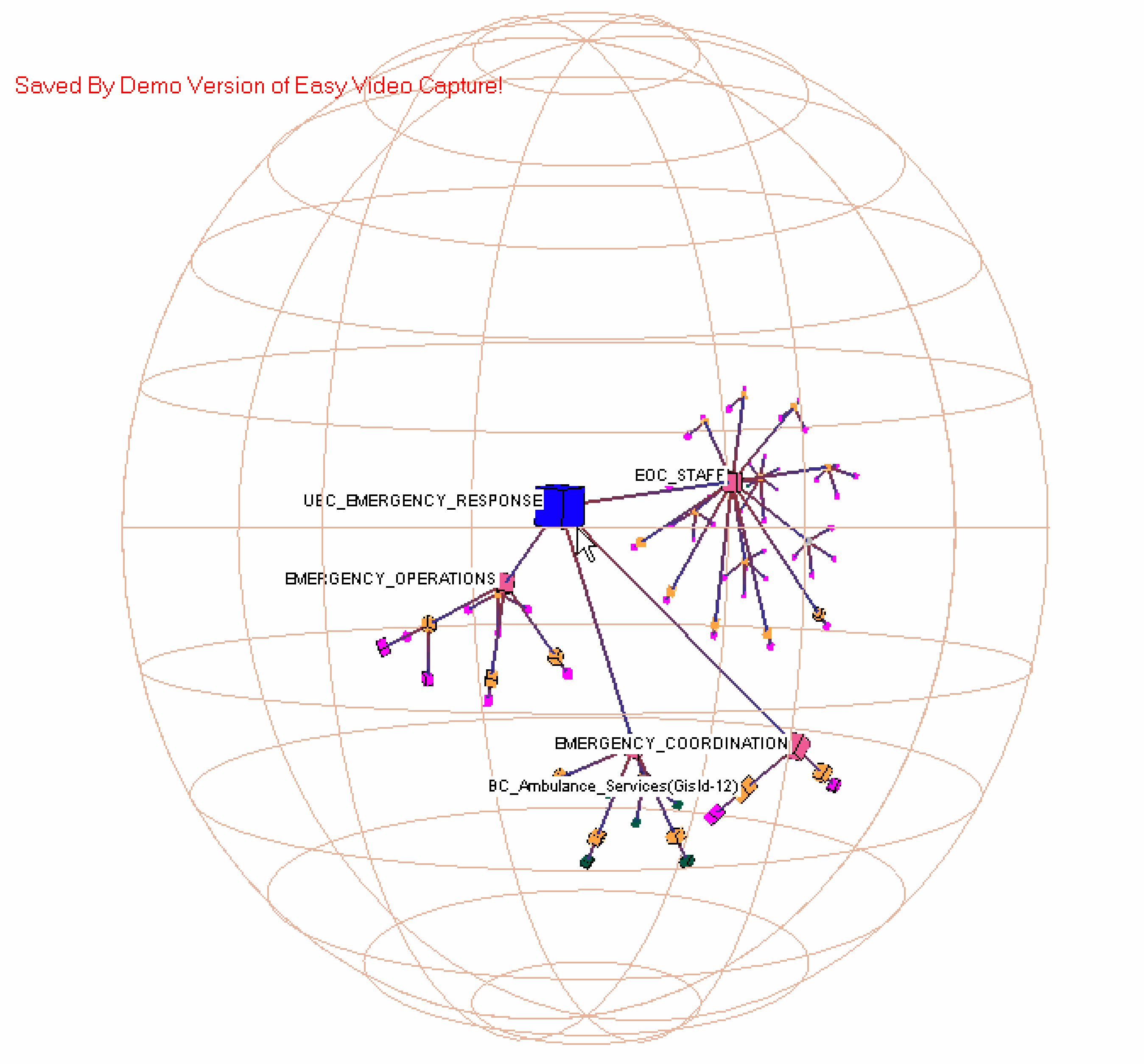
GIS: Decision Makers Risk Mapping

Structural Assessment (MDF X) & Location of Decision Makers



Structural Assessment (MDF X) & Location of Emergency Decision Makers




Saved By Demo Version of Easy Video Capture!
UBC_EMERGENCY_RESPONSE
EOC_STAFF
EMERGENCY_OPERATIONS
EMERGENCY_COORDINATION
BC_Ambulance_Services(GisId-12)

Summary to Date

Industry Feedback (26/FEB/07): Issues, Challenges

- Define coherent infrastructures risk tolerance levels from natural disasters by both industry and public
- Standardize processes and policies regarding the protection of CIs
- Standardize the definition of CIs across federal, provincial and local governments
- Standardize CIs prioritization across all levels of government
- Develop common and agreed protocols for the sharing of CIs information during emergency

Industry Feedback (26/FEB/07): Positive Comments

- Benefits of CC model for data sharing among Ci’s (PSEPC, Ministry of Transportation, Telus)
- Data base of simulation scenarios can preserve institutional memory after experts retire (GVRD, UBC Campus Planning)
- Dependency on foreign service providers (YVR)

Partnerships & Dissemination

- 80 hours of assistance from our partners; 2 Industry Workshops
- 37 internal documents; 9 conference papers; 2 Journal Publications
- 13 Researchers; 6 Doctoral Students; 7 Masters Students; 2 Postdoctoral Research Associates
- I2C Website for knowledge dissemination http://www.i2sim.ca
- I2C Wiki for collaborative research

Continued Developments

1. Integration of visualization and decision support systems
2. Extensions of simulator and support systems:
   - City of Vancouver
   - City of Richmond
   - Vancouver international airport YVR
   - Vancouver 2010
   - Multi-cities coordination GVRD
3. Data exchange standardization
4. Multi-layered coordination

Seismic Risk Assessment of Vancouver

Building Damage - Preliminary Results

Fig. 7. Structural damage distribution in Vancouver.

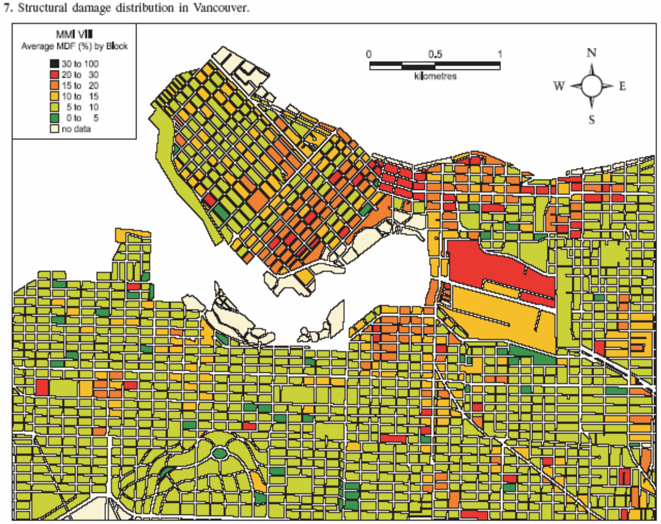


Fig. 9. Monetary loss distribution in Vancouver.