Design for Survival

Coordination of Critical Infrastructure Interdependencies to Maximize Disaster Survival

(JIIRP-UBC Team)

JIIRP-UBC Team

- Kostantin Beznosov, Elec. & Comp. Eng. Data communications and security
- Kelly Booth, Comp. Sc. Virtualization of war room scenarios
- Juri Jatskevich, Elec. & Comp. Eng. Power systems design
- Jeff Joyce, Elec. & Comp. Eng. Formalized scenario-based techniques
- Brian Klinkenberg, Geography. Mapping and GIS systems
- Philippe Kruchten, Elec. & Comp. Eng. Software development processes
- José Martí, Elec. & Comp. Eng. Simulation of large systems
- Tamara Munzner, Comp. Sc. Visualization of complex networks
- Gary Poole, Health Care and Epidemiology, Psychologist. Education and organizational principles
- Rachel Pottinger, Comp. Sc. Database compatibility
- Richard Rosenberg, Comp. Sc. Computers, education and society
- K.D. Srivastava, Elec. & Comp. Eng. Assets monitoring
- Carlos Ventura, Civil Engineering. Earthquakes
- Carson Woo, Sauder School of Business. Business recovery

JIIRP-UBC Partners

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

“First priority during disaster situations is, and should be, human survival”

(J.R. Marti, KD Srivastava, J. Jatskevich, J. Hollman)

Problem Identification

Interdependencies Coordination

1. At present each infrastructure knows very well what to do when problems occur within its system: how to readjust operation while repairs are being made
2. Risk analysis and reliability studies are done internally on each infrastructure, but do not consider the dynamic combined effect of the other infrastructures
3. When large disasters occur, multiple infrastructures are damaged simultaneously. The coordination of their interdependencies becomes critical for effective repair actions without stepping on “each other’s toes”

Our Focus

1. Incorporate the interdependency links into the problem solution
2. Facilitate decisions coordination among infrastructure managers during large disaster situations
3. Strengthen the interdependency links to design more resilient global infrastructure systems

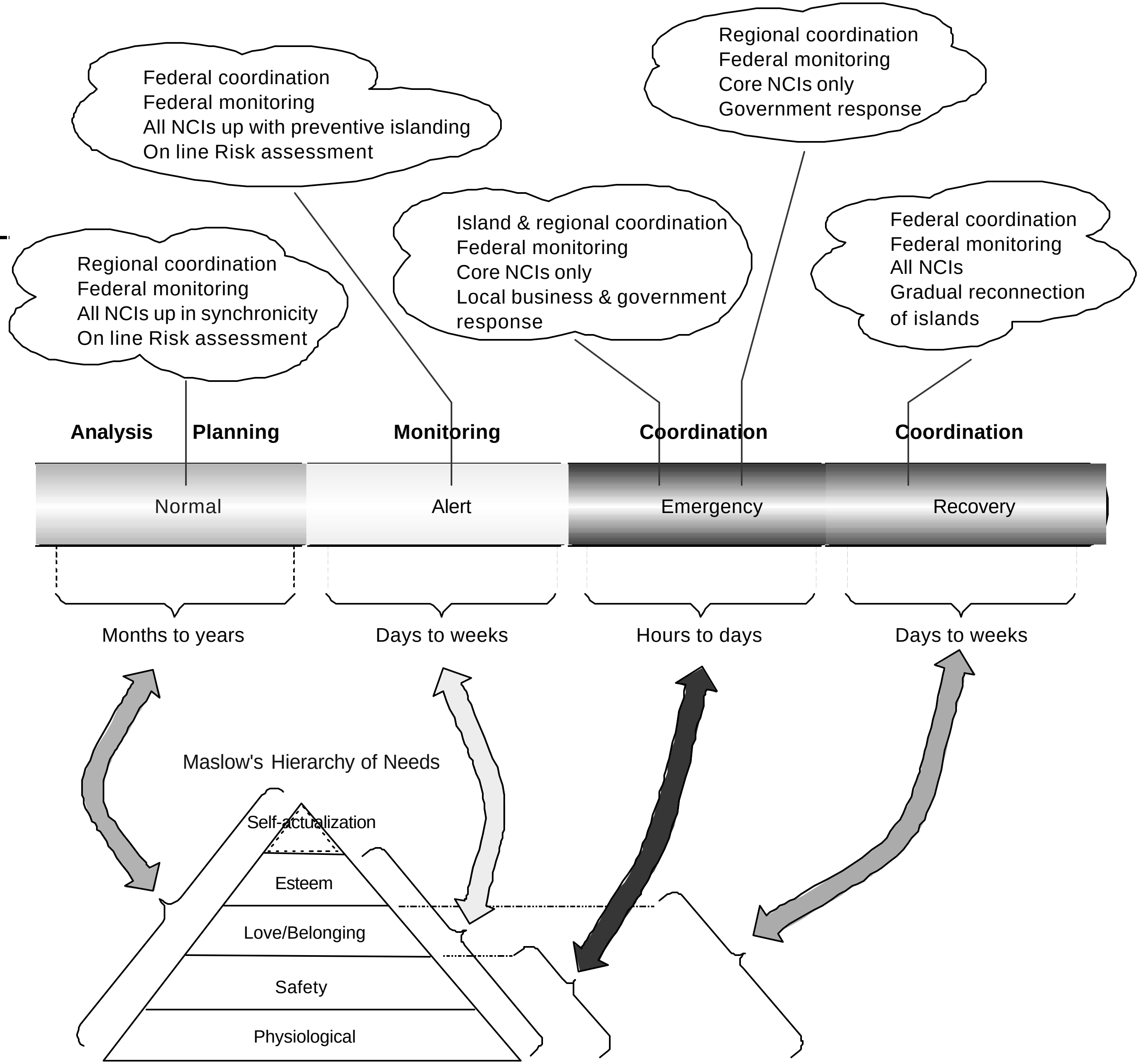
Problem Characteristics

1. Internal details of each infrastructure are known only to that infrastructure
2. Knowledge of each system's internals would be of little use to the other systems
3. What should be known globally is the subsystem of interdependencies
4. Solution of the subsystem of interdependencies is given back to the individual systems, which will then proceed to take the most appropriate internal actions considering the effect of these actions on the global system

Disaster Timeline

1. Long before the disaster (Planning): design for stronger system, strategic planning
2. Short before the disaster (Monitoring): indications of either natural or man-made disasters approaching
3. During the disaster (Coordination): events develop on the ground in real time
4. Short after the disaster (Coordination): infrastructures recovery, business recovery
5. Long after the disaster (Analysis): analysis period before looping back to step 1

Timeline



Regional coordination
Federal monitoring
All NCIs up in synchronicity
On line Risk assessment
Federal coordination
Federal monitoring
All NCIs up with preventive islanding
On line Risk assessment
Island & regional coordination
Federal monitoring
Core NCIs only
Local business & government response
Regional coordination
Federal monitoring
Core NCIs only
Government response
Federal coordination
Federal monitoring
All NCIs
Gradual reconnection of islands
Analysis
Planning
Monitoring
Coordination
Coordination
Normal
Alert
Emergency
Recovery
Months to years
Days to weeks
Hours to days
Days to weeks
Maslow's Hierarchy of Needs
Self-actualization
Esteem
Love/Belonging
Safety
Physiological

Vital Survival Tokens

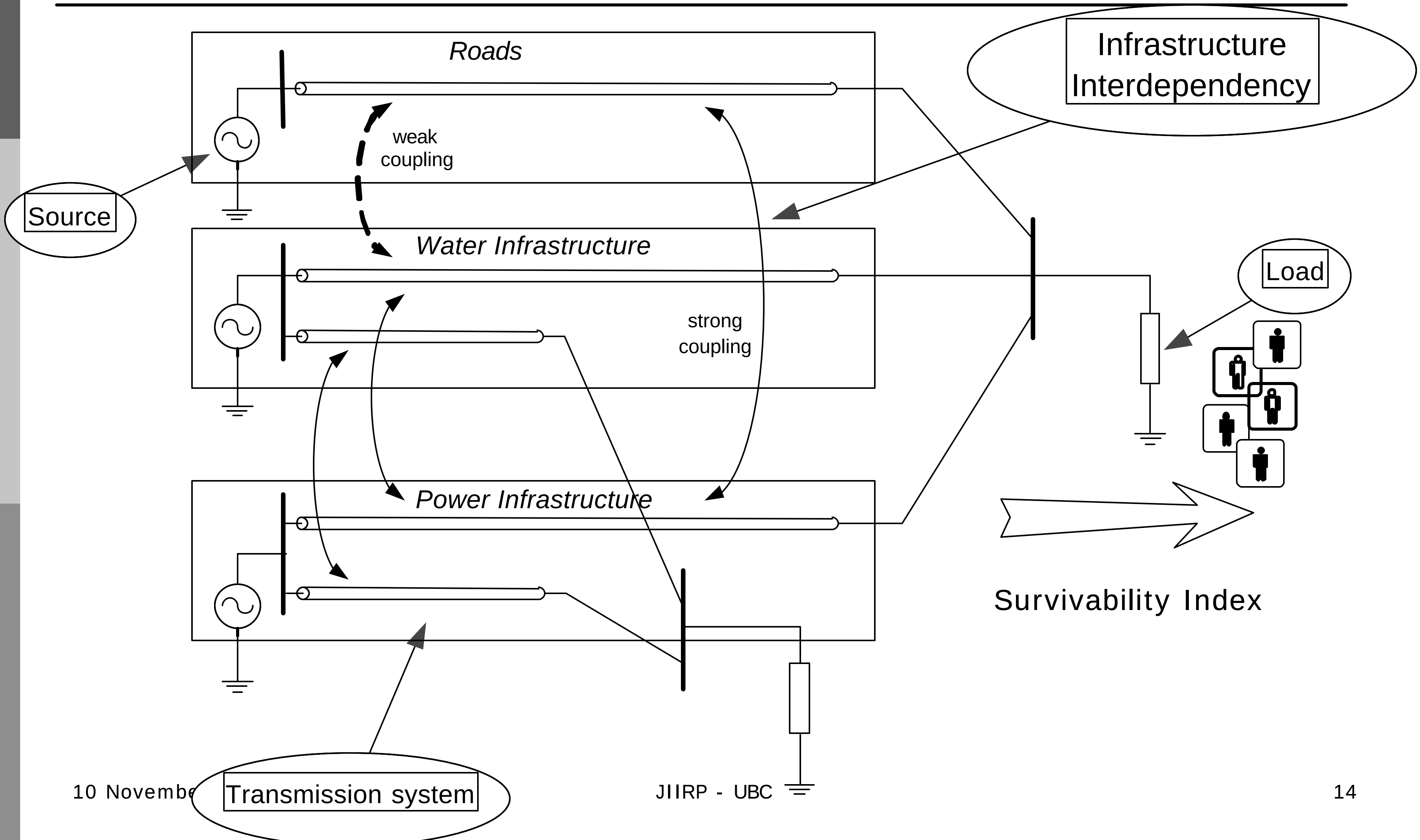
- Water (suitable for drinking)
- Food (adequate for emergency situations)
- Body Shelter (breathable air, clothing, temperature, housing)
- Panic Control (hope, political and religious leaders, psychologists, media)
- Personal Communication (whereabouts of loved ones)
- Individual Preparedness (education)
- Sanitation (waste disposal, washing)
- Medical Care (medicines, physicians, nurses)
- Civil Order (fire fighters, police, army)

Delivery of Survival Tokens

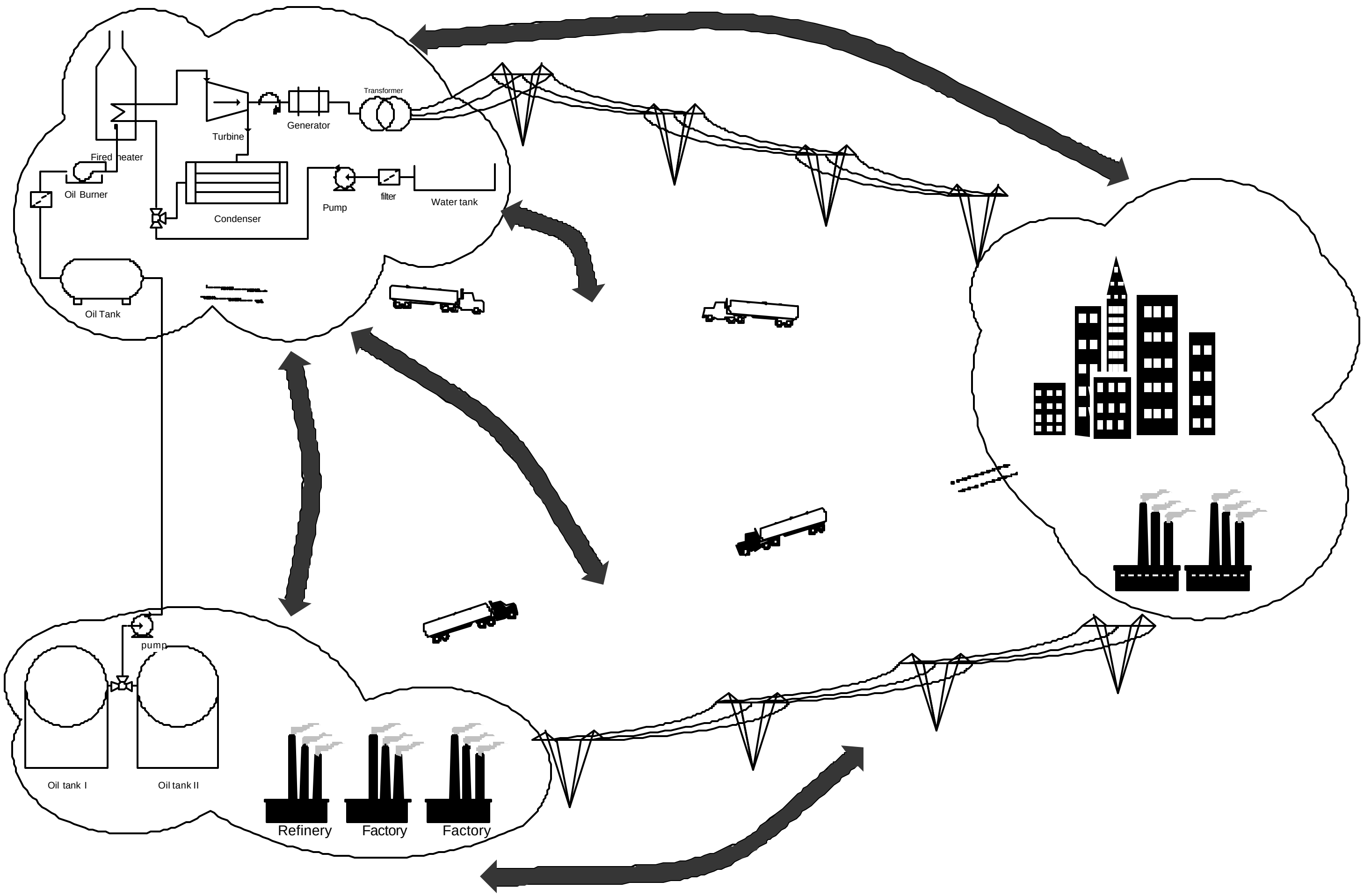
Transportation Networks

- Survival needs (tokens) are delivered from source (repositories) to victims and first responders
- Survival network is a multi-token system involving multiple interdependent infrastructures

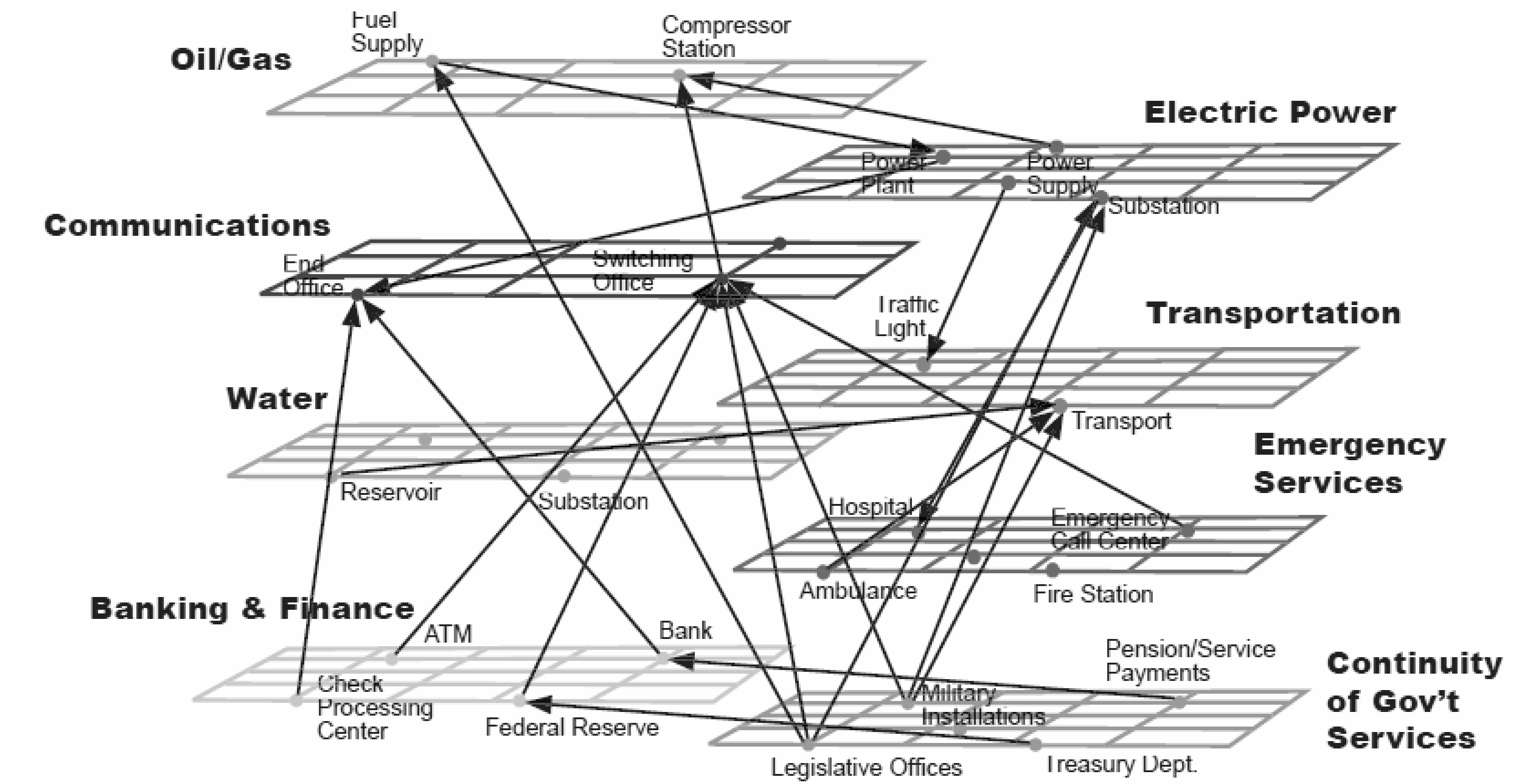
Transmission System Model



Interdependency Links



Interdependency Links[1]



[1]Col. W. Wimbish, Maj J. Sterling, Center for Strategic Leadership, U.S. Army War College, Vol. 06-03, August 2003

Nature of Delivered Tokens

Physical

- Electricity, food, water, medicines

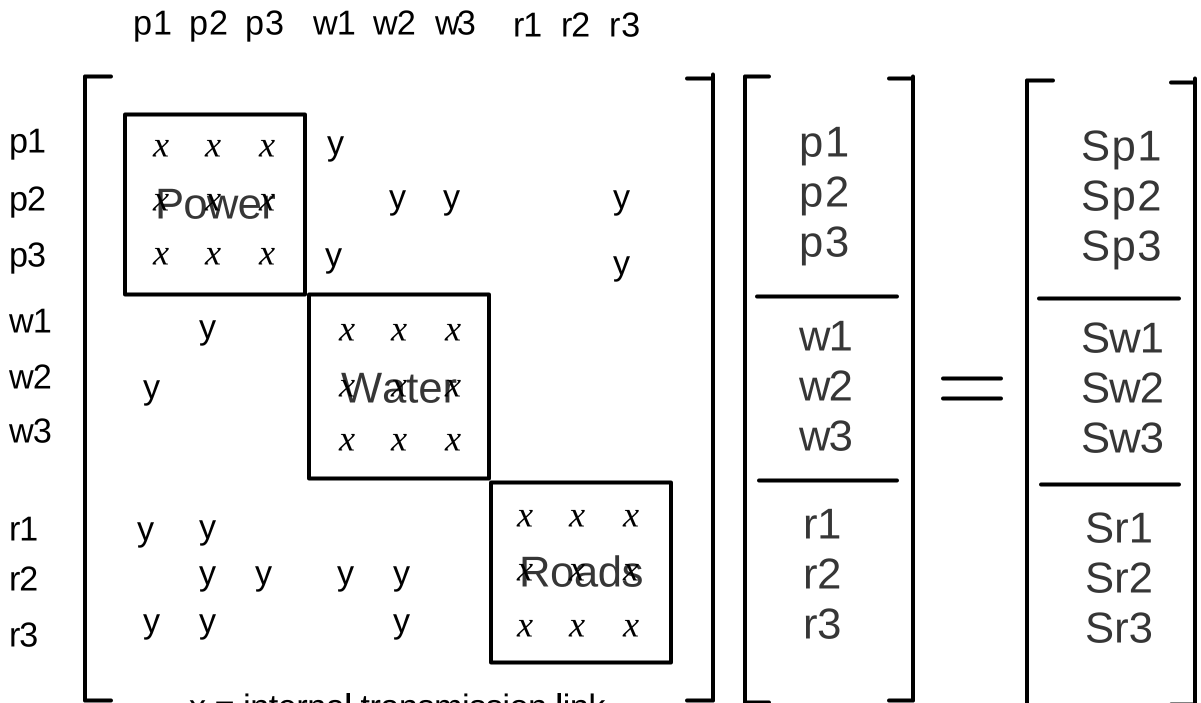
Professional

- Information, education, nurses, doctors, firefighters, police

Nature of Transportation Networks

- Physical layer (e.g., electrical wires, pipes)
- Human decisions layer (e.g., operators, managers, leaders)
- Both physical and human layers introduce delivery delays and distortions
- Human decision layer particularly important at infrastructures interdependency points

Transportation Matrix



x = internal transmission link
y = interdependency link

p1 = power token value node 1
p2 = power token value node 2
...
w1 = water token value node 1
…

Sp1 = power source value node 1
Sp2 = power source value node 2
...
Sw1 = water source value node 1
…

Transportation Matrix

- If the power system stood by itself, we would only have the box “power” relating the power available at the load (p1, p2, p3) with respect to the generated power (Sp1, Sp2, Sp3)
- The same would apply to the “water” and “roads” infrastructures in the example and the global transportation matrix would only have diagonal blocks
- However, water pumps require electricity, diesel generators require fuel, etc. and the boxes need to be connected by the “y” off-diagonal elements (interdependencies) in the global matrix

Mathematical Formulation

For linear (or linearized) systems, the tokens delivery problem can be expressed as

$$\mathbf{TX} = \mathbf{W}$$

Where T = Transportation matrix; X = received goods; W = sent goods

Nature of Interdependency Links

- We cannot carry water in electrical wires
- We cannot carry electricity in water pipes
- Interdependency links relate one kind of quantity with another kind of quantity
- For example, low electrical power can make fuel pumps work at reduced capacity; lack of fuel in a thermo electrical plant will result in reduced electrical power generation
- Often the interdependency link can be a human making a decision; e.g., decision to send a crew to repair a pump

Modelling of Interdependency Links

- In circuit theory, we can have:
  - Dependent sources, e.g., Sw2 = f(p2)
  - Control functions, e.g., road2 available if decision made to send repair crew
- Dependent sources and control (decision) blocks can be easily added to the transmission matrix

Sensitivity Analysis

The well-known “Sensitivity Network Approach” can be directly applied to the transportation matrix

$$\mathbf{TX} = \mathbf{W}$$

$$\frac{\partial \mathbf{X}}{\partial h} = -\mathbf{T}^{-1}\left(\frac{\partial \mathbf{T}}{\partial h}\mathbf{X} - \frac{\partial \mathbf{W}}{\partial h}\right)$$

Where h is some parameter in **T** or **W**

State Matrix

- System dynamics can be expressed in state-space form:

$$\dot{\mathbf{X}}(t) = \mathbf{A}\,\mathbf{X}(t) + \mathbf{B}\,\mathbf{U}(t)$$

Where state matrix **A** represents the system's own dynamics and matrix **B** represents the state transitions forced by the excitation events

- Matrices **A** and **B** can be directly obtained from the system's transportation matrix:

$$\mathbf{T}\mathbf{X} = \mathbf{W}$$

Patterns in the T and A Matrices

- Diagonal strength
- Sparsity patterns
- Short term and long term responses
- Groupings identification

Strategies

Islanding for Survival

The Islanding Concept

- Panic control and prevention of cascading effects requires immediate response
- For immediate response to be possible vital tokens must be available onsite when the disaster strikes
- An island can survive on its own for a limited time period. Beyond this period help needs to be coordinated and delivered from the external world
- In power systems, islanding is a well-known effective strategy to segment the network and prevent cascading effects (large blackouts)

System Survivability Index (SSI)

- *Island Survival Time $S_k(t)$:* how long island k can survive before its links are re-established
- *Link Restoration Time $l_{ki}(t)$:* time needed to restore link i in island k
- $S_k(t) = f\{l_{ki}(t)\}$
- $l_{ki}(t) = f\{l_{ki}(t)\}$ for all k? i}
- *System Survivability Index* ***(SSI)****:* composite index reflecting total system strength

Disaster Room Scenario

Interdependencies Coordination

- During large emergencies, infrastructure managers get together in a physical or virtual "disaster coordination room"
- Global GIS system provides visualization of "key features" to effectively coordinate interdependent actions
- Faster than real time simulator allows for testing out interdependent actions before applying them to the actual systems

Interdependencies Simulator

Distributed Nodes Simulator (DNSIM)

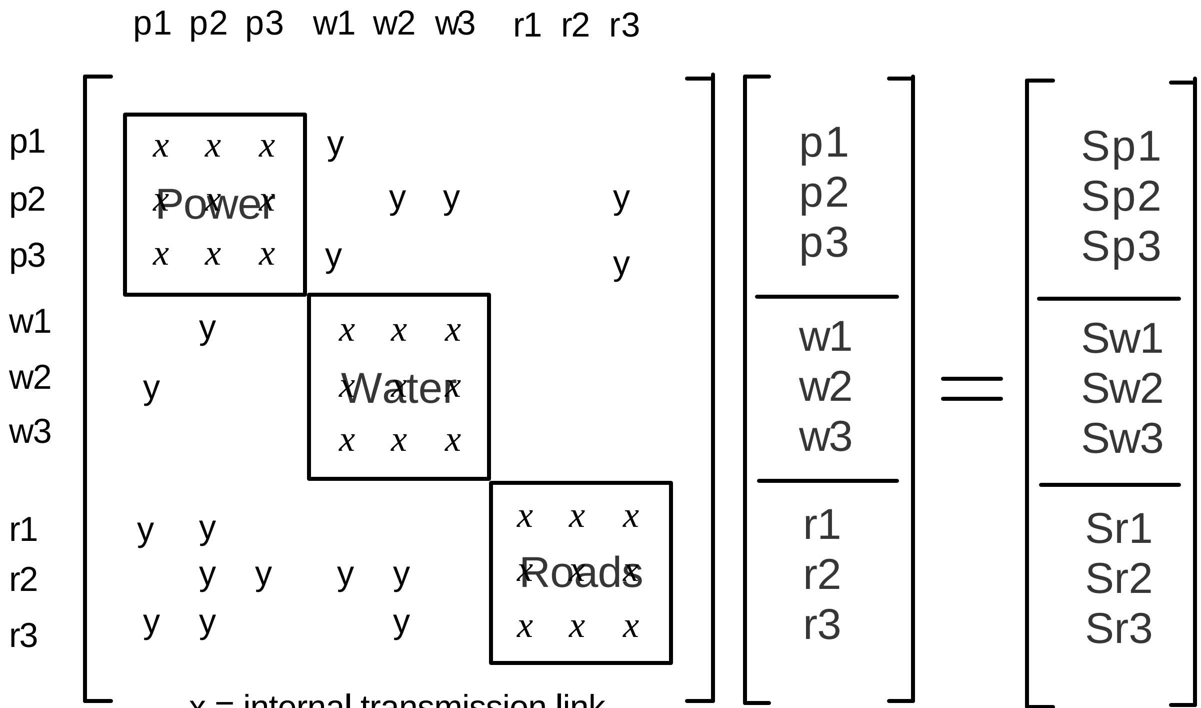
Considerations

- We are interested in looking at the system from the interdependency links viewpoint
- We want to optimize the system of interdependencies (links subsystem) not the internal design of each individual infrastructure
- The simulator is to look at each infrastructure as seen from the interdependency links
- Simulation of the internal details of each infrastructure, beyond the interdependency links, should be done by the internal infrastructures' operators

DNSIM Conceptual Design

- The coordination central nodes will optimize actions from the interdependencies point of view
- The central nodes do not need to know the internal details that generated the information coming from the remote nodes (information hiding concept)
- Solution partitioning allows for multiple processing nodes and hierarchical decision making
- A multiple central nodes approach results in increased overall system resiliency
- System topology can change along the solution time line according to the on-ground events without solution restarting
- Faster than real-time near optimal solutions are required

Mapping of Infrastructures Matrix and Survivability Strategy

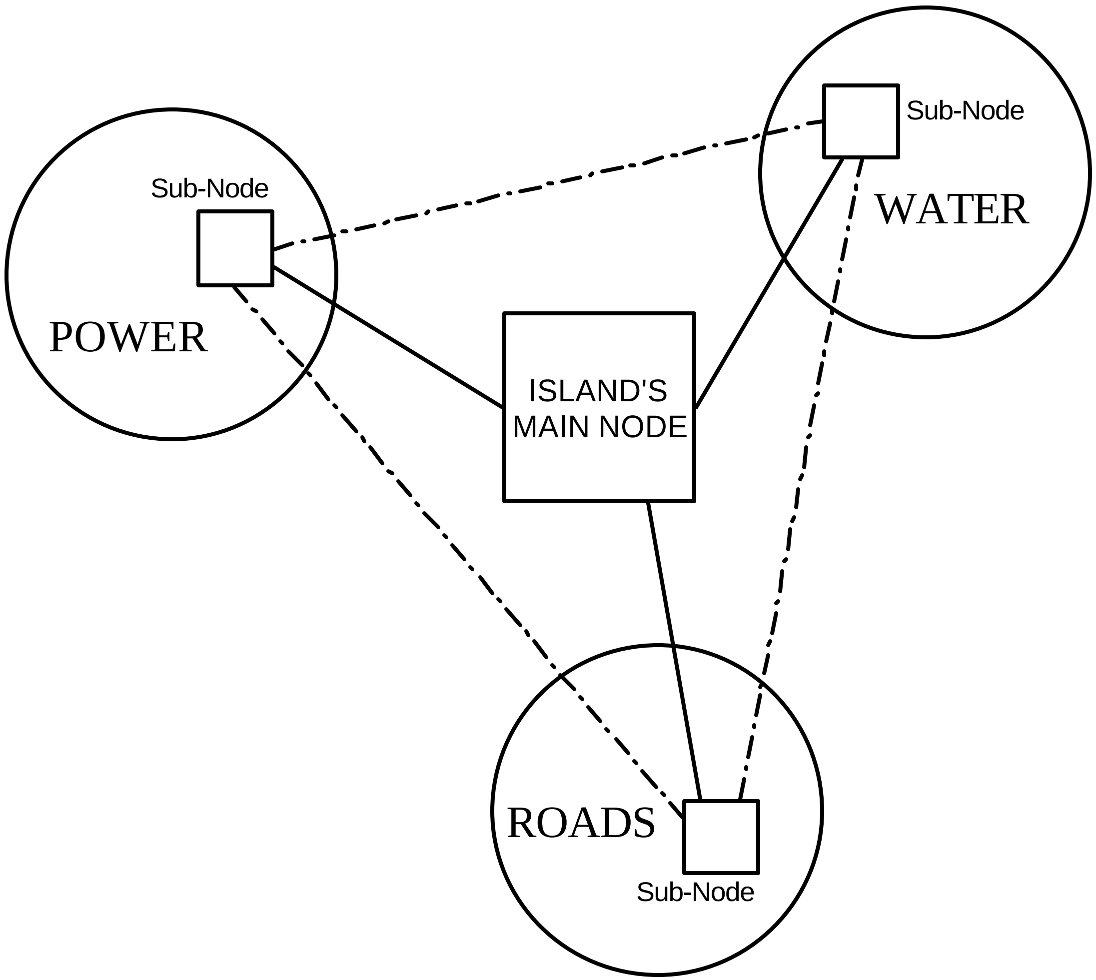


x = internal transmission link
y = interdependency link

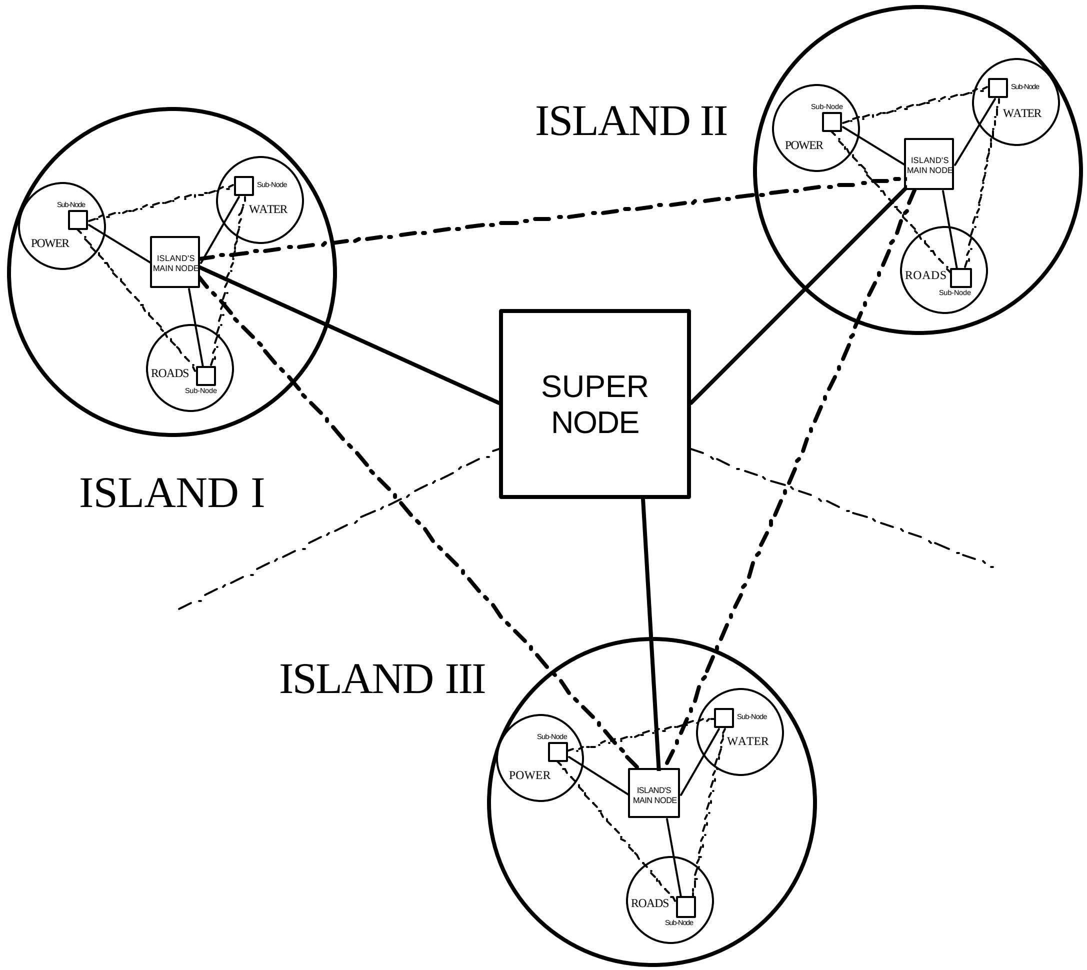
p1 = power token value node 1
p2 = power token value node 2
...
w1 = water token value node 1
...

Sp1 = power source value node 1
Sp2 = power source value node 2
...
Sw1 = water source value node 1
...

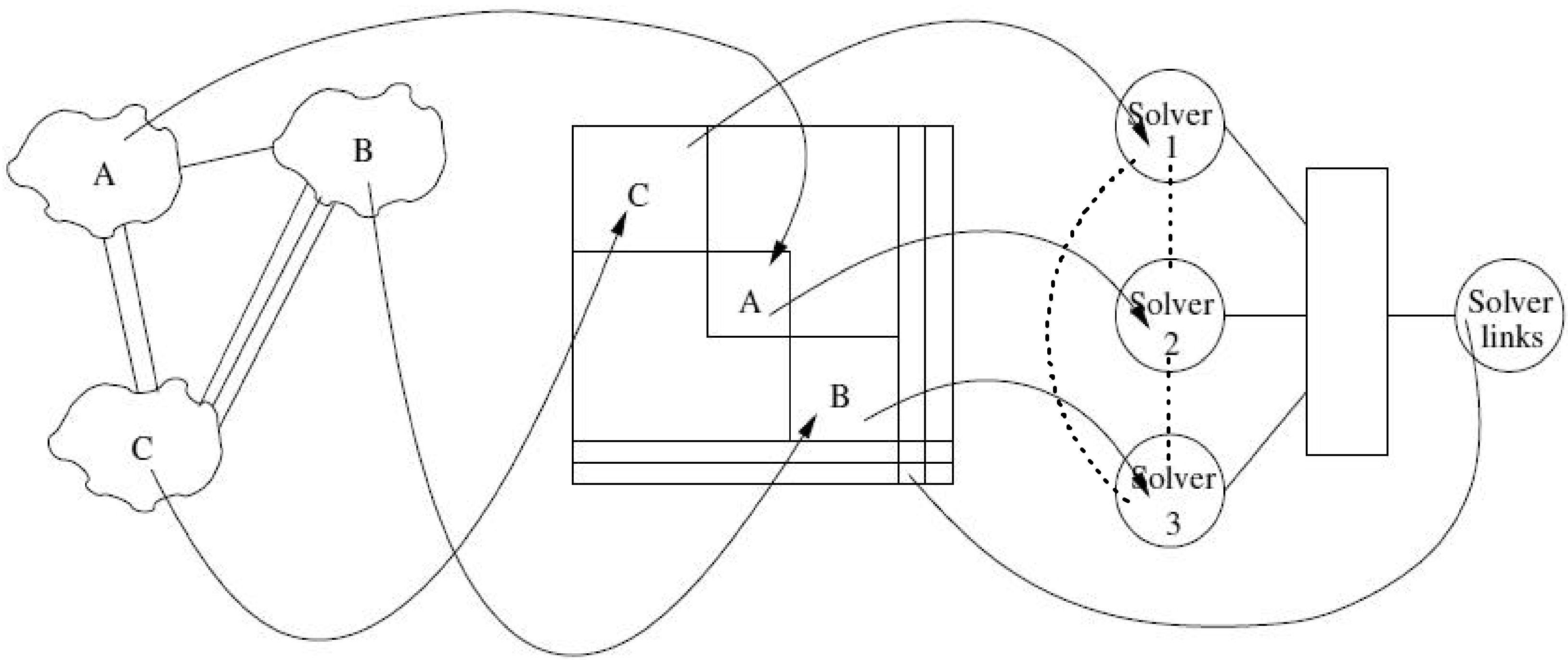
DNSIM Solution (For Each Island)



Hierarchical Solution Scalability



Mapping of Physical, Algorithmical, and Computational Layers



Summary

- Infrastructures and their interdependencies can be modelled as transportation systems for delivery of vital tokens
- The infrastructures transmission matrix and the corresponding state matrices can incorporate all information required to assess the system's survivability index, to dynamically coordinate disaster survival actions, and to assess the resiliency of the system's design
- The islanding concept can be a very effective strategy during the disaster's first-moments to prevent panic and cascading events and to increase the system's survivability index
- The DNSIM simulator implements the concept of individual infrastructure subsystems interconnected through interdependency links