Design for Survival

Coordination of Critical Infrastructure Interdependencies to Maximize Disaster Survival

(JIIRP-UBC Group)

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

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

Problem Identification

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 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 emerge as 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

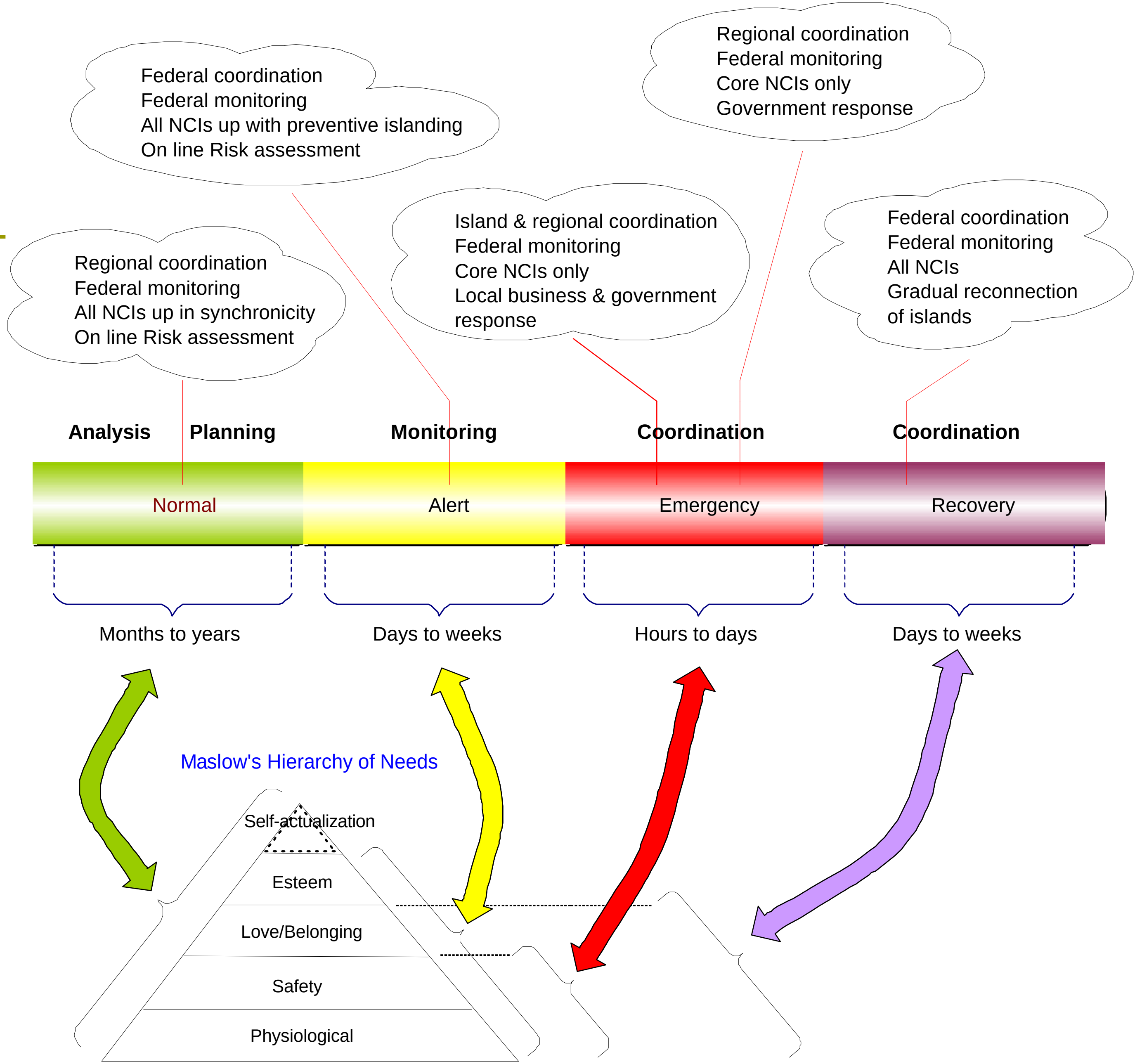
Problem Characteristics

1. Internal details of each infrastructure 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 interdependencies subsystem is given back to the individual systems, which will 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): recovery phase
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)

Individual Needs

1. Potable Water (suitable for drinking)
2. Food (adequate for emergency situations)
3. Body Shelter (breathable air, clothing, temperature, housing)
4. Personal Communication (whereabouts of other family members)
5. Individual Preparedness (education)

Group Needs

6. Sanitation (waste disposal, washing)
7. Medical Care (medicines, physicians, nurses)
8. Panic Control (hope, political and religious leaders, psychologists, media)
9. Civil Order (fire fighters, police, army)

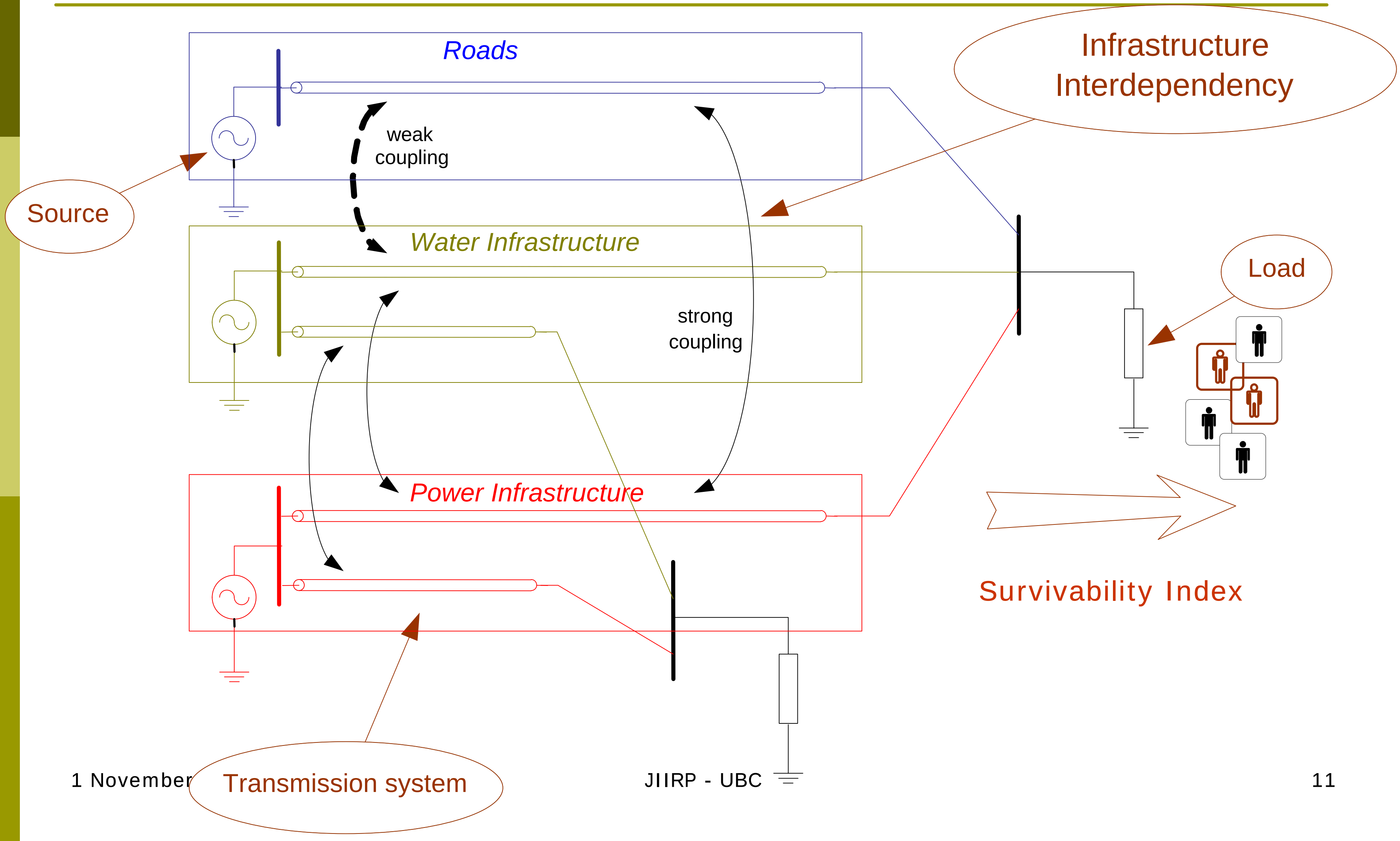
Delivery of Survival Tokens

Transportation Networks for Delivery of Survival Tokens

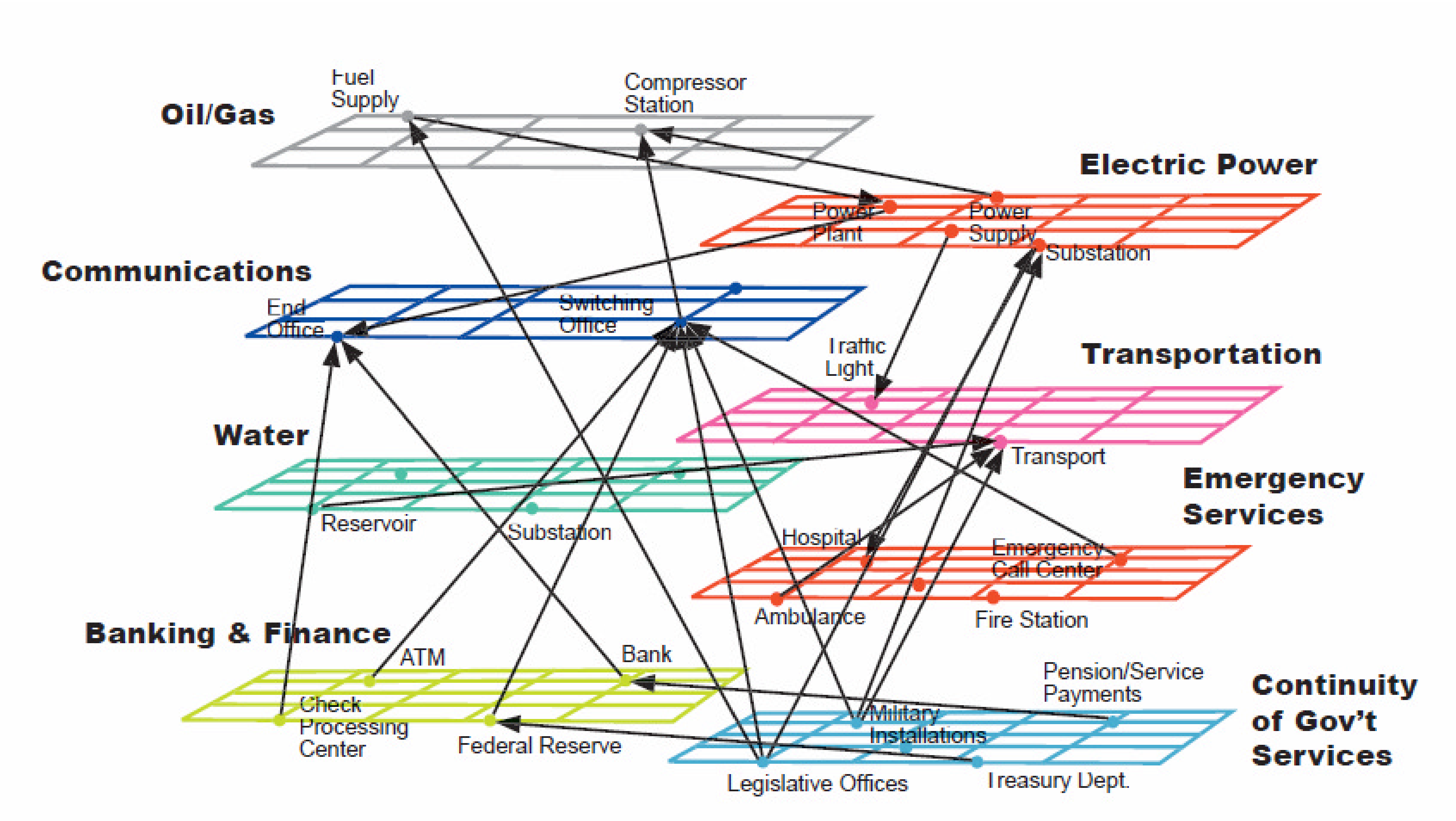
Survival-Tokens Network:

- Survival needs (tokens) are delivered from Source (repositories) to User (victims)
- Survival network is a multi-token system involving multiple interdependent infrastructures

Transmission System Model



Infrastructure Interdependencies



Delivered Tokens

Physical

- Electricity, food, water, medicines

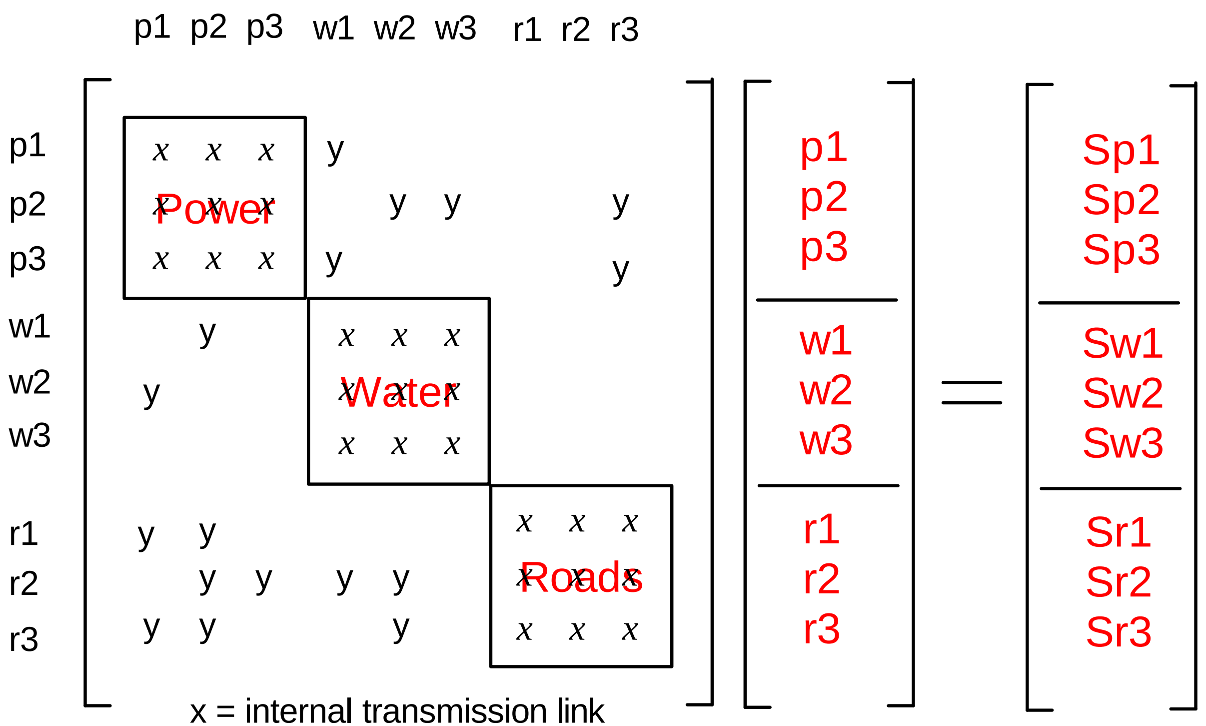
Professional

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

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
...

Mathematical Formulation

For linear (or linearized) systems

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

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

Transportation Matrix

- Goods are transported from source to nodes through the transportation matrix [T]
- If infrastructures were independent of each other [T] would be block diagonal
- Dependencies among infrastructures appear as off-diagonal elements outside these blocks
- Goods (sources) and people (loads) can be relocated along the time line

Interdependency Links (1)

- We cannot carry water in electrical wires
- We cannot carry electricity in water pipes
- Interdependency links relate one observed quantity (input) to a decision (output)
- Input and output can be of different nature; e.g., low power can make water pumps work at half capacity
- The decision maker can be a system or a human

Interdependency Links (2)

- 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 functions can be, for example, nonlinear or probabilistic
- 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's 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:

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

Further Analysis of the Transportation and State Matrices

- Diagonal strength
- Sparsity patterns
- Short term and long term singularities
- Groupings can be used to identify "islands"

Strategies

Islanding for Survival

The Islanding Concept

- Immediately: vital tokens delivered onsite when disaster strikes
  - Island takes first hit, absorbs it and avoids panic and cascading effects
- Later: help to come from external world or other islands
- In power systems, islanding is an effective strategy to segment the network and prevent cascading effects (large blackouts)

Survivability Parameters

- *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

Interdependencies Simulator

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
- Interdependencies simulator is to view each infrastructure as an equivalent as seen from the interdependency links
- Infrastructure equivalents should be provided by the ones that know the system, i.e., the internal operators

DNSIM Mapping of Simulator and Field Strategies

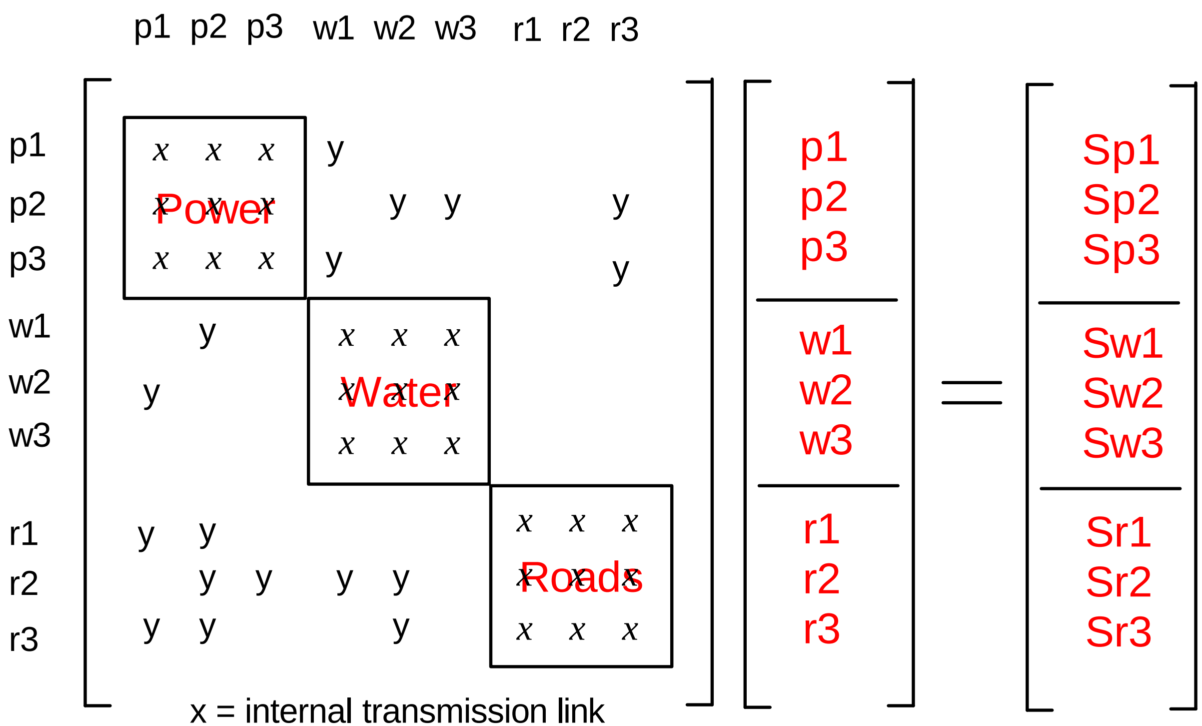
Simulator and field strategies need to be mapped for tool to be effective

- Central nodes do not need to know all the details of the information coming from the remote nodes (information hiding concept)
- Infrastructures do not need to know the details of the other infrastructures to coordinate their actions

DNSIM Conceptual Design

- Solution partitioning allows for multiple processing nodes and hierarchical decision making
- Multiple central nodes approach for increased 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

Mapping of Infrastructures Matrix and Survivability Strategy



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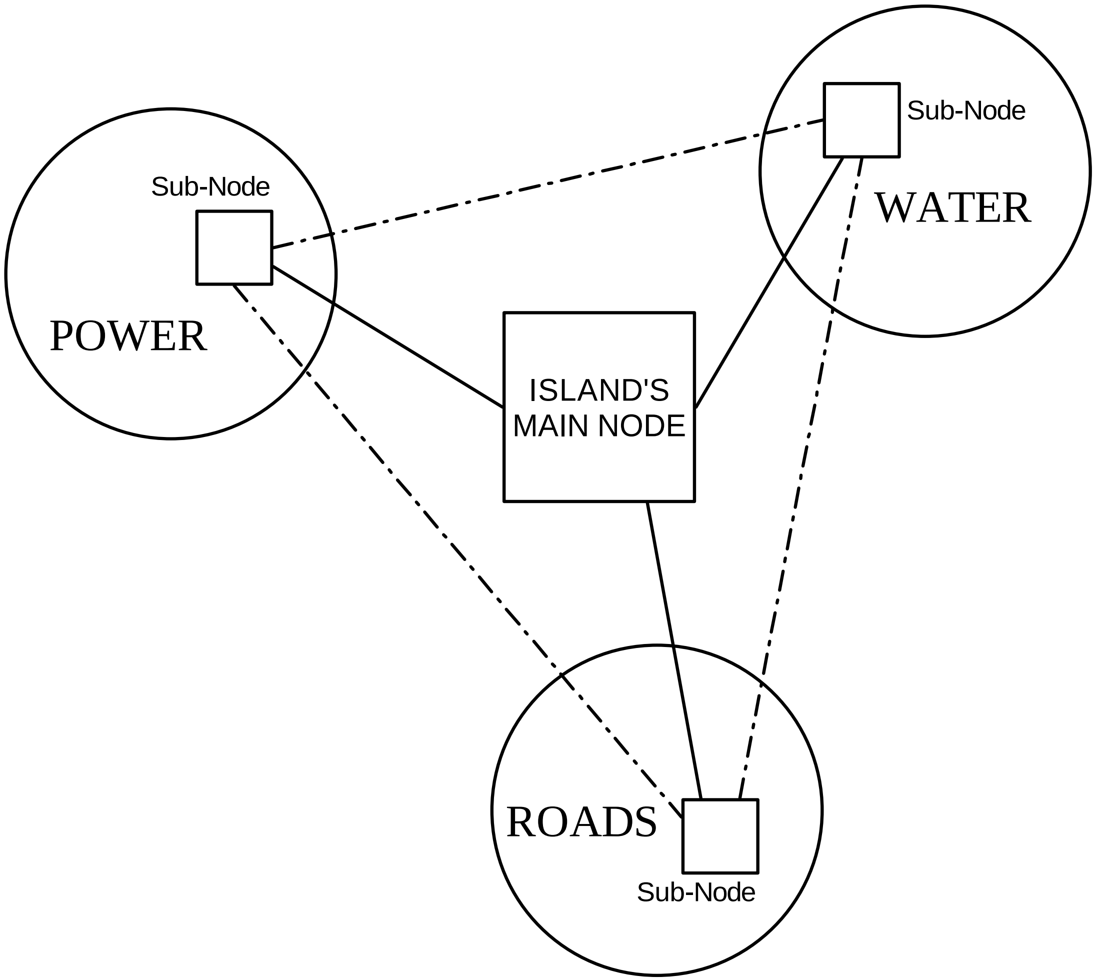
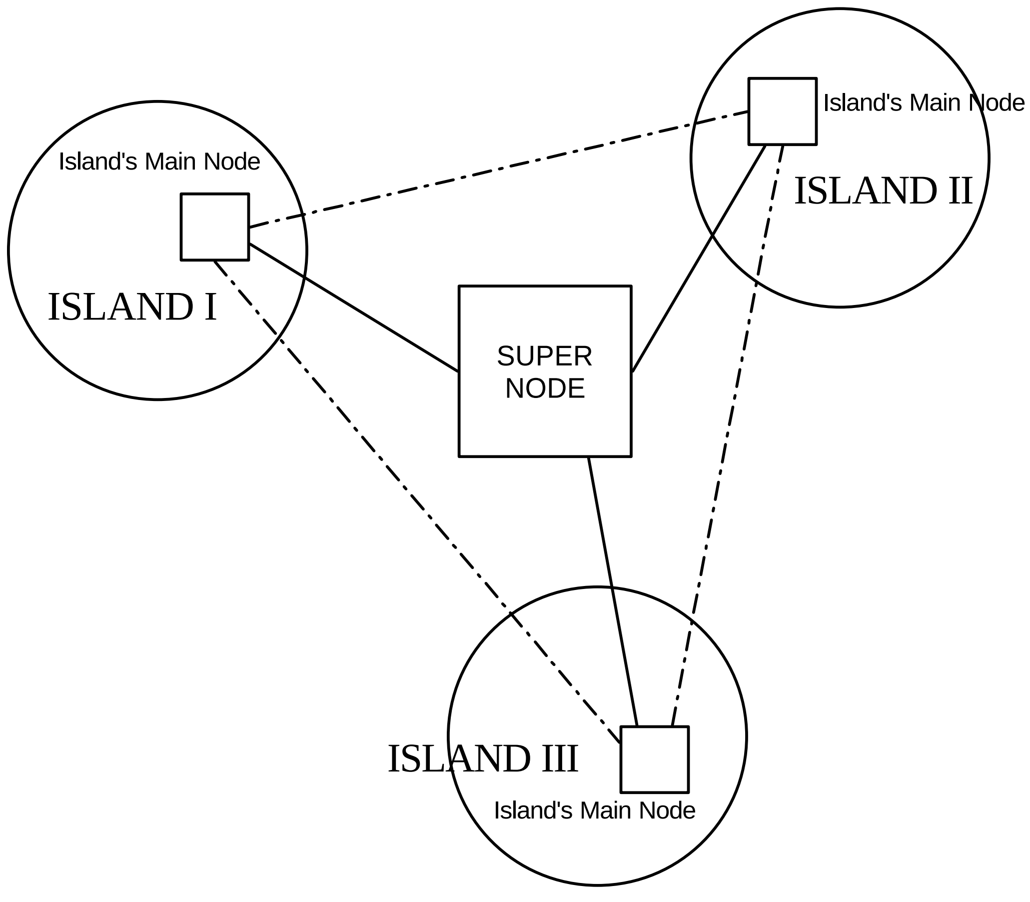
DNSIM Solution (For Each Island)



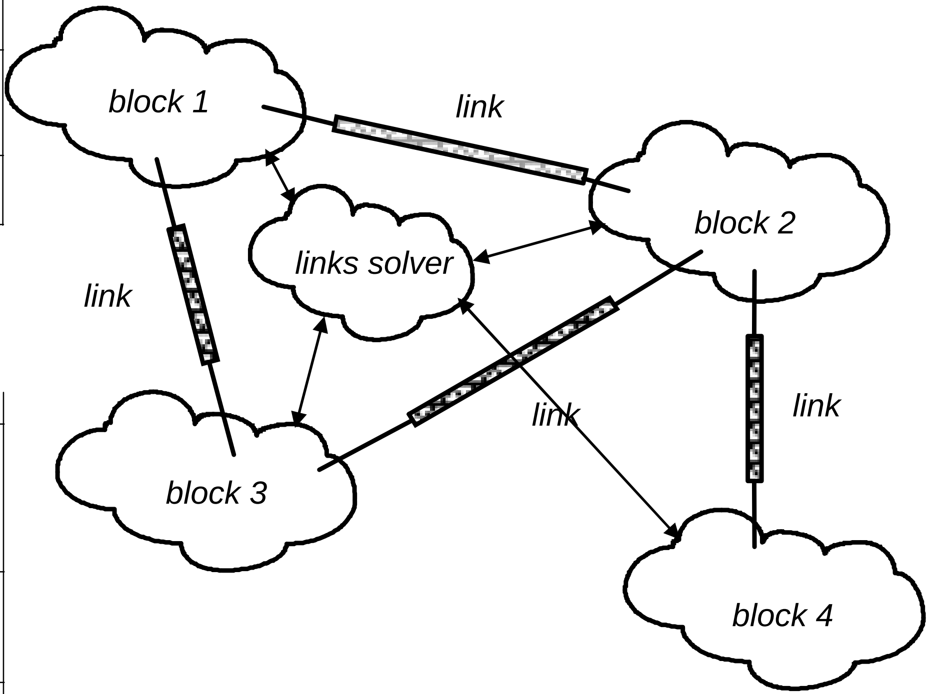
DNSIM Solution (Among Islands)



DSIM Implementation for Each Island and Each Infrastructure

	A1	A2	A3	A4	B1	B2	B3	$a1$	$a2$			
A1	G_{A11}	G_{A12}	0	G_{A14}				0	0	v_{A1}		h_{A1}
A2	G_{A12}	G_{A22}	G_{A23}	0				0	0	v_{A2}		h_{A2}
A3	0	G_{A23}	G_{A33}	G_{A34}				1	0	v_{A3}		h_{A3}
A4	G_{A14}	0	G_{A34}	G_{A44}				0	1	v_{A4}		h_{A4}
B1					G_{B11}	G_{B12}	G_{B13}	-1	0	v_{B1}	=	h_{B1}
B2					G_{B12}	G_{B22}	G_{B23}	0	0	v_{B2}		h_{B2}
B3					G_{B13}	G_{B23}	G_{B33}	0	-1	v_{B3}		h_{B3}
$a1$	0	0	1	0	-1	0	0	$-z_{a1}$	0	i_{a1}		0
$a2$	0	0	0	1	0	0	-1	0	$-z_{a2}$	i_{a2}		0

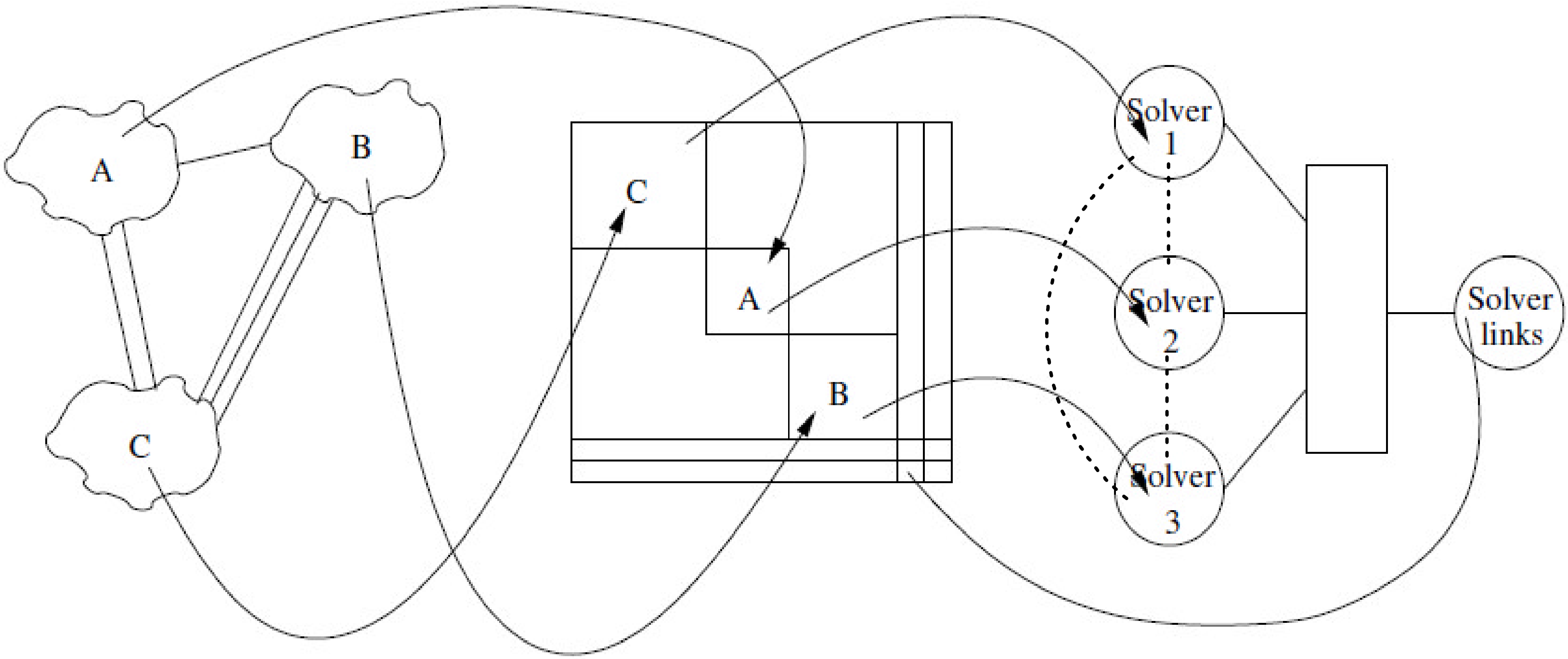
Internal Viewpoint



	A1	A2	A3	A4	B1	B2	B3	$a1$	$a2$			
A1	1							a_{13}	a_{14}	v_{A1}		e_{A1}
A2		1						a_{23}	a_{24}	v_{A2}		e_{A2}
A3			1					a_{33}	a_{34}	v_{A3}		e_{A3}
A4				1				a_{43}	a_{44}	v_{A4}		e_{A4}
B1					1			$-b_{11}$	$-b_{13}$	v_{B1}	=	e_{B1}
B2						1		$-b_{21}$	$-b_{23}$	v_{B2}		e_{B2}
B3							1	$-b_{31}$	$-b_{33}$	v_{B3}		e_{B3}
$a1$	0	0	0	0	0	0	0	Z_{11}	Z_{12}	i_{a1}		e_{a1}
$a2$	0	0	0	0	0	0	0	Z_{12}	Z_{22}	i_{a2}		e_{a2}

Links Viewpoint

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 (strength) 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 interdependencies links