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UNDERSTANDING INTERDEPENDENCIES AMONG CRITICAL INFRASTRUCTURES

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ABSTRACT

The system of critical infrastructures, such as power grid, water network, health system, etc., constitutes the backbone of modern societies. During large disasters (e.g., earthquakes, hurricanes, terrorist attacks, etc.) the situation is very different from normal life because multiple infrastructures are affected simultaneously, and unless they coordinate each other's actions, the overall response process may suffer serious stalls. Several countries have recognized that there is an urgent need to develop knowledge, tools, and recommendations to support coordinated decision making among interdependent infrastructures, particularly during emergency situations. This paper discusses the importance taking into account the interdependencies of critical infrastructures during large disasters, presents a brief review of current research being done in this field, and presents a methodology to address interdependencies recently developed at The University of British Columbia in response to this need.

Introduction

Natural disasters such as earthquakes, tsunamis, forest fires, terrorist attacks and global disease outbreaks can dramatically impact the socio-economic well-being of countries, and in a more serious context, our basic survivability. Recent events have demonstrated the need of fast, dynamic and coordinated action plans to increase the chances of survivability for society. Examples of these include the ice storm in eastern Canada in the winter of 2000; the September 11, 2001 attacks in New York city; the August 14, 2003 power blackout; the catastrophic tsunami in south Asia in 2004, which claimed more than 200,000 lives; and the 2005 hurricane Katrina in the United States with an estimated 125 billion dollars of economic impact. These events have clearly demonstrated that disaster management and preparedness is a dynamic process that requires a holistic analysis of critical interdependencies among core infrastructures in order to mitigate the impact of extreme events and improve survivability of our society.

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Public Safety Canada identifies the following infrastructures as being critical to the nation's safety, security and well-being: Energy and utilities, Finance, Food, Transportation, Government, Communications and information technology, Health care, Water, Safety, and Manufacturing. As the rate and severity of natural and man-made disasters' have increased, so has the possibility that disruption of Critical Infrastructure (**CI**) could result in prolonged loss of essential services. The complex system of interdependencies among critical infrastructure has heightened the risks and vulnerabilities for Canada, and for other countries. And hence, the consequences can lead to cascading effects expanding across sectors and borders, (Public Safety Canada, 2008).

Background on Interdependencies of Critical Infrastructure

The 1995 Kobe earthquake showed that disruption of regional lifeline systems can generate a profound effect on the entire country, because of the economic interdependence of lifeline systems and their functions (NIST, 1996). Heath (1995) argued that the response management in Kobe earthquake was non-optimal. Integration, coordination, communication, and planning were insufficient to cope with large disasters. The greatest lesson from the Kobe earthquake was that response managers have almost no time to respond "right" to the crisis. Another important lesson from Kobe is that operational and functional human errors can lead to cascading effects in other systems. This was illustrated by the decision to re-establish power service in the affected areas, where wooden structures were collapsed, which resulted in post-earthquake fires with catastrophic consequences.

The September 11, 2001 terrorist attacks in the US had a great effect on local critical infrastructure. Local emergency services were seriously affected when hundreds of responders were killed in the collapsing towers. Public transportation was affected and water supply suffered severe damage as a consequence of the collapsed towers and nearby buildings. Due to the rupture of main water pipelines and disruption of local communications, firefighters had to deal with lack of infrastructure and water pressure to deal with fires that followed the collapses; a telecommunication hub and a cable system were also damaged and caused the system to stop their activities. The financial stock exchange market suffered the consequences immediately after the event. The decisions made after those events also impacted CIs. For instance, the Federal Aviation Authority (FAA) cancelled all commercial flights; the financial and banking sector temporarily closed key markets as a safety precaution; and increased demand for telephone and Internet connections forced carriers to truncate their services to avoid crashing their networks (O'Rourke, et al., 2003).

The lessons learned from the Canadian point of view were compiled in OCIPEP (2002) and some of them are summarized here:

- *Communications:* Predetermined emergency phone lines should have call priority and immediate service attention. This will assist emergency response in crisis. During a crisis, a deployable emergency information management capacity will assist first responders and victims; it will also help mitigate the affliction on government and health infrastructure following a disaster.
- *Transportation:* The ability of transportation infrastructure to sustain normal functions will be jeopardized if sufficient planning and resources are not dedicated to cope with

disasters. The interruption of one transportation channel (air) will result in mass usage and delays of alternative transportation channels (marine, rail, roads, etc) and will affect operations involving critical personnel and sensitive materials.

- *Energy:* Communications and business continuity will collapse after the initial impact of a disaster if backup power generation is not provided with guaranteed access to fuel and maintenance. The rapid restoration of power to critical sites will depend on a list identifying and prioritizing sites which are particularly vulnerable to prolonged outages.
- *Banking and finance:* Advanced planning and communication among CIs will minimize the impact of interdependencies on business continuity plans.
- *Government:* The development of a wide alert system with high levels of security and infrastructure redundancy will improve the government's ability to coordinate its response to CI threats. Web portals that post emergency response information will help governments to convey important information to citizens during times of crisis; also emergency communications will assist in dealing with the difficult situations. Rescue services and law enforcement should reach agreements on how to manage the rescue of survivors and restoration of normal city functioning while preserving evidence for criminal investigations.

In August 14th, 2003 power outages in the Northeast United States "a wake-up call to decision makers," Nozik (2003) stated that existing systems of the US can trigger a cascading series of errors that would leave the population vulnerable. In 1996, western United States lost power because a power line heated up, sagged, and shorted out. In 1998, there were two power failures: ice storms knocked out power systems in eastern Canada and the United States. The Northeast blackout of 2003 appeared to be caused by a strike of lightning, an about 55 million people were affected in the US and Canada. Some areas lost water pressure, the northeast corridor of railroad service was stopped, passenger screenings were affected at airports, and regional airports were shut down. In New York, flights were cancelled due to difficulties accessing "electronic ticket" information, communication through cell phones was disrupted, wired telephone was functional, ELCON (2004).

On August 23rd, 2005, Hurricane Katrina became a tropical storm somewhere near the coasts of the Bahamas. The tropical storm grew into a catastrophic hurricane in the following seven days, and it made landfall in Florida and then in Louisiana and Alabama. Katrina caused physical destruction along its path, flooded the historic city of New Orleans, ultimately killed over 1,300 people. The hurricane hit several towns, cities and states. Individual local and state plans, as well as new plans created by the federal government after the September 11th, 2001 events failed to account for widespread or simultaneous catastrophes. Hurricane Katrina hit small towns and large cities, thus the largest search and rescue operations in US history was originated. Hurricane Katrina's national response included all levels of US government—Federal, State, and local—the private sector, other countries, and individual citizens. People and resources were sent to the region to aid the emergency response. Despite these efforts, the response was not enough and it became the most destructive natural disaster in US history.

Townsend (2006) presented "The Federal Response to Hurricane Katrina (Lessons learned)" and 17 Critical Challenges were addressed in the report: National Preparedness; Integrated Use of Military Capabilities; Communications; Logistics and Evacuations; Search and

Rescue; Public Safety and Security; Public Health and Medical Support; Human Services; Mass Care and Housing; Public Communications; Critical Infrastructure and Impact Assessment; Environmental Hazards and Debris Removal; Foreign Assistance; Non-Governmental Aid; Training, Exercises, and Lessons Learned; Homeland Security Professional Development and Education; and Citizen and Community Preparedness

Interdependency studies: In the last few years more attention has been given by the research community to this field of research, as demonstrated by the work published by Alexoudi et al,(2008), Strasser et al. (2008), Tsuruta et al. (2008), Wang and Au (2008), Lee and Graf (2008), Hosseini and Vayeghan (2008), Shi et al (2008), Corotis and Hammel (2008), Furuto et al. (2008), Mitsunari et al. (2008), Mujumdar (2008), and Kuo et al (2008). Specific research related to interdependencies of CI in earthquake engineering has been published by O'Rourke (2007), Dueñas-Osorio, et al. (2007), Bruneau and Reinhorm (2007), Bruneau et al. (2003), Marti, et al. (2008) and Juarez-Garcia (2010).

Other important studies include:

- The US President's Commission on Critical Infrastructure Protection (PCCIP) in 2001 stated that the economy and national security of the US depend upon 5 critical infrastructure sectors: Banking and Finance; Transportation; Information and Communications; Vital Human Services (Emergency Services, Government Services, and Water Supply Systems) and Energy (Electrical Power and Oil and Natural Gas Production and Storage). These five critical infrastructures are highly interdependent. Potential threats to the normal functioning of these infrastructures are both natural and man-made. PCCIP also addresses that in infrastructure protection, failure to adopt new security technologies means that vulnerabilities in the nation's critical infrastructures will persist. To eliminate these vulnerabilities, the government cannot afford to deal only with those firms that are highly motivated to collaborate – it should also engage those private sector owners, operators, providers, and users of critical infrastructure products and services that may not know of, or may not be particularly motivated to adopt, technologies developed through government investment. This PCCIP program, along with private sector efforts, should enhance the security of US critical infrastructures by rapidly identifying, developing, and facilitating the fielding of technological solutions and management tools and techniques to address existing and emerging infrastructure threats and vulnerabilities. PCCIP program only provides guidelines, but no methodology was developed for this implementation of this program.
- Rinaldi et al. (2001) discussed that: *"...critical infrastructures are highly interconnected and mutually dependent in complex ways, both physically and through a host of information and communications technologies (so-called "cyberbased systems"), is more than an abstract, theoretical concept".* Infrastructures affect fundamental systems and services that are critical to the security, economy, and social well-being of the study region. The authors explain that there are other factors that affect infrastructure operations, and that in order to describe the infrastructure interdependencies, it is necessary to define: the infrastructure characteristics; state of operation; types of interdependencies; environment; coupling and response behaviour; and the types of failure. They presented a conceptual framework for addressing infrastructure interdependencies that is used to explore the challenges and complexities of interdependency.

- In 2003 the National Infrastructure Advisory Council (NIAC) established a working group to study cross-sector interdependencies and provide risk assessment guidance. The Study Group reviewed previously published studies and recruited participation from all critical infrastructures. The Working Group concluded that cross-sector crisis management coordination is fundamental to the rapid restoration of critical infrastructure(s) and integral to sustain the public's confidence in those infrastructures. The working group advised the Department of Homeland Security (DHS) to adopt the following set of fundamental principles: by defining short-term deliverables, establishing a method to monitor progress of those deliverables, and fostering the commitment of the public and private sectors to partner for progress. The Working Group identified nine issues for the NIAC that if not addressed, could polarize efforts to coordinate across sectors before, during, and after an event. These are:
    1. *Inconsistencies exist in the definitions of the critical infrastructures.*
    2. *The "sector coordination" role is not broadly understood by industry and therefore is not viewed as a focal point for crisis management coordination within and across the sectors. Further, sector coordinating mechanisms have not been identified for all critical infrastructures.*
    3. *Crisis management plans do not exist for each sector and are not tested end-to-end across the sectors.*
    4. *A National Command Center does not exist as a confluence point for the private sectors during times of crisis.*
    5. *Government-sponsored exercises should actively solicit private industry representation.*
    6. *There is an underestimation of the dependency of the nation's critical infrastructures on the Internet.*
    7. *Coordination in planning and response between public emergency management (federal, state, and local) and private critical infrastructure is inadequate and/or inconsistent.*
    8. *There is a lack of incentives that would help defray the additional expense burden resulting from strengthening the resiliency of the critical infrastructures.*
    9. *Sophisticated modeling capabilities exist at the national laboratories and multiple research and development (R&D) studies on cross-sector interdependencies have been completed."*

  NIAC concluded that cooperation and collaboration are our best defence against risks resulting from cross-sector interdependencies. Critical infrastructures are inextricably linked and they also advised that the infrastructures' human counterparts should likewise be linked (McGuinn, 2004).
- In 2008, O'Rourke and EERI published the "Contributions of Earthquake Engineering to Protecting Communities and Critical Infrastructures from Multihazards". The purpose of this document, as stated in the report is: *"...to articulate, with examples, the ways earthquake engineering has enhanced public safety and improved the protection of U.S. communities from hazards beyond earthquakes."* The development of probabilistic seismic hazard analysis (PSHA) is a good example of innovation stimulated by earthquake engineering. Another example in the report is the rapid procedures for post-earthquake building inspection that were applied in 9/11, which helped in the restoration of the affected area of New York City. The document provides a series of contributions in

the US that have helped increasing the mitigation and reduction of risk due to earthquakes, and how they have translated these technologies to solve for the risk that other hazards have imposed to the network of critical infrastructure systems of the US. This document, however, does not provide a methodology to integrate several lifeline systems that are under stressed by a disaster event.

The critical infrastructures are, in a technical/operational context, very different from each other. Their internal "time constants" vary from fractions of a second to several hours. So, formulating a modelling and simulation framework of this complex system requires not only a finer-grained understanding but also an overarching system conceptualization. It has to be recognized that decision coordination occurs in different domains of the complex overarching system of systems, such as within and across the infrastructures and in relation to cascading impacts across regional and national boundaries. It also occurs at different time scales, and in different operational modes (for example, manual or automatic) or during simulation exercises for awareness training of the first responders, or for generating and simulating scenarios for planning or during an escalating major disaster.

The Joint Infrastructure Interdependencies Research Program (JIIRP)

JIIRP was part of an effort by the Government of Canada, through the Natural Sciences and Engineering Research Council (NSERC) and former Public Safety and Emergency Preparedness Canada (PSEPC) now Public Safety Canada to fund research to develop innovative ways to mitigate large disaster situations. Six universities across Canada were involved. The University of British Columbia (UBC) studied decision making for critical linkage in infrastructure networks. The stated objectives of the JIIRP initiative were to develop knowledge, tools and recommendations to support coordinated decision making among interdependent critical infrastructures. The UBC-JIIRP project was successfully able to assemble a multidisciplinary team of over 24 researchers. The remainder of this paper describes the highlights of this program and elucidates the novel features incorporated throughout the course of this project. Additional information about this project is available at http://www.i2sim.ca

The UBC-JIIRP project proceeded on two parallel interlinked investigations. First, an actual local area of study comprising several infrastructures, for example, energy, water, transportation and health services, etc. was modelled. The various vulnerabilities and interdependencies, during emergencies, were identified after discussions with the respective infrastructure operators. Second, in parallel, the UBC-JIIRP team investigated possible metamodels of mutual interdependencies and appropriate simulation methodologies. The teams kept in focus the necessity of ensuring that the modelling/simulation tools should be able to operate seamlessly from the pre-emergency to the recovery phases. The work plan for the entire project was, therefore, divided into four layered sub-investigations, each with an associated set of tasks.

- Layer 1. Conceptual Framework for Modelling of Critical Infrastructure Interdependencies
- Layer 2. Investigation of Specific Infrastructures
- Layer 3. Development of Scientific and Engineering Solutions
- Layer 4. Development of Human Resources and Organizational Solutions

Emergency management is a multidisciplinary field and faces many technical challenges, such as lack of a high-level conceptual framework that defines a common context for utilizing decision support methodology and tools, lack of a common technical terminology or vocabulary and lack of semantic coherence. It is, therefore, essential to adopt and develop a common ontological approach, when modelling and simulating complex and diverse systems.

In addition to the question of a common ontology for the UBC-JIIRP project, there was the need to select approaches for modelling and simulation. The well-known Universal Modelling Language (UML) was one option. The UBC-JIIRP team, however, was of the opinion that for emergency operation of a limited set of very diverse critical infrastructures, the modelling should focus on the "flow" of essential "resources" to user entities, which convert or transform the input resources into other "goods" or "services" or "resources". The flow or transport of resources would be over a variety of "channels". The UBC-JIIRP team decided to pursue two parallel modelling and simulation approaches: one was utilizing the UML and intelligent agents methodologies, and the other using a system of resources, channels and cells, etc.

A comprehensive modelling and simulation framework was defined where the main system objective is human survival during the disaster and accelerated business recovery. Human survival is characterized in terms of the system being able to deliver, as fast as possible, the first two levels and part of the third level of Maslow's hierarchy of needs: (1) physiological, (2) safety, and (3) belonging. These needs are characterized in terms of survival tokens that need to be delivered from the places where they are produced or stored (sources) to where they are used by the victims (loads).

The following survival tokens were identified: (1) potable water; (2) food; (3) body shelter (breathable air, clothing, temperature, housing); (4) personal communication (whereabouts of loved ones); (5) individual preparedness (education); (6) sanitation (waste disposal, washing); (7) medical care (medicines, physicians, nurses); (8) panic control (hope, political and religious leadership, psychologists, media); (9) civil order (fire fighters, police, army).

A transportation networks paradigm was formulated whereby the vital survival tokens are delivered from source to load (victims). For example, electric power is delivered from source to load through electrical wires; water and some kinds of fuel are delivered from source to user through pipes; other goods are delivered through roads by trucks, through railways by trains, or through airports by planes. If there were no interdependencies among infrastructures, each individual delivery system, for example the power grid, could be represented by a mathematical matrix formulation relating generated goods (electric power, for example, at a hydro station) with goods received at the load (also electric power to drive, for example, a motor). The matrix relating generated goods with received goods is the **Transportation Matrix**. Transportation systems can carry the goods through very long distances (e.g., from hydro dams) or through short distances (e.g., diesel generators). Similar constructs can be formulated for the other infrastructures, for example, water, fuel and roads. If one were to put all individual infrastructures' matrices into a common container, this larger matrix would contain the blocks representing each separate infrastructure. In mathematical terms, in this idealized case the global system's transportation matrix would be block diagonal. In reality, however, the various infrastructures are not independent of each other; for example, electricity is needed to actuate a water pump and fuel is needed to generate electricity in a thermal plant or to operate a diesel generator.

The interdependencies among infrastructures appear outside the diagonal blocks representing the individual infrastructures. The interdependency elements in the global infrastructures matrix can be a physical control function (e.g., electricity driving a water pump) or can be a human control function, i.e., a human decision-making process (e.g., decision to send a crew to repair a bridge). Regardless of their nature, they can be represented as control functions (links) relating a quantity in one infrastructure with a quantity in another infrastructure.

For system planning purposes, the transportation matrix formulation can be used to perform sensitivity analysis of the delivered tokens with respect to the parameters defining the interdependency links. Strong and weak links can be identified. The transportation matrix can also be directly converted into a state matrix formulation where the dynamic tendencies of the system with respect to changes in the interdependency links can be identified. Other mathematical tests can be applied to these matrix formulations to quantify the strength and dynamic behaviour of the combined system of infrastructures.

During the emergency management period (immediately before or after the disaster occurs), the transportation matrix concept allows for rapid dynamic updating of the various sources, loads, and transportation links according to the changing field conditions. Transmission system delays and losses in delivering the survival tokens can be directly represented in the transmission matrix. This allows for coordination of the sequencing of actions (timing) of the rescue and system recovery efforts by the various infrastructures to achieve an optimum delivery of the survival tokens without "stepping on each other's toes". To build the system's transportation matrix we needed: (a) the infrastructures' internal blocks, which are known to each infrastructure manager (e.g., the power transmission grid), and (b) the interdependencies among infrastructures (off-diagonal elements) which need to be identified and shared by the infrastructure partners.

It is envisioned that during the emergency management period, infrastructure managers will come together in a disaster-room scenario (virtual or physical room) to coordinate the decisions that affect infrastructure interdependencies. Each manager should be able to visualize his/her own system (which he/she is able to understand in detail) and he/she should be able to have a simplified but meaningful visualization (at a level he/she can understand) of the other infrastructures at the interdependency points. An important tool for this visualization is the availability of Geographical Information Systems (GIS) with feature extraction and simplification. The other tool that should be available in the disaster room is a real-time version of the infrastructures interdependencies simulator (I2Sim). The simulator will use information continuously updated from the developments in the field to resolve the interdependencies. It will also allow the disaster-room managers to play "what-if" scenarios in faster-than-real time, so that possible actions can be tested out in the simulator before applying them to the physical system.

The design of cooperative, coordinated, stronger, and more resilient systems is a very crucial objective. A strategy to improve survivability has been defined. We call this strategy

"Islanding for Survival" to draw a parallel with the well-known technique to avoid cascading effects during power system blackouts. The main idea behind this concept is that vital survival needs should be delivered to the victims as quickly as possible after the disaster occurs. Immediate response has a very powerful psychological effect in preventing panic, maintaining civil order, and facilitating strategies that involve victims' reallocation. Under the islanding concept, the geographical area affected by the disaster is subdivided into islands. Each island must have enough internal resources to locally supply (very quickly) the survival tokens for a limited period of time. After this time period, survival will depend on help from external resources. Each island may have a different survival time, and the external rescue operations and infrastructure recovery operations have to be coordinated accordingly.

Ontology for an Infrastructure Interdependency Simulator (I2Sim)

Due to their different intrinsic natures and their separate evolution, different infrastructures, for example, the power grid or hospitals may use very different descriptions to model their operation. A fundamental first step in the design of a modelling/simulation tool, named I2Sim by the UBC-JIIRP team, was to define an ontological representation that would allow the large diversity of entities that make up the system of infrastructures to be characterized using the same concepts (Marti, et al, 2008a and 2008b). Another crucial reason to develop this ontology was the large geospatial and temporal extension of the physical systems that need to be represented during major disasters. For example, in order to know how water can be delivered from the water pumping station to the hospital after damage has occurred in the pumping station, it is not necessary to model all the pieces of pipes that connect the station to the hospital. It is sufficient to know how much water can be carried from the pumping station to the hospital and how much spillage there will be. I2Sim's ontology defines a study scenario space where the following entities exist (Fig. 1):

a) Cells (Production Units): A hospital cell requires inputs: electricity, water, doctors, medicine, etc., and produces outputs: patients discharged.
b) Channels (Transportation Units): The electricity is carried to the hospital by wires, the water is carried by pipes, and doctors are carried by the transit system.
c) Tokens (Exchange Units): Quantities that are the inputs and the outputs of the cells, e.g., water is a token, a doctor is a token, a phone call is a token.
d) Controls (Distributor & Aggregator Units): interface the physical layer with the decision making layer, e.g., if electricity supply is limited, how much should go to the hospital and how much to the water-pumping station (distributor). The total electricity supplied to the hospital is the sum (aggregator) of the electricity that comes from the external source (substation) and from the reserve diesel generator. Distributors provide the links (dotted lines in the diagram) between the physical distribution of output resources and the human layer of decision makers.
e) Scenarios: describe the simulation cases. A scenario manages a simulation case, including the disasters, cells and channels in the study, events to the simulation (including real events and "what if" events) and simulator states for branching and resuming.
f) Events: trigger the change of cell-channel states. Events are inserted into a thread of a scenario both at real time or pre-scripted. Events inserted at real time trigger a spawning of a new simulation thread; events inserted at a past time (with regard to the simulation)

ask the simulation to rewind and spawn threads; events inserted at a future time are queued for the simulator to take future actions.

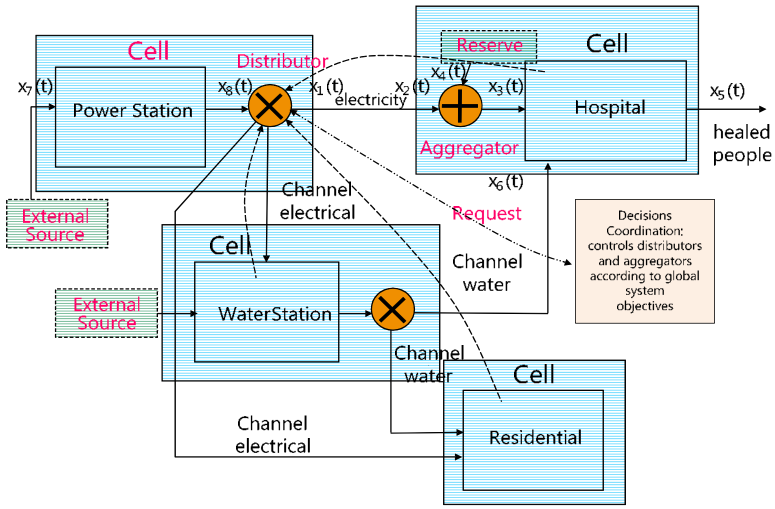

Figure 1: Cells, channels, distributors, and aggregators

Cells represent functional units, for example a hospital. Functional units are modeled in terms of a production model that relates the inputs needed for the unit to produce its outputs. A generic cell model is shown in Fig. 2. In general the relationship between outputs and inputs of the cell will correspond to a multidimensional nonlinear function.

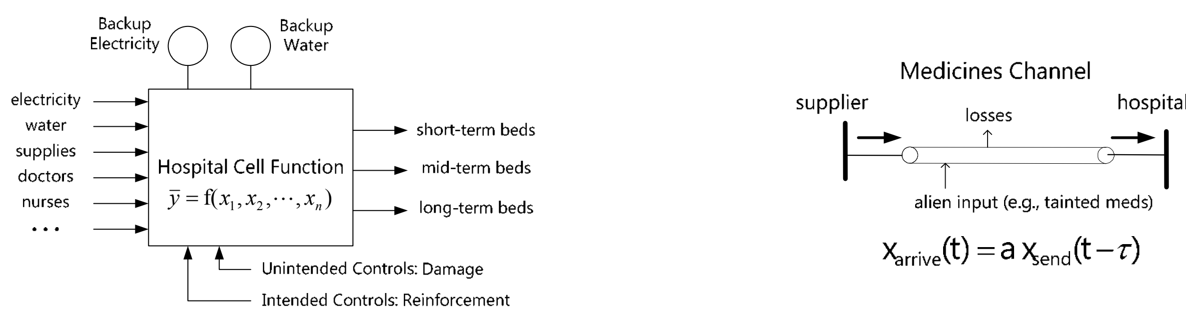

Figure 2: Cell and channel models

A key aspect of I2Sim modeling is that the internal details needed to relate the inputs and outputs of cells and channels are determined by the owner of the infrastructure. In the case for example of the power grid, the relationship between the input sources of energy (e.g., the high voltage generation and transmission system) and the feeder lines to the loads is determined by very sophisticated software run by the power system control centre, which takes into account a number of technical and operational constraints. From the point of view of I2Sim, all that is needed is for the power utility to provide a table (“Human Readable Table”, HRT) relating availability of output power for a number of possible operating states of the power system.

The Operational Modes take into account the degree of damage that the cell unit may have suffered as a result of the disaster event. HRTs relate multiple inputs to multiple outputs forming multidimensional hyper-surfaces. The simple case of Figure 3 corresponds to a cell with two inputs and one output. Realistic cells, for example, a hospital cell, may have representations with say ten inputs and three outputs. I2Sim derives the linearized "Thévenin Equivalent" (TE) representations from these multidimensional surfaces to represent the state of the cells at the current operating point along the time line of evolving events.

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

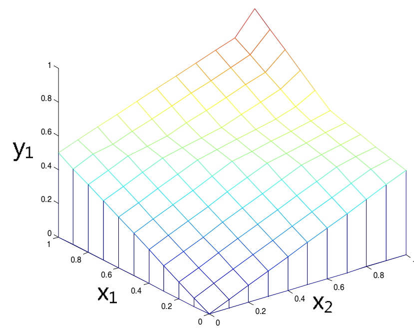

Figure 3: Left: simple HRT table with two inputs x1, x2, and one output y1. Right: multidimensional representation

Channels represent the means by which tokens (e.g., medicines) are transported from a source cell (e.g., medical warehouse) to a consumption cell (e.g., the hospital). Channels are characterized by a loss coefficient and by a time delay. The loss coefficient accounts for leakage, e.g., in the water pipes, while the time delay accounts for the transportation time, e.g., of the truck delivering the medicines. In a similar way to the cell descriptions, channels are represented by HRT description tables but with the added parameter of a time delay.

Cells and channels are discrete abstractions of the physical world. These abstractions and their input output descriptions allow I2Sim to set up a mathematical description of the interrelationships among interdependent systems. At each operating point along the time line of the developing event, this linearized description, corresponds to a system of discrete time equations (Rinaldi, et al., 2001) and can be represented with a system "transportation" matrix (Fig. 4) relating the input quantities that "arrive" at the cells with the "source" quantities that are produced at the output of other cells.

Considering, for example, row w5 in Fig. 4, we see that the water that arrives in cell 5 (input to cell 5), xw5, is "composed" of water that comes from the output at cells yw13, yw14, and yw15 (through coefficients x), but also "of" electric power that comes from the output of cell yp10 (through coefficient y). If there were no interdependences among systems all the water would come from water sources (coefficients x) but since water needs to be pumped up, and pumps require electricity, coefficient y appears in the row of the matrix. This mathematical formulation also allows us to perform sensitivity analysis to determine the strongest interdependencies and the most vulnerable points. I2Sim's core solution is based on network partitioning techniques (Anderson, 2008) implemented on a PC-cluster environment. Systems of thousands of variables are solved in seconds of computer time allowing for instant feedback on the evolution of the system dynamics (Marti, et al., 2008).

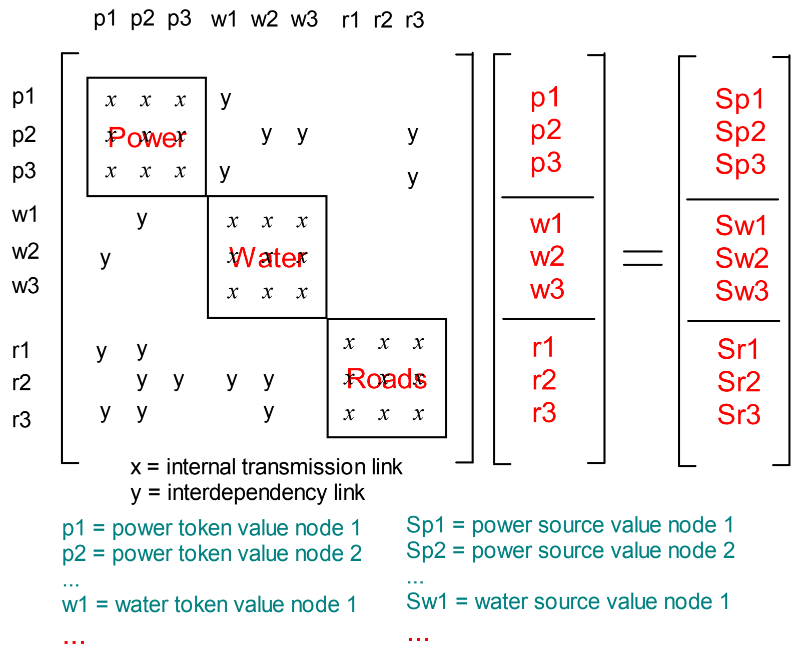

Figure 4: System transportation matrix showing interdependencies among infrastructures

Interdependency among Critical Infrastructures

Interdependencies of Critical Infrastructures in a "study space", in general, should cover the following steps:

1. Characterize the "study space": a venue, a region, a urban sector, a city, a province
2. Define to which extend the risk will be measured
3. Select the critical lifelines
4. Acquire general information
5. Disassembled the "study space" into physical and human layers
6. Define the hazard or events (scenarios)
7. Obtain GIS maps to represent the physical and human layers
8. Acquire detailed information: Hazard and Lifelines (vulnerabilities)
9. Perform damage assessments: compute the risk and interdependencies for the set of lifelines
10. Discuss the results with the operators of the system (high and low level)
11. Define cells, channels and tokens
12. Define Human Readable Tables HRTs for the "study space", and operating modes
13. Define the necessary databases
14. Prepare I2SIM
15. Evaluate evident and hidden interdependencies
16. Define strategies to mitigate risk
17. Perform different solutions in the simulator
18. Define action plans for the "study space"

In a city, there are many infrastructure networks which interact and rely on each other to deliver utilities and services to the community. JIIRP-UBC aims to model the real time effects of a disaster and identify the interdependencies among critical infrastructure networks. There are six principal components of the projects architecture: "study space" physical and human layers, the hazard (event or scenario), the damage assessment (I2DAM), database (I2DB), the infrastructure interdependencies simulator (I2Sim) and visualization, Figure 5.

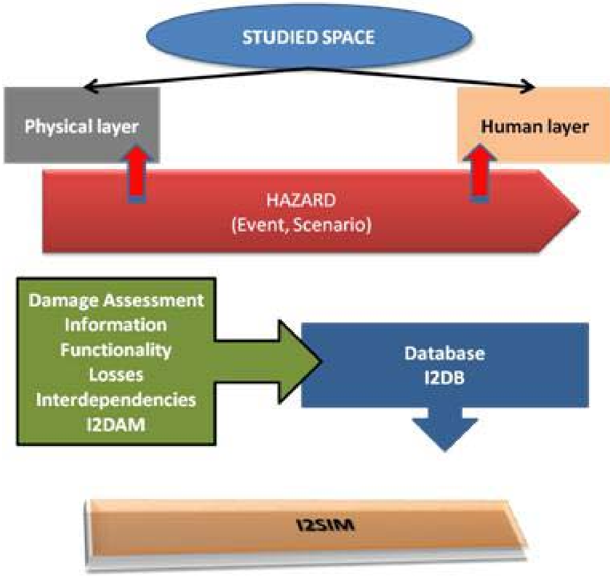

Figure 5. Components of the architecture

The results of the simulation can be viewed both statically and dynamically. Static visualization provides "snapshots" of the state of the whole study area at certain moments in time, by mapping the data using a GIS platform. Dynamic visualization allows the monitoring of individual buildings or components in the study area.

The functionality or output of these components is plotted with respect to time. Known interdependencies between the infrastructure networks are also included in the human layers. The first-responder layer models the flow of first responders and investigates psychological effects such as post-traumatic stress disorder.

Behaviour and psychological factors affecting disaster victims are evaluated in terms of five factors: perceived vulnerability, panic, identity and family, grieving and social and antisocial tendencies. Perceived vulnerability evaluates the "preparedness" of a community for disasters. Communities that are more prepared will respond better to stressful situations and their citizens will be less likely to panic. Identity and family takes into account human behaviour regarding loved ones in disaster events. Social behaviours include community outreach and people helping each other, while antisocial behaviour takes into account common problems like looting and civil unrest. Decision makers play significant roles in disaster events and are taken into account in the human layers through the use of software agents. These agents perform two functions. The first is to capture and test emergency management policies already in place in the study area. The second is to provide support to emergency personnel. This support includes diagnosis of root causes of system failures and the evaluation of the effects of decisions through the I2Sim simulator.

Infrastructure interdependencies classifications

Infrastructures are socio-technical systems; they have a physical or material component and a human component. Interactions between humans and objects are a necessary element of such systems. Rinaldi (2004) describes the different interdependencies between infrastructure networks according to the elements their state depends upon: a) Physical interdependency: the state of one infrastructure depends upon the material output from another; b) Cyber interdependency: the state of one infrastructure depends upon information transmitted through the information infrastructure; c) Geographical interdependency: several infrastructures' states are modified by a local event; and d) Logical interdependency: a policy, legal or any other sort of regulatory regime that gives rise to a logical dependency.

A classification from a different perspective was proposed by Dudenhoffer et al. in 2006:

a) Physical (the relationship is defined by supply/consumption/production of an asset);
b) Informational (infrastructures rely upon information transmitted from one to another);
c) Geospatial (infrastructures are located within the same defined space); and
d) Policy (a binding of infrastructure components due to policy or high level decisions).

A summary of the different methods used to classify infrastructure interdependencies according to the criteria used to define the relationship between infrastructure networks is presented below (Table 1).

Table 1 - Interdependencies Taxonomy

Relationship Defining Criteria	**Dependency Instances**
Nature of the involved entities	Human – Object (Physical network) Object – Object Human – Human
Direction of the relationship	Unidirectional Bidirectional
Nature of the relationship (what is shared between the involved entities)	- Information (a flow of information is the link between entities) - Physical (an element produced by one is consumed by the other) - Geographical (both entities share the same location) - Organizational/human/societal (established policies and procedures within organizations)
State of the relationship	Static (no variation before, during, or after a disruptive event) Dynamic (behaves differently according to circumstances)
Type of failure if disrupted	Cascading failure in associated entities Escalating failure Common origin

Modeling infrastructure interdependencies

There are four objects of study when dealing with CI interdependencies (Fig. 6):

- The infrastructure network and its internal structure and state
- The relationship between one infrastructure and another (the interdependency)
- An internal event that triggers an abnormal state in one infrastructure network

- An external event that triggers an abnormal state in one or more infrastructure networks

Given these four elements, the following are some problem instances that can be analyzed:

1. Given infrastructure A's internal structure, what external events would affect it, and how?
2. Given an internal or external event that triggers a failure in infrastructure A, and given a set of rules that define the relationship between infrastructures A and B, how does this affect infrastructure B?
3. Given a dependency of infrastructure B on infrastructure A, what event affecting A, and what state of A, could cause a given disturbed state of infrastructure B?
4. Given a dependency of infrastructure B on infrastructure A, what is the minimum performance of A that would keep B functioning?
5. Given an internal or external event, and given abnormal states of infrastructures A and B, what are the set of rules that define the relationship (the interdependency)?
6. Given an event, and given the interdependency between infrastructures A and B, what decision in infrastructure A maximizes the functionality of infrastructure B.

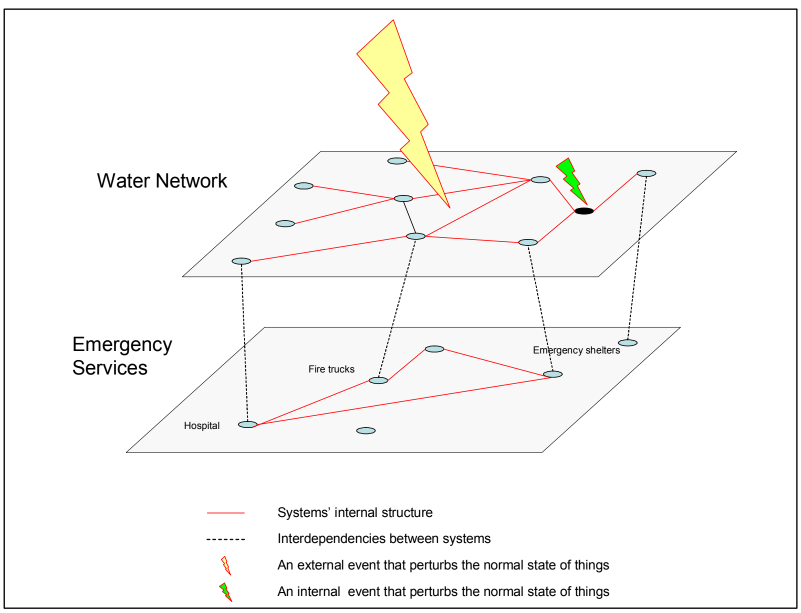

Figure 6 - The Four Objects of Study

According to these 6 instances of the problem, and the types of interdependencies to be analyzed, a variety of tools and modeling approaches (ranging from simulation models, analysis of risks, decision support systems, etc.) have been developed in the past few years with the purpose of studying the relationships between infrastructure systems.

In general, however, there are two approaches that can be taken when studying the interdependencies between infrastructure networks (Fig. 7):

A. A top down or integrated approach in which various infrastructure networks are modeled in the same system. Although this second approach would seem naturally a better way of tackling the problem, designing a system that contains each infrastructures' network topology and the definition of the relationship rules between the different layers is very complicated. Using this approach necessarily implies a higher level of abstraction in the modeling process.

B. The bottom-up or coupled approach, in which the internal structure of an individual infrastructure system is studied, a failure is then simulated within it, and then the results of that simulation are extended to other individual infrastructure systems to study cascading effects. An example of this would be a simulation of a substation breaking down resulting in a certain area with no power service for 6 hours. This information is passed onto a water system that estimates the areas where no water will be delivered, and to a telecommunications system that calculates the effect on the telephone/cell phone network. These results are then passed onto an emergency operator (e.g., a fire chief) that evaluates the situation and decides which actions she would to take.

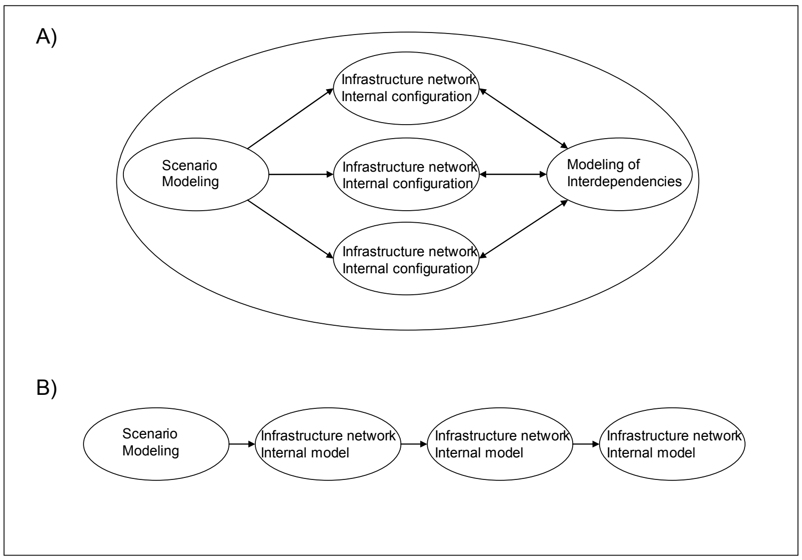

Figure 7 – Integrated (A) vs. Coupled (B) modeling approaches

A coupled or bottom-up approach is generally more viable in a short/medium term project. The data sharing can be minimized in this approach. In an integrated model, a complete data sharing between infrastructures is necessary. This is a major obstacle because most of this information is sensitive (i.e., location of critical infrastructure assets, types of technologies, etc.) and many of the owners of the data are usually competitors. In an integrated model, a common framework--a cross organizational and multi-disciplinary ontology, needs to be defined. A coupled model can be very precise, with the internal structure of each one of the systems defined at the finest available granularity. On the other hand, it would be practically impossible to construct an integrated model with the finest granularity available for each of the infrastructure networks. Some of the advantages and disadvantages of each of the approaches are presented in Table 2.

The simulator I2Sim is a powerful tool, that embodies a holistic approach, and that will allow the owner of the "study space" to investigate possible outcomes, vulnerabilities, risks, interdependencies among Critical Infrastructure, so that impacts can be minimized. This can be achieved in future developments of i2Sim. I2Sim capabilities range from individual infrastructure systems to region assessments. It is possible to observe the performance of individual systems. Stakeholders can predict the result of having vulnerabilities in the system, and how to cope with them once the hazard has developed. With this tool they can enhance the resiliency of the system, and can also share valuable information with other stakeholders.

On the data management side, the UBC-JIIRP project facilitates a centralized data management. We also envisioned the need to manage the data in a distributed way and deploy a data integration system to coordinate the data sources. A distributed system is usually more robust than a centralized system. Consider that in UBC-JIIRP we study large scale natural disasters such as earthquakes which may also destroys information infrastructure, we need to make sure the disaster management system keeps working in a condition that some of the data sources suddenly become unavailable. A distributed data integration system such as the peer data management system (PDMS) is more preferable in this sense.

Table 2. Advantages/Disadvantages of Integrated and Coupled Modeling Approaches

Coupled	**Integrated**
Utilizes existing models developed for individual infrastructure networks	A completely new development needs to be undertaken
Requires less data sharing between organizations	Access to critical data from multiple infrastructures is essential
A common framework is desirable but not essential	A common interdisciplinary/cross-organizational ontology needs to be developed
A very detailed model can be achieved within each infrastructure system	Integrated models are necessarily of higher level of abstraction (it is impossible to model everything at the maximum level of detail)
Interdependencies are not parameterized in the system, they can be discovered while using the system. This gives an added flexibility to this approach.	Interdependencies are parameterized within the system. Their discovery process occurs in the conceptualization of the system, not in its use.
The consequences of the interdependencies are obtained; interdependencies are not fully formalized.	Interdependencies between infrastructures are formalized.
A common data sharing model needs to be developed for information flow between systems	Data model is inherent to the system

Common language is essential to understand the different techniques and methodologies used by interdisciplinary teams. Exchange of information and units definition are key elements for the overall assessment of the system. The wellness of the society will be preserved when the consequences of a certain event are accurately predicted and defined. Analyzing complex systems such as those formed by infrastructure networks and decision makers requires a multidisciplinary holistic approach. The field of research in infrastructure interdependencies is fairly new, and lies in the intersection of areas of knowledge such as emergency management, geography, simulation modeling, planning, and safety engineering.

Closing Remarks

Four major conclusions can be drawn from the UBC-JIIRP project:

As urban areas develop and expand, new interdependencies emerge and become complex. The development of new urban sectors has posed a major task for evaluating Risk. New and upgraded construction technologies and new infrastructure systems are being designed and built. Therefore new developed interdependencies among CIs are being generated, these interdependencies are complex and hard to evaluate.

- Privacy of information and lack of tools to assess the vulnerabilities and risk will impose challenges to risk assessment methodologies. Organizations are very reluctant to expose the internal details of their operation for fear of losing competitive advantages or exposing vulnerabilities. There is a lack of tools to clearly identify and quantify how risks and vulnerabilities affect other infrastructures. In this project it was possible to use the information available, to properly assess the risk of each individual CI, and; to be able to show and rank the interdependencies among them; and still be able to keep the information private for each specific stakeholder.
- Information will challenge agencies, they will need to work together in interdisciplinary teams, and the selection of information would be critical for decision making and for planning strategies. Not all information is important. All the planning for the Interdependency of CIs cannot take place in isolation, it requires multi agency planning so that objectives, assessments and outcomes will be properly matched. Exchange of information might become relevant in the future; nowadays internet shows a lot of information from different systems. The system owners can be ahead of their competitors in terms of assessing their vulnerabilities, and reduce their risks. Exposing the weaknesses may in fact lead to more resilient systems. Being the weakest link in the chain, might translate in difficult times for business purposes, and unplanned reaction during emergency events might cause more damage or economic loss to the system than revealing information to other competitors.
- The i2Sim simulator, that embodies the holistic approach described here, will help individual or regional stakeholders enhance and make more resilient CI Networks**.**

Our infrastructures are not monoliths. They are aggregates of many parts, with limited local autonomy. Some are nested, with layers of hierarchy and multiple levels of intentional redundancies, and their security, commercial and proprietary concerns constrain these enterprises from freely sharing their operational strategies with other infrastructure owners. Inherent linkages and interdependencies, often unintended and unplanned do nonetheless exist. Cascading failures involving multiple infrastructures have occurred. Major catastrophic events, such as power blackouts, earthquakes, storms and malicious attacks further underscore the complexities of this critical interconnected and interdependent system of systems. Predictive and preventive technologies and coordinated and mutually agreed upon decision protocols are still in their infancy. Concerted cooperative R & D effort is needed, particularly for coping with extreme emergencies.

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