Survival from Disaster: Interdependencies Management in Critical Infrastructure Networks

by

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Abstract

Today's critical infrastructure networks are becoming increasingly interdependent. The complexity of these interdependencies has created a new dimension of vulnerability, making the whole system very fragile under unexpected events.

To make the whole system more resilient during disasters, the Joint Infrastructure Interdependencies Research Program (JIIRP), aimed at developing methods for reducing its vulnerabilities. As part of the research work in JIIRP, this thesis mainly consists of three sections:

- (I) Interdependencies Control Strategy (ICS): Since to prevent all vulnerabilities would be intractable, an interdependencies control strategy, which can help to maintain the survival of the critical services is proposed in Chapter 2. A generalized adjacency matrix (GAM) is proposed to represent the physical interdependencies among infrastructure networks. By computation of GAM, decision making for ICS can be made more effective. Moreover, measures for improving survivability of the system are proposed. ICS application to a case study at the UBC campus is detailed in Chapter 3, its effectiveness during the response stage and the recovery stage of the emergency management cycle are demonstrated.

- (II) Identification of Cascading Pathways for Mitigating Snow-Caused Power Outages : Since most of the present de-icing and anti-icing methods are not fully developed for industrial applications, building a power network that can tolerate any snow storm would be infeasible. In Chapter 4, based on investigation of Vancouver's power outage in November 2006, a dependency network has been built to represent how the cascading pathways unfolded during this disaster. The effects of a changed climate, the causalities and their consequences are illustrated by this model. Through analyses of the dependency network, we propose a systematic strategy to mitigate the impacts of a snow storm to power systems.

- (III) Contributions to I2Sim: I2Sim is a simulator which was developed to simulate disasters and to develop strategies for dealing with emergencies (Appendix A). The author's contributions to I2Sim are: (a) the modelling and implementation of methods to represent complex cells with multi-input and multi-output (Appendix B); (b)integration of the cluster demon into one single machine; (c) development of a library of functions on GAM operations(Appendix C).

Table of Contents

List of Tables

List of Figures

Acronyms

AIMS Agent-Based Infrastructure Modelling & Simulation

APS Artificial Precipitation Stimulation

CC Climate Change

CIMS Critical Infrastructure Modelling System

CIP Critical Infrastructure Protection

DEW Distributed Engineering Workstation

EMTDC Transients Simulation Software by Manitoba HVDC Research Centre

EMTP Electromagnetic Transients Program

EMIP Energy, Matter, Information, Policy.

EWS Early Warning System

GAM Generalized Adjacency Matrix

GUI Graphical User Interface

HRT Human Readable Table

ICS Interdependencies Control Strategy

IEISS Interdependent Energy Infrastructure Simulation System

I2Sim Infrastructures Interdependencies Simulator

I2DB Infrastructures Interdependencies DataBase

IPCC International Panel of Climate Change

JIIRP Joint Infrastructure Interdependencies Research Project

LSE least square error

MATE Multi Area Thevenin Equivalent

MCP Manageable Cascading Pathway

MDG multi-arc di-rected graphs

MIMO multi-input and multi-output

MUNICIPAL Multi-Network Interdependent Critical Infrastructure Program for Analysis of Lifelines

NCIs National Critical Infrastructures

NERC North American Electric Reliability Council

NSRAM Network Security Risk Assessment Model

OVNI Object Virtual Network Integrator

PSC Public Safety Canada

SAM semi-certain Adjacency Matrix

SCC Strongly Correlated/Coupled Cells/Components

SII Survivability Index of Island

UMCP UnManageable Cascading Pathway

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Co-authorship Statement

Dr. Marti's contributions to the paper in Chapter 2, the paper in Chapter 3 and the paper in Chapter 4 are identification and design of research programs, and manuscript preparations.

Dr. Srivastava's contributions to the paper in Chapter 2, the paper in Chapter 3, and the paper in Chapter 4 are manuscript preparations.

Mandana Sotoodeh's contribution to the paper in Chapter 2 is manuscript preparation.

Kafui Monu's contribution to the paper in Chapter 2 is manuscript preparation.

Chapter 1

Introduction

1.1 Background

In modern society, our living quality is determined by the reliability of the national critical infrastructure networks (**NCIs**), which include electrical networks, transportation networks, communications networks, water (oil and gas) networks, banking and finance service networks, food distribution networks, health and emergency services networks etc. [1][2]. Since none of them can be independent from the others, as a whole, this multi-layer network can be seen as a "system of systems". Since the multiple layers of this system of systems are interweaved with each other today, it is very robust to most disturbances, but affected by some specific factors, it can be very fragile [3][4]. For instance, Table I lists factors that can make this multi-layer system collapse [5][6].

Table I: Catastrophic Factors on Infrastructure Networks

Factor	Content
Natural disasters	Earthquake, floods, landslides, tsunamis, wild-fires, volcanic activities etc. [7].
Adverse weather	Extreme winds, snow, sleet, ice storm etc.[8][9].
Technical failures	Design faults etc.
Managerial factor	Inadequate maintenance etc.[10].
Investment factor	Unskilled workers, aging infrastructure, aging workforce, excessively prolonged service etc.[10].
Human factors	Mis-operation, sabotage, terrorism, and war etc.

Also in a background of changed climate , scientists believe in that factors like extreme adverse weather conditions have a high probability to be more frequent [11-13]. This opinion can also be justified by the data [14] in Fig.1.1.

To protect our critical infrastructure networks against various disastrous factors, especially to mitigate or prevent cascading events that may lead to a system collapse, a better understanding on the behavior of each component in the network, the internal interaction mechanisms among them in different

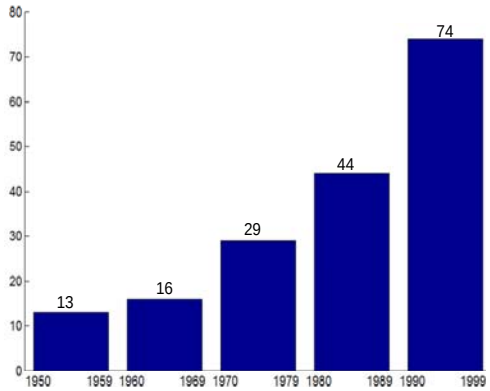

Figure 1.1: The number weather related natural disasters around the world at each decade [1950-1999] is roughly ruled by a Fibonacci sequence.

layers of the critical infrastructure networks are required. Since related historical data is rare and usually incomplete, and the cost of real-world physical experiments is extremely high, analysis by network modelling and computer simulation will be more practical and feasible.

1.2 Motivation

Generally speaking, the more complex a system is, the more fragile it will be. A system with higher complexity usually has more subsystems, more uncontrollable parameters, more possible interference sources, more interdependent interfaces among the internal subsystems and with the external environment, and thus it has more unpredictable behaviors.

In this sense, for today's increasingly interconnected infrastructure networks, the probability of system failures will increase after inter-connections [8][9][15]. For instance, the scale of disturbance that two electrical networks can tolerate together is usually larger than the tolerance of each individual network. But, because of deregulation and market competition [16], shared spare capacity is usually used to its limit. Therefore by interconnection, the whole system's risk of collapse might be increased instead of decreased. In some extreme situations, when all these components in one layer of this multi-layer network are simultaneously in critical states, which is usually induced by a global adverse condition, similar to the process of chain reaction, a small local disturbance can easily develop into a large cascading failure during its propagation. This is consistent with the small world model

[17] where the interdependent interfaces can seriously impact other layers [18][19][20][21].

Research work on identifying, understanding and analyzing these interdependencies is extremely important and has significant challenges. These challenges are greatly magnified by the wide breadth and high complexity of our critical national infrastructures. Moreover, a broad range of interrelated factors and system conditions complicated this challenge. These include the technical, economic, business, social/political, legal/regulatory, public policy, health and safety, and security concerns etc.. These interdependencies can be physical, cyber, related to geographic location, or logical in nature. The interdependencies and the resultant infrastructure topologies can create subtle mechanisms that often lead to unexpected behaviors and consequences during disruptions.

Most recent studies in this area are concentrated on qualitative and local analysis [5][19][21][25], although these works articulate the inherent dangers of uncontrolled interdependencies, they do not provide a methodology for thinking about or analyzing this phenomenon. For large-scale multi-layers network, such as our NCIs, tractable methodology as well as a framework of interdependency analysis at systems level is greatly required.

1.3 Literature Review

After 9/11, mainly financially supported by the U.S.A, the E.U and Canada, many organizations, institutes and universities have focused their research directions onto critical infrastructure networks. Some of these supporting organizations include the Department of Homeland Security (DHS), Department of Energy (DOE), Department of the Air Force (DAF),Defense Advanced Research Projects Agency (DARPA) etc. Here, we give an overview on the work on infrastructure interdependency modelling, simulation and vulnerability assessment done in recent years. Their differences from our current simulator are also mentioned here.

1.3.1 Work on Infrastructure Interdependency Modelling

- **Agent-Based Infrastructure Modelling & Simulation (AIMS)** [26]: developed at the University of New Brunswick, AIMS is an agent-based system to simulate and model interdependencies and survivability of Critical Infrastructures in Canada. However, as opposed to the methodologies in our simulator, risk assessment and vulnerability analysis are not considered in this project.

- **Critical Infrastructures Modelling System (CIMS)**[27-29]: developed by Idaho National Laboratory (INL), is a modelling and simulation framework that combines geo-spatial information and a four dimensional (4D) environment (time-based) to support 'what if' analysis. In our I2Sim team, exhaustive analysis can be done by the tool using the generalized adjacency matrix developed in this thesis.

- **Interdependent Energy Infrastructure Simulation System (IEISS)** [30-31]: developed by Los Alamos National Laboratory, is an actor-based infrastructure modelling, simulation, and analysis tool designed to assist individuals in analyzing and understanding interdependent energy infrastructures. As opposed to our simulator, the human layer is not considered in IEISS.

1.3.2 Work Based on Graph theory

- **MIT Screening Methodology**[32][33]: This research proposes a methodology for the identification and prioritization of vulnerabilities in infrastructures. But this method only considers terrorism factors.

- **Distributed Engineering Workstation (DEW)** [34-35]: DEW is being used to identify and analyze interdependencies in large scale electrical power systems and fluid systems of aircraft carriers. But here the human decision layer and risk assessment are not considered.

1.3.3 Work on Vulnerability Analysis and Risk Assessment

- **CARVER** [37-39]: Designed by Infrastructure Expertise Critical Infrastructure Library, CARVER2 is a simple software program that provides a quick and easy way to prioritize potential terrorist targets. It compares and rates critical infrastructures and key assets in jurisdictions by producing a mathematical score for each potential target. But in CARVER human activity is not modelled and terrorist attacks are considered as the only disaster factors.

- **Knowledge Management and Visualization in Support of Vulnerability Assessment of Electricity Production**: This work is being done by Carnegie Mellon University to analyze vulnerabilities associated with delivery of fuel. It is designed to help ensure availability of supply and to visualize the impacts for decision support.

The project has focused on coal deliveries to power plants. But human activity is not modelled, and only the electrical infrastructure is considered.

- **Multi-Network Interdependent Critical Infrastructure Program for Analysis of Lifelines (MUNICIPAL)** [40]: Designed at Rensselaer Polytechnic Institute (RPI), is a geographic information system (GIS) user interface. It is built on a formal, mathematical representation of a set of civil infrastructure systems that explicitly incorporates the interdependencies among them. But vulnerability and risk assessments are not considered.

- **Network Security Risk Assessment Model (NSRAM) Tool for Critical Infrastructure Protection (CIP) Project** [41][42]: developed by James Madison University (JMU), it is a complex network system simulation modelling tool that emphasizes the analysis (including risk analysis) of large interconnected multi-infrastructure models. However, interdependencies among critical infrastructures are not modelled.

1.4 Research Objectives

For a system of systems, various measures can be taken to reduce the frequency of failures. But compared with the objective of preventing large cascading failures, the survival of essential critical services is a more tractable issue. As Dr. Marti et al. suggested in [22][23], a practical approach is to dynamically segment the system, according to related risk analyses of the disaster context, into several "self-sufficient islands" to prevent cascading failures.

In this thesis, all my research investigations (cell modelling and representation, interdependency modelling and analysis by graph theory, interdependencies control strategy, mitigating snow-caused blackout along cascading pathways etc.) are developed under the environment of our I2Sim team. The team's research goal is to better understand, model, analyze, and simulate critical infrastructure interdependencies in the context of various disasters [43][44], to develop effective decision-making tools, which can help policy makers and infrastructure service providers to save a maximum number of human lives, to keep a maximum time of reliable service, to minimize the down time and restoration process as well as monetary loss during natural or man made disasters.

To achieve such a goal, the research objectives in this thesis are specified as follows:

- Development of an interdependencies control strategy (ICS) based on computation of the generalized adjacency matrix (GAM) and based on our results on dynamic islanding methods; development of related algorithms for vulnerability assessment, bottleneck detection and islands identification.
- Further development of the GAM-based interdependencies control strategy, which will help the decision making activity in the four phases of the emergency management cycle, as well as to maintain the survival of the critical services and to minimize the system's loss during a disaster. An index to measure the survivability of a system is also proposed.
- Identification of the cascading pathways, as well as modelling the cascading mechanism, which can help prevent large disasters in critical infrastructure networks, particulary in electrical power networks.

1.5 Outline of the Thesis

The outline of this thesis is organized as follows:

Chapter 1 introduces the research background, motivation, related work and the objectives of this research.

Chapter 2 is on managing interdependencies among NCIs. where adjacency matrix (GAM) is generalized, based on which an interdependencies control strategy (ICS) is proposed, which can help keep the survival of the most critical services.

The application of ICS on the UBC test case is described in Chapter 3, where based on the 2006 snow-caused power outage of Vancouver, decision making processes with/without ICS are demonstrated with different scenarios.

Chapter 4 is on mitigating snow-caused blackouts along cascading pathways. Based on our investigation of the Vancouver's snow-caused power outage in November 2006, a dependency network has been built to represent the causalities among these root conditions and the related consequences. Through analysis on this causal dependency network, related countermeasures to inhibit the development of a wet-snow disaster, as well as to strengthen the vulnerabilities are described.

In Chapter 5, conclusions are given and future work is proposed.

The theoretic foundation for this study can be found in the Appendix sections. Appendix A introduces the I2Sim (Infrastructure Interdependency Simulator) simulator. Appendix B includes two sections: one is on the Human Readable Table (HRT) method and its application in I2Sim. Another section is on graph representation of modellable interdependencies among critical infrastructures. A library of functions for operations on GAM was developed in Appendix C.

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Chapter 2

Interdependencies Control Strategy

2.1 Introduction

In modern societies, the standard of living is determined by the reliability of the national critical infrastructure networks (**NCIs**), which include electrical networks, transportation networks, communications networks, water (oil and gas) networks, banking and finance service networks, food distribution networks, health and emergency services networks, etc. [1][2]. Since as a whole, none of them can be fully independent from the others, this multi-layer network can be seen as a "system of systems". By sharing larger reserve capacity, today's inter-connected infrastructure networks can make efficient use of limited resources; the availability of these resources are also guaranteed by their diversity. Therefore these interdependencies are making the infrastructure networks so robust that it can handle most local disturbances or stochastic fluctuations. On the other hand, this "system of systems" is becoming more fragile. Through cascading effects, an event which may have collapsed one single layer of the networks before, now due to the inter-connection, may cause catastrophe in all possible layers of the critical infrastructure networks. In some extreme situations, those global disturbances, such as earthquakes, adverse weather conditions, terrorist attacks etc., can trigger many events simultaneously, either making the whole system devolve into a critical state, or revealing many unexpected hidden and detrimental interdependencies. In this paper, this "robust yet fragile" duality is treated as the inherent vulnerability of our critical infrastructure networks, which will become more vulnerable due to climate change.

[1] A version of this chapter has been accepted for publication. DeTao Mao, Mandana Sotoodeh, Kafui Monu, Jose R. Marti and K. D. Srivastava (2009), Interdependencies Control: Compensation Strategies against the Inherent Vulnerability of Critical Infrastructure Networks, *IEEE Canada, the 2nd Climate Change Technologies Conference (CCTC 2009), McMaster, Hamilton, Canada, May, 2009.*

Table 2.1: Number of Weather Related Global Disasters at Each Decade (1950-1999)

Decade Interval	**Number of Event(s)**	**Fitting Value**
1950-1959	14	13
1960-1969	16	18
1970-1979	29	28
1980-1989	44	44
1990-1999	74	71
2000-2009		114 [1]

Under a changing climate, scientists believe that extreme adverse weather disasters will be more frequent [4]. This opinion can also be justified by the data [3] in Table 2.1 above. With these data, we find that, in each decade from 1950 to 1999, the number of weather related natural disasters around the world is roughly ruled by a Fibonacci sequence:

$$Z(n) = 2.29\,(\frac{\sqrt{5}-1}{2})^n + 10.3\,(\frac{\sqrt{5}-1}{2})^{-n} \tag{2.1}$$

with $n \in N$. According to formula 2.1, this ten years (2000-2009), weather related disaster will be more frequent than before.

Moreover, based on the power outage data (1984-2006) from the North American Electric Reliability Council (NERC) [5], we find that these weather related power outages are strongly correlated with all power outages. In this analysis, the annual power loss caused both by all the events together: $\{x_i\}(i \in [1, 12])$ and by weather related events separately: $\{y_i\}(i \in [1, 12])$ have been accumulated for each month. The curves are displayed in Fig.2.1. The correlation coefficient between $\{x_i\}$ and $\{y_i\}$ is:

$$R(x_i, y_i) = \frac{Cov(x_i, y_i)}{\sqrt{Cov(x_i, x_i)\,Cov(y_i, y_i)}} = 0.8732 \tag{2.2}$$

where the covariance of variable$\{x_i\}(i \in [1, 12])$ and $\{y_i\}(i \in [1, 12])$ is $cov(x_i, y_i) = E[(x_i - \mu_{x_i})(y_i - \mu_{y_i})]$. E is the mathematical expectation, $\mu_{x_i} = E(x_i)$, $\mu_{y_i} = E(y_i)$. The coefficient $R(x_i, y_i)$ indicates the degree of linear dependence between x_i and y_i. A high value of $R(x_i, y_i)$ implies

[1] Predicted value by formula 2.1

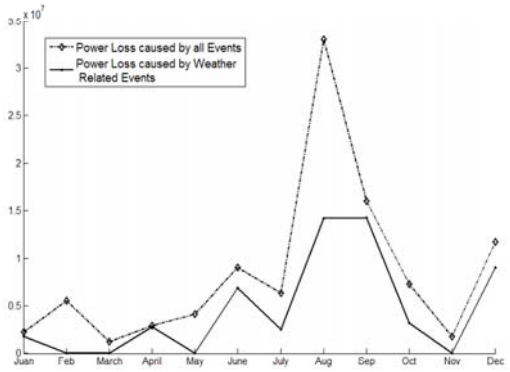

Figure 2.1: Power loss caused by all events together vs. power loss caused by weather related events (NERC data, 1984-2006).

that most of those power outage events during 1984 to 2006 were directly or indirectly affected by weather. Based on Eqn.2.1 and Eqn.2.2, we can conclude that critical infrastructure networks, especially electric networks, will be more unreliable in the future.

As the climate patterns are changing, many of the previous assumptions related to system planning, reliability standards, and anticipated responses during emergencies, may no longer be tenable. During recent severe disasters, such as the 1998's winter ice storm in eastern Canada, and hurricane Katrina, it proved impossible to either prevent the disasters or keep the system's integrity. As we have stated before, the vulnerability of NCIs is mainly caused by the complicated interdependencies among them. Therefore, during an emergency, to assure the continuation of critical services by controlling the interdependencies will be a more tractable problem.

This paper is organized as follows. In Section 2.1, the inherent vulnerability of our infrastructure networks is briefly introduced, and the impact of climate change on critical infrastructures (NCIs) is justified based on our research results. In Section 3.2, the concept of the adjacency matrix is generalized to represent multi-arc directed physical interdependencies among critical infrastructures. Related logic rules and operations are also defined. In Section 3.3, based on the generalized adjacency matrix (GAM) as well as our research results [6][7][8], an interdependencies control strategy (ICS) is proposed. By either controlling the interdependencies among NCIs, or splitting the network into several autonomic islands, it can keep essential activities survival during a disaster. Related methods on how to improve

the survivability index of the island are also described here. We conclude our study in Section 2.4.

2.2 Representation of Multi-arc Directed Physical Independencies by the Generalized Adjacency Matrix (GAM)

To control the interdependencies among critical infrastructures, it is necessary to represent the topology, dependency direction, and interacting degree(s). Physical interdependencies between two components in various infrastructure networks can be seen as directed linkages in graph theory. In this chapter, the concept of the semi-certain adjacency matrix (SAM) [21], which is usually employed to represent undirected graphs by Boolean variables $\{0, 1\}$, is generalized to represent multi-arc directed graphs with loops by using a complex matrix. For instance, in Fig.3.1, the UBC campus case in [9] can be represented by GAM with the following matrix:

$$GAM_{ubc} = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ i & 0 & 0 & 0 & 0 & 1 & 0 & i & 1 \\ 0 & i & 0 & 0 & i & 0 & i & 2i & 0 \\ 0 & 0 & i & 0 & 0 & 1 & 0 & 1 & 2i \\ 0 & 0 & 0 & i & 1 & 2 & i & 0 & 2i \\ 0 & 0 & 0 & 0 & i & 0 & 2 & 2 & 0 \end{bmatrix}$$

2.2.1 Algebraic Operation and Logic Rules for GAM

Since the logic rules for matrix operations on semi-certain adjacency matrix (SAM) cannot be adopted here directly, we have redefined the **multiply operator** $\otimes$ for GAM as follows:

$$B = A^2 = A \otimes A$$
$$b_{ij} = \sum_{k=1}^{n} a_{ik} \cap a_{kj}$$

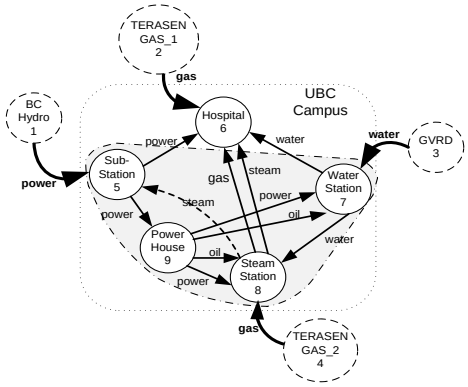

Figure 2.2: UBC campus model with strong coupled components/cells(SCCs).

where b_{ij} denotes the element of matrix B, a_{ij} or a_{jk} denotes the element of matrix A, and $\sum$ denotes algebraic "sum" in the regular sense. $\cap$ denotes the logical "and" (&), but with a generalized definition as fellows:

$$x \cap y = re(x) \cdot re(y) + i \cdot img(x) \cdot img(y) \tag{2.3}$$

here $re(x)$ represents the real part of variable x, and $img(x)$ represents the imaginary part of variable x (the same for $re(y)$ and $img(y)$). Variables x and y are complex numbers whose real parts and imaginary parts represent the incoming and outgoing degree(s), respectively. Hence, both are all non-negative integers.

2.2.2 Further Information Abstraction Based on GAM Computation

With the physical interdependencies at the same hierarchical level represented by GAM, further information of NCIs can be abstracted from related computations on GAM, such as the following properties:

External Sources

In GAM, external sources can be identified by detecting those elements owning no incoming degrees, i.e., the imaginary parts of all complex numbers representing interdependencies between this element and other elements are zeroes.

Critical Services

In GAM, critical services can be identified primarily by detecting those elements owning no outgoing degrees, i.e., the real parts of all the complex numbers representing interdependencies between this element and other elements are zeroes.

nth order Influence Domains of a Cell

Influence Domain of a cell refers to elements that will be affected by the deletion of a cell from the graph. For a graph with m elements, according to their graph distance [11], there exist a 1st order influence domain, a 2nd order influence domain, $\cdots$, and (at most) a $m-1$th order influence domain.

nth order Influence Domains of a Channel

Influence domains of a channel refers to the $n-1$th order influence domains of the downstream cells connected to this channel. The $1st$ order influence domain of a channel refers to the downstream cells connected to this channel. The 2nd order influence domain refers to the union of the $1st$ order influence domain of the downstream cells connected to this channel. Similarly, the nth order influence domain of a channel refers to the union of the $n-1$th order influence domain of the downstream cells connected to this channel.

Strongly Coupled Components as typical Critical Components

A directed graph is called strongly coupled/connected, if for every pair of vertices $\{u, v\}$, there is a path from u to v and a path from v to u [12]. The strongly connected components (SCCs) of a directed graph are its maximal strongly connected subgraphs that form a partition of the graph (Shadow area of the UBC campus cells [9] in Fig.3.1. Note that, in this figure, to demonstrate the existence of SCC, the broken line is added artificially. In the real world, the steam pipe from the Steam Station to the Substation does not exist). By introducing the concept of Strongly Coupled Components (SCCs), further topological knowledge about the multi-arc directed graph can be calculated explicitly and efficiently.

Critical Level of External Resources or internal Cells

For instance, by GAM computation, we can get that the impacting domain or influence domain of cell $BCHydro : 1$ in Fig.3.1 is $\{1, 5, 6, 7, 8, 9\}$; while

the impacting domain of cell 2 : $TerasenGAS_1$ is $\{6\}$; the impacting domain of cell 3 : $GVRD$ is $\{6, 7, 8\}$; the impacting domain of cell 4 : $TerasenGAS_1$ is $\{6, 8\}$. Therefore, roughly, we can know that the importance of critical level of each external cells.

Considering both the backup cost and the restoration cost of the utility supplied by each external cell, we can precisely evaluate the important level of each of them.

2.2.3 Advantages of Interdependency Analysis Based on GAM

In this paper, all interdependency analysis during interdependencies control is based on computations on the generalized adjacency matrix (GAM), this approach offers the following advantages:

- By finding all the pathways between any pair of elements (vertices), GAM can detect the existence of interdependencies between any pair of elements, and identify all the nth order influence domains for any element in the graph. Therefore it is an exhaustive analysis instead of a 'what if' analysis;

- The order of the influence domain implies that the impact index from one element to the others, which may give both essential information on where to buffer the cascading failures with minimum cost and the priority of these elements under a given disaster context;

- Since the vulnerability of strongly coupled components is determined by its weakest section, based on the calculated results of the SCC, critical components can be detected, and a vulnerability assessment can be obtained. Furthermore, by SCC identification, interdependencies control strategies (ICS) are more rational and effective.

2.3 Interdependencies Control Based on GAM

For critical services in the NCIs to work, many utilities need to be available simultaneously and running at full capacity. For instance, to maintain the normal operability of a hospital, the simultaneous availability of electricity, water, steam, natural gas, medicine, nurses, doctors, foods, communication, and transportation must be assured. This full capacity state is more fragile than any other state, for in this state, a number of requirements must hold simultaneously. According to the theory on "the fragility of goodness"[13],

once one of them fails, the functionality of the hospital will be greatly degraded.

The purpose for proposing the concept of interdependencies control in this paper is to try to reduce the sensitivities of critical services on unexpected fluctuations of external resources. This can be implemented by adjusting the interdependency degree by either splitting the network into several islands or just shutting down the related physical connectivity. Based on computation of GAM and a reliability assessment of the utilities, as proposed in this paper, interdependencies control strategy can help to assign limited resources to the most critical services, while avoiding the propagation of cascading failures to other infrastructure layers.

Since the interdependencies control strategy (ICS) is mainly focusing at the response stage of the four phases of emergency management, it is convenient and necessary to briefly review the conceptual framework for emergency management as follows.

2.3.1 Brief Introduction to Emergency Management

Emergency management is the discipline of dealing with and avoiding risks [14]. As Fig.3.7 illustrates, it generally includes four different stages [6]:

- **Mitigation**: Long before the disaster. This refers to the sustained actions to reduce or eliminate the long-term impacts and risks associated with disasters.
- **Preparedness**: Long and shortly before the disaster. This refers to the policies, procedures and plans for how to best manage an emergency.
- **Response**: During and shortly after the disaster. This refers to the actions taken during or directly after an emergency occurs.
- **Recovery**: Shortly and long after the disaster. This refers to the efforts taken to repair and restore communities after an emergency.

Based on Maslow's theory of human motivation [16], humans have different levels of needs constrained by their socio-economic background factors. A connection has been established between human motivation theory and emergency management due to the dynamic characteristics of emergency conditions [6](as shown in Fig.3.7). The connection can give helpful information on prioritizing the different infrastructure lifelines during emergency states.

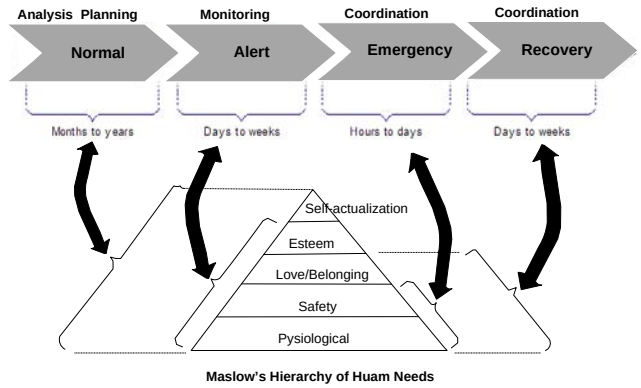

Figure 2.3: The time line for emergency management. The five levels of human needs imply the priority of these critical infrastructure networks during emergency states.

2.3.2 Survivability Index of an Island (SII)

By applying the GAM-based interdependencies control strategy (ICS), the infrastructure networks can be divided into several islands during a disaster. The survivability index of each island can be briefly expressed as how long this island can survive before its linkages are re-established. Mathematically, for an island with m internal backup resources, and n linkages connected with external resources, assume the availability duration of the backup resource i is t_i, here $t_i \leq 0$ indicates that utility i has been used up for t_i (time units). The estimated recovery time under a certain disaster context $\widetilde{D}$ for linkage j is T_j. The survivability index of island k can then be defined as:

$$SII_k^{\widetilde{D}} = \frac{min(t_i)}{max(T_j)} \quad (i \in [0, m], j \in [1, n], t_i \in R, T_j \in R^+.) \tag{2.4}$$

The objective of interdependencies control during a disaster $\widetilde{D}$ is to maintain $SII_k^{\widetilde{D}}$ not less than 1. The details on ICS will be discussed in Section 2.3.3, the related measures to improve SII during the four phases of emergency management cycle will be addressed in Section 3.3.4.

2.3.3 Description of Interdependencies Control Strategy

Among our modern infrastructure networks, the electrical network is the most fundamental and important infrastructure. Since it is in the lowest

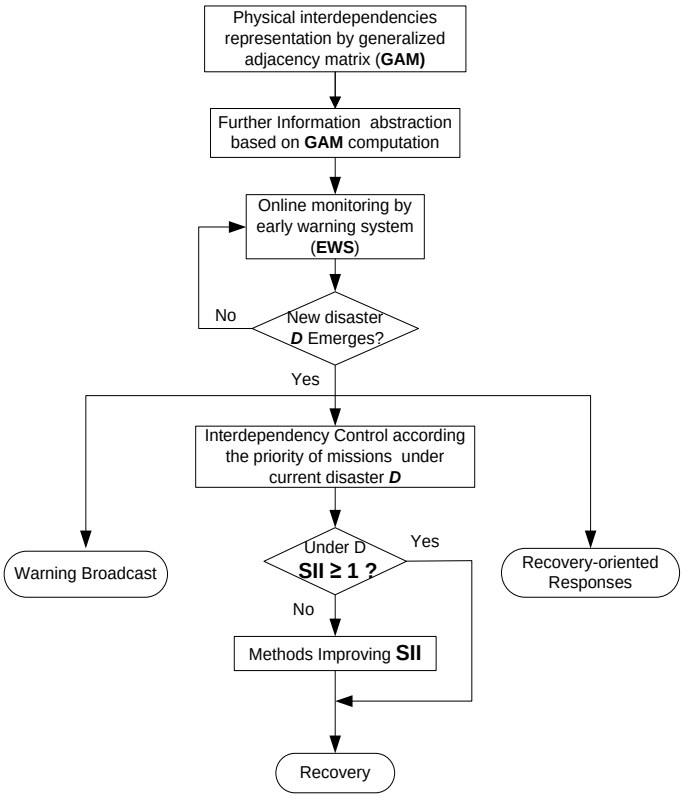

Figure 2.4: Decision making flow chart for interdependencies control strategy.

layer of our infrastructures pyramid, it supports the operation of most other infrastructures. The concept of interdependencies control is based on our previous work [6][7][8], and it also has been inspired by the controlled islanding strategy of power networks. It is well known that in power systems, controlled islanding is a special protection strategy aimed at preventing a system-wide blackout as a result of the cascading of low probability events [17]. The difference between controlled islanding strategy and ICS is that, in ICS, it is usually not necessary to split the network into several islands. In most cases, interdependencies control means shutting down several outgoing linkages, thus ensuring the availability of scarce resources, or isolating failures (e.g. epidemics), to a certain limited area.

The decision making process for the GAM-based interdependencies control strategy (see Fig.3.8) is briefly explained as fellows:

Step 1: Identify all these modelable physical interdependencies, and represent them with the generalized adjacency matrix (GAM);

Step 2: Based on the calculation of GAM, identify the supporting utilities for these critical services with higher priority and sections with vulnerabilities, such as strongly coupled components (SCCs);

Step 3: Monitor the possibility of new disasters online with an early warning system (EWS). If a disaster happens, broadcast warning, carry out the anticipated recovery-oriented actions, and finally perform ICS according to the priority of the essential missions;

Step 4: After interdependencies control, if the SII for each island is not less than 1, the recovery processes will receive the highest priority. Otherwise, there are many measures to maintain the critical service survival as long as possible. The detailed content on improving SII will be described in the next section.

2.3.4 Measures for Improving SII in Emergency Management

As the survivability index of island (SII) is mainly determined by (1) the scarce resource, or the backup lifeline with the minimum supporting duration; (2) the recovery time; hence to improve SIS of each island, various measures at the four phases of emergency management cycle are described below.

Mitigation Stage

- Infrastructure design taking the following properties in consideration: risk-decentralized redundancy, multi-functionality, adaptivity to the statistic patterns of local events, maintenance/recovery-oriented characteristics, etc.

Preparedness Stage

- Early warning capability by monitoring possible disasters online, pre-solutions based on historical experiences, etc.

Response Stage

- Redistribute the limited resources from other external resources, or redirect them from other islands whose SII is less than 1.

- Degrade the operability capacity of the island.
- Supply critical missions in the island with "synchronized rolling availability", which is very similar to a rolling blackout during power outage, but instead of losing services totally, it can keep the system operated at a low quality of service.
- Mobilized lifelines/resources, such as mobile generators, etc.
- Make use of convertible utilities, as well as multi-functional resources. As there exists overlap of these utilities' functionality, it is possible to move from one to the other during a disaster state, like switching between gas, oil, steam, or electricity for heating.

Recovery Stage

- Personnel training, prioritization of critical infrastructures under all possible scenarios; Optimization of the restoration time by dynamic programming etc.

2.4 Conclusion

For a system of systems, such as interdependent critical infrastructure networks, various measures can be taken to reduce the frequency of failures; however, tracking all such interdependencies is too complex. The survival of critical missions is more tractable than preventing all large cascading failures. With multi-interdependencies represented by the generalized adjacency matrix (GAM), also based on our previous results [6][7][8], we have proposed a more practical approach to respond to a large disaster. This approach helps to control the interdependencies among the critical infrastructure networks, according to a risk analysis under the disaster context, and therefore prevent failures from spreading. The proposed strategy is an effective means to reduce the inherent vulnerability, as well as to increase the resiliency of critical infrastructure networks.

Future work can be on:

- Developing methods for optimizing the survivability index of an island's SII according to the local event spectrum.
- Identification of complicated cascading patterns by data mining [18].

- Detecting time-dependent hidden interdependencies with the help of formal verification methods, or further analysis with complex network theory [19][20].
- Building a database for all those hidden interdependencies experienced under certain disaster contexts.

2.5 Acknowledgment

The authors gratefully acknowledge the contributions of J. A. Hollman, J. Jatskevich, and C. Ventura for their inspiring work on this topic. We also deeply give our thanks to Tom De. Rybel, for his suggestions in manuscript preparation of this paper.

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Chapter 3

Survival from Disaster by Interdependencies Management

3.1 Introduction

In modern societies, the standard of living is determined by the reliability of the critical infrastructure networks, which include electrical networks, transportation networks, communications networks, water (oil and gas) networks, banking and finance service networks, food distribution networks, health and emergency services networks etc. [1]. Since as a whole, none of them can be fully independent from the others, this multi-layer network can be seen as a "system of systems". By sharing larger reserve capacity, today's inter-connected infrastructure networks can make efficient use of limited resources; the availability of these resources is also guaranteed by their diversity. Therefore these interdependencies are making the infrastructure networks so robust that it can handle most local disturbances or stochastic fluctuations. On the other hand, this "system of systems" is becoming more fragile. Through cascading effects, an event which may have collapsed one single layer of the networks before, now due to the inter-connection, may cause catastrophe in all possible layers of the critical infrastructure networks. In some extreme situations or global disturbances, such as earthquakes, adverse weather conditions, terrorist attacks, etc., can trigger many events simultaneously, either making the whole system devolve into a critical state, or revealing many unexpected hidden and detrimental interdependencies. In this paper, this "robust yet fragile" duality is treated as the inherent vulnerability of our critical infrastructure networks, which will become more vulnerable due to climate change.

As the climate patterns are changing, many of the previous assumptions

[1] A version of this chapter is to be submitted for publication. DeTao Mao, Jose R. Marti and K. D. Srivastava, Survival from Disaster by Interdependencies Management.

related to system planning, reliability standards, and anticipated responses during emergencies, may no longer be tenable. During recent severe disasters, such as the winter 1998 ice storm in eastern Canada, and hurricane Katrina, it proved impossible to either prevent the disasters or keep the system's integrity. As we have stated before, the vulnerability of NCIs is mainly caused by the complicated interdependencies among them. Therefore, during an emergency, to assure the continuation of critical services by controlling the interdependencies will be a more tractable problem.

3.2 Representation of Modellable Physical Independencies by the Generalized Adjacency Matrix (GAM)

To control the interdependencies among critical infrastructures, it is necessary to represent their topology, dependency direction, and interacting degree(s). Modellable physical interdependencies between two components in various infrastructure networks can be seen as directed linkages in graph theory. In this paper, the concept of the semi-certain adjacency matrix (SAM) [6], which is usually employed to represent undirected graphs by Boolean variables $\{0, 1\}$, is generalized to represent multi-arc directed graphs with loops by using a complex matrix. For instance, in Fig.3.1, the UBC campus case in [5] can be represented by GAM with the following matrix:

$$GAM_{ubc} = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ i & 0 & 0 & 0 & 0 & 1 & 0 & i & 1 & 0 \\ 0 & i & 0 & 0 & i & 0 & i & 2i & 0 & 0 \\ 0 & 0 & i & 0 & 0 & 1 & 0 & 1 & 2i & 1 \\ 0 & 0 & 0 & i & 1 & 2 & i & 0 & 2i & 1 \\ 0 & 0 & 0 & 0 & i & 0 & 2 & 2 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & i & i & i & 0 \end{bmatrix}$$

3.2.1 Operation Rules for GAM

Since the logic rules for matrix operations on semi-certain adjacency matrices (SAM) cannot be adopted here directly, we have redefined the **multiply**

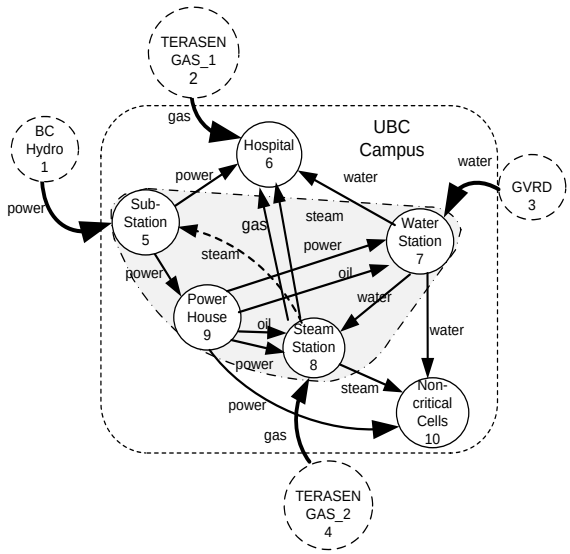

Figure 3.1: UBC campus model with strong coupled cells(SCCs).

operator $\otimes$ for GAM as follows:

$$B = A^2 = A \otimes A$$
$$b_{ij} = \sum_{k=1}^{n} a_{ik} \cap a_{kj}$$

where b_{ij} denotes the element of matrix B, a_{ij} or a_{jk} denotes the element of matrix A, and $\sum$ denotes the algebraic "sum" in the regular sense. $\cap$ denotes the logical "and" (&), but with a generalized definition as fellows:

$$x \cap y = re(x) \cdot re(y) + i \cdot img(x) \cdot img(y) \tag{3.1}$$

here $re(x)$ represents the real part of variable x, and $img(x)$ represents the imaginary part of variable x (the same for $re(y)$ and $img(y)$). Variables x and y are complex numbers whose real part and imaginary part represent the incoming and outgoing degree(s), respectively. Hence, both are all non-negative integers.

Figure 3.2: Graph characteristic of external resource (left) and critical service (right).

3.2.2 System Information Abstracted by GAM Computation

With the modellable physical interdependencies at the same hierarchical level represented by GAM, system information of NCIs can be abstracted from related computations on GAM, such as the following properties:

External Sources

In GAM, external sources (as in Fig.3.2) can be identified by detecting those elements owning no incoming degrees, i.e., the imaginary parts of all complex numbers representing interdependencies between this element and other elements are zeroes.

Critical Services

In GAM, critical services (as in Fig.3.2) can be identified primarily by detecting those elements owning no outgoing degrees, i.e., the real parts of all the complex numbers representing interdependencies between this element and other elements are zeroes.

nth order Influence Domains of a Cell

Influence Domain refers to elements that will be affected by the deletion of an element from the graph. For a graph with m elements, according to their graph distance [8], there exist 1st order influence domain, 2nd order influence domain $\cdots$, and at most $m-1$th order influence domain of a channel. For instance, in Fig.3.3, for element 3 (GVRD), its first order influence domain is $\{7\}$ (water station), its second order influence domain is $\{6, 8\}$ (hospital and steam station). For instance, in Fig.3.4, the $1st$ order influence domain of this broken channel is $\{a\}$, the $2nd$ order influence domain is $\{b, c\}$, the $3rd$ order influence domain is $\{d, e, g, f\}$.

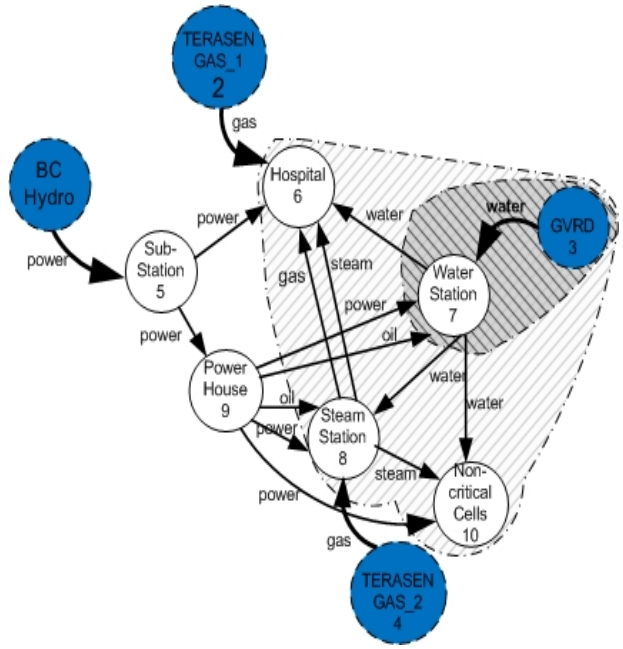

Figure 3.3: First order influence domain $\{7\}$ and second order influence domain $\{6, 7, 8, 10\}$ of cell 3 (cell GVRD).

nth order Influence Domains of a Channel

which refers to the $n-1$th order Influence Domains of the downstream cells connected to this channel. For example, the $1st$ order influence domain of a channel refers to the downstream cells connected to this channel; The 2nd order influence domain of a channel refers to the union of the $1st$ order influence domain of the downstream cells connected to this channel. Similarly, the nth order influence domain of a channel refers to the union of the n-1th order influence domains of the downstream cells connected to this channel.

Strongly Coupled Components as typical Critical Components

A directed graph is called strongly coupled/connected, if for every pair of vertices $\{u, v\}$, there is a path from u to v and a path from v to u [9]. The strongly connected components (SCCs) of a directed graph are its maximal strongly connected subgraphs that form a partition of the graph (Shadow area of the UBC campus cells [5] in Figure 3.1. Note that, in this figure, to demonstrate the existence of SCC, the broken line is added artificially. In the real world, the steam pipe from the Steam Station to the Substation does

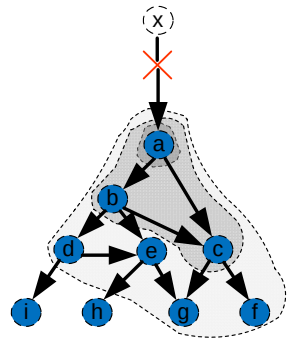

Figure 3.4: nth order influence domain of a damaged channel.

not exist). By introducing the concept of Strongly Coupled Components (SCCs), further topological knowledge about the multi-arc directed graph can be calculated explicitly and efficiently.

Critical Level of External Resources or internal Cells

For instance, by GAM computation, we can get that the impacting domain or influence domain of cell $BCHydro : 1$ in Figure 3.1 is $\{1, 5, 6, 7, 8, 9\}$; while the impacting domain of cell $2 : TerasenGAS_1$ is $\{6\}$; the impacting domain of cell $3 : GVRD$ is $\{6, 7, 8, 10\}$; the impacting domain of cell $4 : TerasenGAS_2$ is $\{8\}$. Therefore, roughly, we can know that the importance of critical level of each external cells.

With considering both the backup cost and the restoration cost of the utility supplied by each external cell, we can precisely evaluate the important level of each of them.

Number of Islands Detected by Eigenvalue Calculation of the Laplacian Matrix

In the mathematical field of graph theory the Laplacian matrix [18], sometimes called admittance matrix or Kirchhoff matrix, is a matrix representation of a graph.

Given a graph G with n vertices (without loops or multiple edges), its

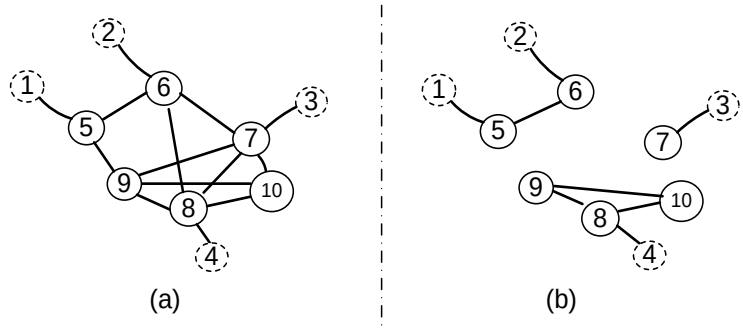

Figure 3.5: The infrastructure networks in the UBC campus before (a) and after an earthquake (b).

Laplacian matrix $L := (\ell_{i,j})_{n\times n}$ is defined as

$$\ell_{i,j} := \begin{cases} \deg(v_i) & \text{if } i = j \\ -1 & \text{if } i \neq j \text{ and } v_i \text{ is adjacent to } v_j \\ 0 & \text{otherwise.} \end{cases} \tag{3.2}$$

That is, it is the difference of the degree matrix and the adjacency matrix of the graph. In the case of directed graphs, either the in-degree or the out-degree might be used, depending on the application. For a graph G and its Laplacian matrix L with eigenvalues $\lambda_0 \leq \lambda_1 \leq \cdots \leq \lambda_{n-1}$:

- L is always positive-semidefinite ($\forall i, \lambda_i \geq 0$).
- The number of times 0 appears as an eigenvalue in the Laplacian is the number of connected components (isolated islands) in the graph.
- λ_0 is always 0.
- λ_1 is called the algebraic connectivity.
- The smallest non-trivial eigenvalue of L is called the spectral gap.

The rules to covert from the generalized adjacency matrix (GAM) to the Laplacian Matrix can be described as follows. Assume $G_{n\times n}$ is a generalized adjacency matrix, its element is g_{ij}, $L_{n\times n}$ is a converted Laplacian matrix,

its element is $\ell_{i,j}$, then the rule from the GAM to the Laplacian matrix is

$$\ell_{i,j} := \begin{cases} \sum_{j=1}^{n} ||sign(g_{ij})|| & \text{if } i = j \text{ and } g_{ij} \neq 0 \\ -1 & \text{if } i \neq j \text{ and } g_{ij} \neq 0 \end{cases} \tag{3.3}$$

For instance, UBC's five cells case in Fig.3.1 can be represented as a labelled graph in Fig.3.5, and its Laplacian matrix is :

$$LM_{ubc} = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 3 & -1 & 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 & -1 & 4 & -1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & -1 & 5 & -1 & -1 & -1 \\ 0 & 0 & 0 & -1 & 0 & -1 & -1 & 5 & -1 & -1 \\ 0 & 0 & 0 & 0 & -1 & 0 & -1 & -1 & 4 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & 3 \end{bmatrix}$$

Assume channels CH_{5-9}, CH_{6-7}, CH_{6-8}, CH_{7-8} , CH_{7-9} and CH_{7-10} are broken after an earthquake, the infrastructure networks in the UBC campus are isolated into several subnetworks as shown in Fig.3.5 (here channel CH_{i-j} refers to the channel that connects cell i and cell j).

$$LM_{ubc}^{islands} = \begin{bmatrix} 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 2 & -1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -1 & 2 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 3 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 2 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 2 \end{bmatrix}$$

The eigenvalues of $LM_{ubc}^{islands}$ are $\{0,\ 0,\ 0,\ 0.5858,\ 1,\ 2,\ 2,\ 3,\ 3.42,\ 4\}$, there are three zeroes in them, corresponding to three subnetworks or islands. After reordering the cell numbers, the islands can be visualized in Fig.3.6 (b), where the cells represented by the number can be seen in Fig.3.3.

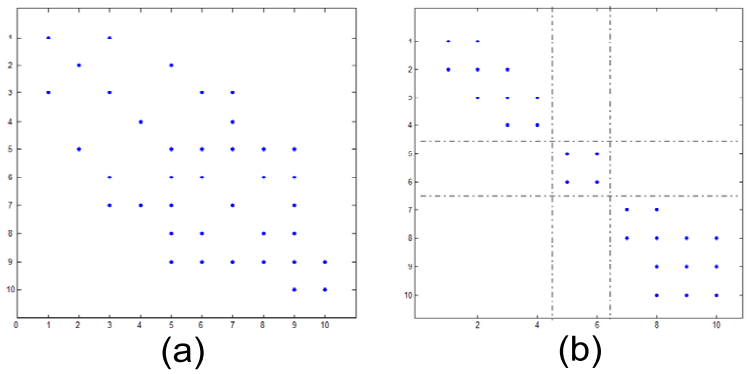

Figure 3.6: (a) Visualized sparsity matrix of the UBC campus case before re-ordering the cell numbers; (b) Visualized sparsity matrix after re-ordering the cell numbers $\{1, 2, 3, 4, 5, 6, 7, 8, 9, 10\} \rightarrow \{2, 6, 5, 1, 7, 3, 4, 8, 10, 9\}$. The three islands can be identified: $\{1, 2, 5, 6\}$, $\{3, 7\}$ and $\{, 4, 8, 9, 10\}$.

3.2.3 Advantages of GAM-based Interdependency Analysis

In this paper, all interdependency analysis during interdependencies control is based on computations on the generalized adjacency matrix (GAM). This approach offers the following advantages:

- By finding all the pathways between any pair of elements (vertices), GAM can detect the existence of interdependencies between any pair of elements, and identify all the nth order influence domains for any element in the graph. Therefore, it is an exhaustive analysis instead of a 'what if' analysis.

- The order of the influence domain determines the impact index from one element to the others. Thus it may give both essential information on where to buffer the cascading failures with minimum cost and the priority of these elements under a given disaster context;

- Since the vulnerability of strongly coupled components is determined by its weakest section, based on the calculated results of the SCC, critical components can be detected, and a vulnerability assessment can be obtained. Furthermore, by SCC identification, interdependencies control strategies (ICS) are more rational and effective.

3.3 Interdependencies Control Strategy (ICS) Based on GAM

For critical services in the NCIs to work, multiple utilities need to be available simultaneously and running at full capacity. For instance, to maintain the normal operability of a hospital, the simultaneous availability of electricity, water, steam, natural gas, medicine, nurses, doctors, foods, communication, and transportation must be assured. This full capacity state is more fragile than any other state, for in this state, a number of requirements must hold simultaneously. According to the theory on "the fragility of goodness" [10], once one of them fails, the functionality of the hospital will be greatly degraded.

The purpose of proposing the concept of interdependencies control in this paper is to try to reduce the sensitivities of critical services on unexpected fluctuations of external resources. This can be implemented by adjusting the interdependency degree by either splitting the network into several islands or just shutting down the related physical connectivity. Based on computation of GAM and a reliability assessment of the utilities, as proposed in this paper, interdependencies control strategy can help to assign limited resources to the most critical services, while avoiding the propagation of cascading failures to other infrastructure layers.

Since the interdependencies control strategy (ICS) is mainly focused on the response stage in the four phases of emergency management, it is convenient and necessary to briefly review the conceptual framework for emergency management as follows.

3.3.1 Basic Introduction to Emergency Management

Emergency management is the discipline of dealing with and avoiding risks [11]. As Figure 3.7 illustrates, it generally includes four different stages [2]:

- **Mitigation**: Long before the disaster. This refers to the sustained actions to reduce or eliminate the long-term impacts and risks associated with disasters.

- **Preparedness**: Long and shortly before the disaster. This refers to the policies, procedures and plans for how to best manage an emergency.

- **Response**: During and shortly after the disaster. This refers to the actions taken during or directly after an emergency occurs.

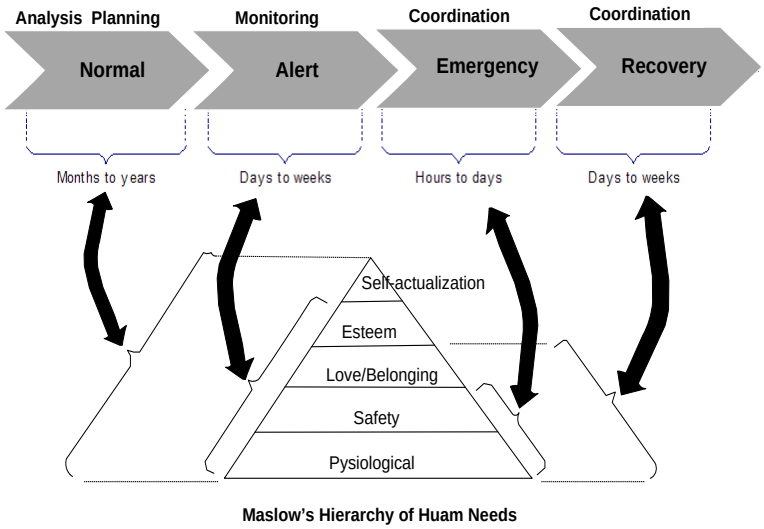

Figure 3.7: The time line for emergency management. The five levels of human needs imply the priority of these critical infrastructure networks during emergency states.

- **Recovery**: Shortly and long after the disaster. This refers to the efforts taken to repair and restore communities after an emergency.

Based on Maslow's theory of human motivation [13], humans have different levels of needs constrained by their socio-economic background factors. A connection has been established between human motivation theory and emergency management due to the dynamic characteristics of emergency conditions [2] (see Fig.3.7). The convection can give helpful information on prioritizing the different infrastructure lifelines during emergency states.

3.3.2 Survivability Index of an Island (SII)

By applying the GAM-based interdependencies control strategy (ICS), our infrastructure networks can be divided into several islands during a disaster. The survivability index of an island can be briefly expressed as how long this island can survive before its linkages are re-established. Mathematically, for an island with m internal backup resources, and n linkages connected with external resources, assume the availability duration of the backup resource i is t_i ($i \in [1, m]$), here $t_i \leq 0$ indicates that utility i has been used up for t_i (time units). The estimated recovery time under a certain disaster context

$\widetilde{D}$ for linkage j is $E(T_j)$ ($j \in [1, n]$). The survivability index of island k can then be defined as:

$$SII_k^{\widetilde{D}} = \begin{cases} \frac{\min(t_i)}{\max(E(T_j))} & (\max(E(T_j)) > 0) \\ \\ \min(t_i) & (\max(E(T_j)) = 0) \end{cases}$$

The objective of interdependencies control during a disaster $\widetilde{D}$ is to maintain $SII_k^{\widetilde{D}}$ not less than 1. The details on ICS will be discussed in Section 3.3.3, the related measures to improve SII during the four phases of emergency management cycle will be addressed in Section 3.3.4.

3.3.3 Interdependencies Control Strategy

It is well-known that among our modern infrastructure networks, the electrical network is the most fundamental and important infrastructure. Since it is in the lowest layer of our infrastructures pyramid, it supports and thus assures the operation of most other infrastructures. The concept of interdependencies control is based on our previous work [2][3][4], and it also has been inspired by the controlled islanding strategy of power networks. It is well known that in power systems, controlled islanding is a special protection strategy aimed at preventing a system-wide blackout as a result of the cascading of low probability events [4]. The difference between controlled islanding strategy and ICS is that, in ICS, it is usually not necessary to split the network into several islands. In most cases, interdependencies control means shutting down several outgoing linkages, thus ensuring the availability of scarce resources, or isolating failures (e.g. epidemics), within a certain limited area.

This decision making process for the GAM-based interdependencies control strategy (see Fig.3.8) is briefly explained as fellows:

Step 1: Identify all modellable physical interdependencies, and represent them with the generalized adjacency matrix (GAM);

Step 2: Based on the calculations of GAM, identify the supporting utilities for these critical services with higher priority and sections with vulnerabilities, such as strongly coupled components (SCCs);

Step 3: Monitor the possibility of new disasters online with an early warning system (EWS). If a disaster happens, broadcast warnings, carry out the anticipated recovery-oriented actions, and finally perform ICS according to the priority of the essential missions;

Step 4: After interdependencies control, if the SII for each island is

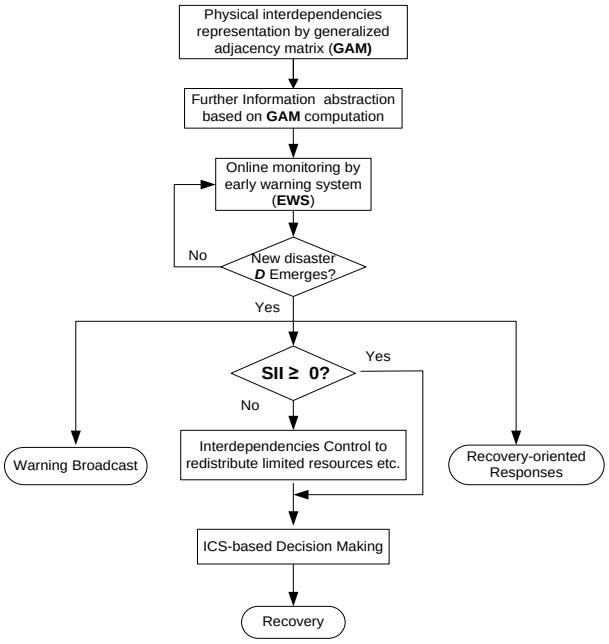

Figure 3.8: Decision making flow chart for Interdependencies Control Strategy (ICS).

not less than 0 after the expected duration of restoration, its recovery processes will receive the highest priority. Otherwise, there are many measures to maintain the critical service survival as long as possible. The detailed content on improving SII will be described in the next section.

3.3.4 Measures for Improving SII

As the survivability index of island (SII) is mainly determined by (1) the scarce resource, or the backup lifeline with the minimum supporting duration; (2) the recovery time; hence to improve SIS of each island, various measures at the four phases of emergency management cycle are described below.

Mitigation Stage

- Infrastructure design taking the following properties in consideration: risk-decentralized redundancy, multi-functionality, adaptivity to the

statistic patterns of local events, maintenance/recovery-oriented characteristics, etc.

Preparedness Stage

- Early warning capability by monitoring possible disasters online, presolutions based on historical experiences, etc.

Response Stage

- Redistribute the limited resources from other external resources, or redirect them from other islands whose SII is less than 1.
- Degrade the operability capacity of the island.
- Supply critical missions in the island with "synchronized rolling availability", which is very similar to a rolling blackout during power outage, but instead of losing services totally, it can keep the system operated with a low service quality.
- Mobilized lifelines/resources, such as mobile generators etc.
- Make use of convertible utilities, as well as multi-functional resources. As there exists overlap of these utilities' functionality, it is possible to move from one to the other during a disaster state, like switching between gas, oil, steam, or electricity for heating.

Recovery Stage

- Personnel training, prioritization of critical infrastructures under all possible scenarios; Optimization of the restoration time by dynamic programming etc.

3.4 Application of ICS on the UBC Campus Case

In this section, based the snow-caused power outage of Vancouver in the winter of 2006, which affected the utilities in the campus of UBC, comparisons of survivability of the isolated critical service(s) with and without ICS is presented. Decision making processes aided by GAM calculation during the mitigation, response and recovery phases of emergency management cycle are also presented.

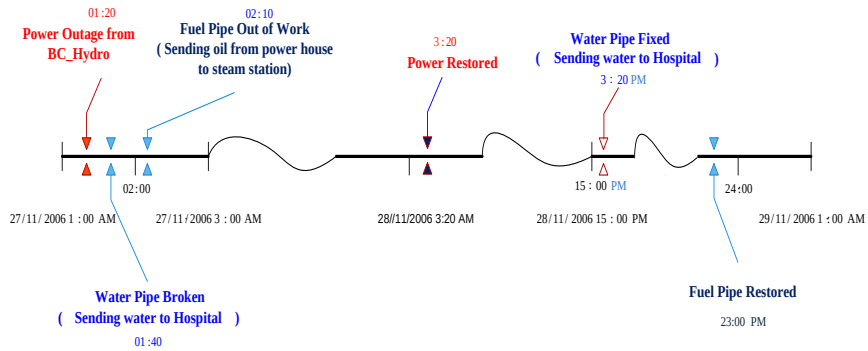

Figure 3.9: Time line of the events at UBC campus triggered by the 2006 winter snow storm and their restoration processes optimized by GAM-based ICS strategy.

3.4.1 Scenario Description

On November 26, 2006, 20-40 cm of heavy snow fell across Greater Vancouver, Victoria, and the rest of the South Coast. The weight of the heavy snow brought branches and trees down on power lines [19][20]. Because of the snow and the resulting power outage at the UBC-Point Grey campus, the whole campus was closed on November 27, 2006, following the No.68 university policy. The campus power outage lasted for about 24 hours [5].

Time-line of the scenario

The time line for this scenario can be seen in Fig.3.9. The detailed description for the triggering events in this scenario is as follows:

- Initial state: t = t_0, the whole campus runs normally;
- $t_2 = t_0$+21(min), Event E_a: Fallen trees brought down the transmission lines sending power to the UBC Substation ;
- $t_3 = t_0$+40(min), Event E_c: The water pipe linking the water station to UBC hospital burst;
- $t_3 = t_0$+70(min), Event E_b: The fuel pipe linking the power house to the steam station is out of work.

The topological locations of the events: E_a, E_b and E_c of the UBC case can be found in Fig.3.10.

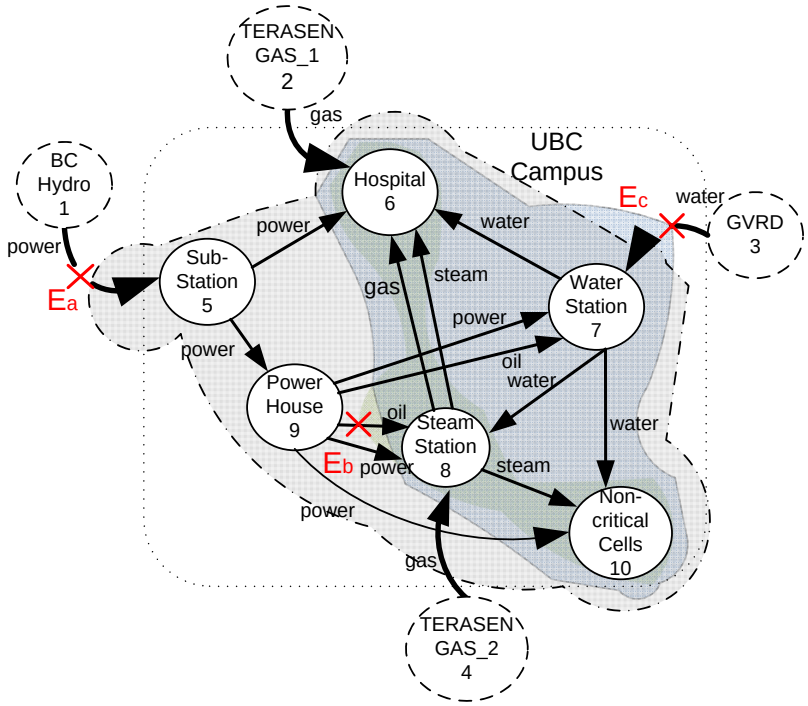

Figure 3.10: Cells on UBC campus. Where the cross "X" in the figure represents the topologicallocation of an event.

Related Parameters and Data

To calculate the survivability index of a component in the UBC case, related parameters of the cell on UBC campus can be seen in the following Table 4-A [5][1].

Table 4-A: Duration of Reserved Resources in Cells

Reserved Resources in Cells	After ICS	Before ICS
t^6_{ele} backup electricity in cell 6	48 hours (with steam) 32 hours (no steam)	24 hours
t^6_{wat} reserved water in cell 6	24 hours	24 hours
t^7_{wat} reserved water in cell 7	24 hours	12 hours
t^9_{oil} reserved oil in cell 9	24 hours	12 hours

The expected recovery duration of these events are in the following Table

[1]Due to information privacy, part of the data were estimated by Lucy from her interview meetings with the utility guys of UBC.

4-B.

Table 4-B: Expected Recovery Duration of Event

Event	Restoration Duration
E_a	24 hours
E_b	12 hours
E_c	8 hours

The duration of emergence response operations can be seen in Table 4-C, where $Normal$ refers to normal response action, and ICS refers to response action of Interdependencies Control Strategy.

Table 4-C: Duration of Emergence Response Operations

Response Action	Duration
$Normal$	1 hours
ICS	2 hours

3.4.2 ICS-based Decision Making Activity during Emergency and Recovery State

The purpose is to prevent the functionality of the whole campus from collapsing, and especially, to keep the critical service(s) survive during this constructed scenario. With limited restoration resources, aided by GAM-based calculation, the Emergency Operation Center (EOC) will take the following steps to make decision:

Step 1: With the represented topological relationship in Fig.3.10, after GAM-based calculation, a critical service : the UBC hospital is identified. (since our research objective of JIIRP is to save as many lives as possible during a disaster). External sources or external cells, such as cell {1} (BC Hydro), cell {3} (GVRD), cell {2} (TERASEN GAS1) and cell {4} (TERASEN GAS2) are identified;

Step 2: No strong coupled cells (SCCs) are identified in this case;

Step 3: Identified by GAM calculation, the influence domain of these events through the impacted channels.

Cells impacted by the T-line fault event E_a is $\{5, 6, 7, 8, 9, 10\}$; Cells impacted by the fuel pipe fault event E_b is a set of cells $\{6, 8, 10\}$; Cells impacted by the water pipe fault event E_c is a set of cells $\{6, 7, 8, 10\}$.

Without applying ICS, there are three islands identified by GAM computation: island $\{1\}$, island $\{3\}$ and island $\{2, 4, 5, 6, 7, 8, 9, 10\}$. After applying ICS method to shed these non-critical loads: cell $\{10\}$, there are four islands identified: island $\{1\}$, island $\{3\}$, island $\{10\}$ and island $\{2, 4, 5, 6, 7, 8, 9\}$.

Step 4: SII Computation: which requires computing both the internal

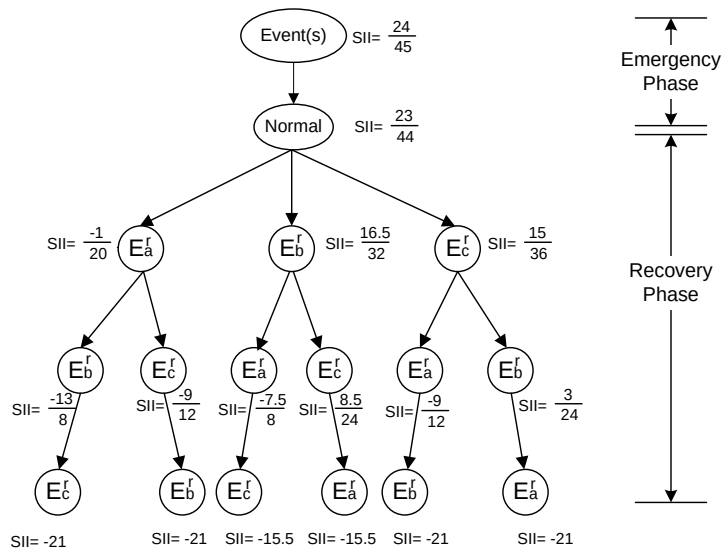

Figure 3.11: Decision making tree for the recovery phase without ICS operations. Where E_a^r (E_b^r, E_c^r) refers to the recovery actions of E_a (E_b, E_c).

self-sufficient duration t_i^{int} and the external self-sufficient duration t_i^{ext} of one utility. The external self-sufficient duration of one lifeline can be calculated along its upstream pathway identified by GAM computation. The restoration duration of each event can be estimated by their expectation value from historical records.

Step 5: Decision making for restoration order of multiple events based on SII value. Due to limited recovery and maintenance resources, we assume that the restoration actions for these events have to be executed one by one.

Case I: During Step 3 to Step 5, the restoration process without ICS operations can be seen in Fig.3.11. Here we can see that without ICS operations, the critical service (UBC hospital) can not survive during this disaster. Since by this decision making tree, non-option has a SII greater than zero after the final restoration.

Case II: During Step 3 to Step 5, with ICS operations can be seen in Fig.3.12, where represented by "$\otimes$", event E_{ICS1} (E_{ICS2}) refers to shedding the non-critical loads on UBC campus. The restoration process based on ICS can be seen in Fig.3.13, were we can see that after ICS operations, the critical service (UBC hospital) can survive in this disaster. Due to this decision making tree in Fig.3.13, there are four options with a SII greater than zero

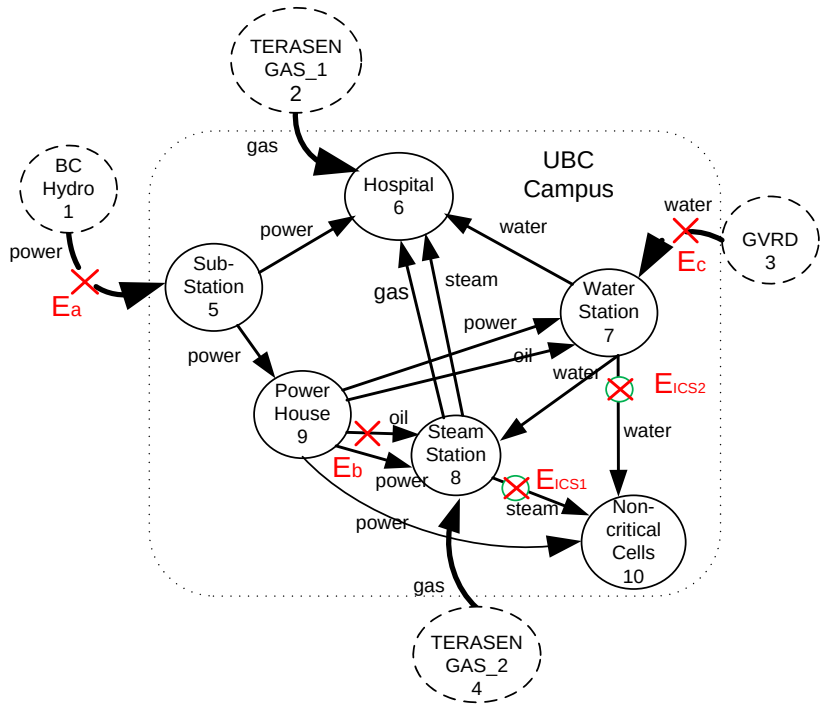

Figure 3.12: ICS operations (represented by circled cross "⊗") of redistributing scarce resources during emergency stage.

after the final restoration. According to the obtained results in Step 3, the order of the size of the influence domain of these events is $E_a > E_c > E_b$, therefore the decision branch with the restoration order $E_a^r \rightarrow E_c^r \rightarrow E_b^r$ is picked.

By comparing the above two processes, we can see that without ICS operations, the critical service on UBC campus can not survive during this diaster; While with ICS operations, its survivability can be assured. If ICS operations are taken during emergency response phase, even the recovery actions are executed randomly, there is a 66% probability that the critical cells will survive in this snow disaster.

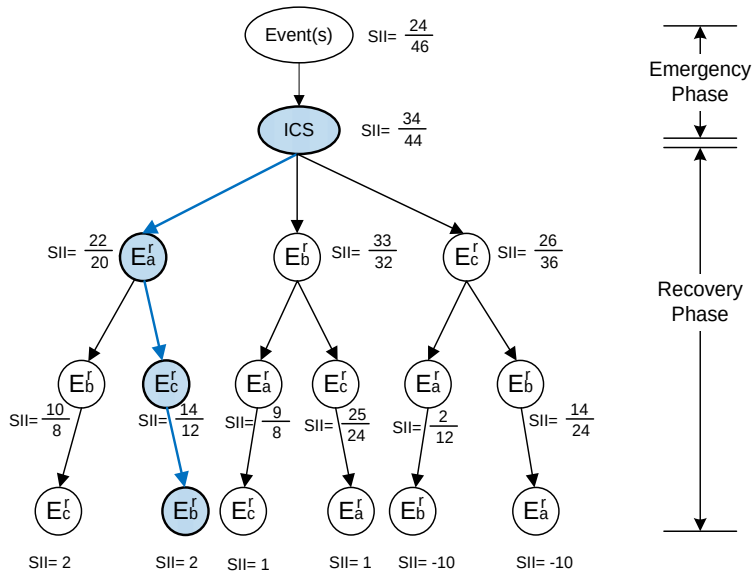

Figure 3.13: Decision making tree for the recovery phase after ICS operations. Where E_a^r (E_b^r, E_c^r) refers to the recovery actions of E_a (E_b, E_c).

3.5 Conclusion

For a system of systems, such as the interdependent critical infrastructure networks, various measures can be taken to reduce the frequency of failures. However, tracking all such interdependencies is too complex, the survival of critical missions is more tractable than preventing all large cascading failures. With the multi-interdependencies represented by the generalized adjacency matrix (GAM), also based on our previous results [2][3][4], we have proposed a more practical approach to respond to a large disaster. This approach helps control the interdependencies among the critical infrastructure networks, according to a risk analysis under the disaster context, and, therefore, prevents failures from spreading. The proposed strategy is an effective means to reduce the inherent vulnerability, as well as to increase the resiliency of critical infrastructure networks.

Future work can be on

- developing methods for optimizing the survivability index of an island (SII) according to the local event spectrum;
- identification of complicated cascading patterns by data mining [15];

- further analysis with complex network theory [16, 17];
- building a database of all these hidden interdependencies experienced under certain disaster contexts;
- application of queueing theory in GAM-based decision making process against multiple events.

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Chapter 4

Identifying Cascading Pathways for Power Outage Mitigation

4.1 Introduction

During the past several decades, as a result of heavy ice/wet-snow storms, many countries experienced large-scale power blackouts with huge monetary loss, for example, Western Canada-Northeast USA in Jan. 1998 [2], B.C. Canada in Nov. 2006 [3], Southern and Central China in Feb. 2008 [4], Northeast USA in Dec. 2008 [5], and Southern and Eastern USA in Jan. 2009 [6]. Affected by climate change, not only the damage degree of these storms were unbelievably higher than before, but their spatio-temporal patterns were becoming uncertain, for instance, Southern and Central China (2008) [4] and Southern USA (2009)[6], which have not experienced such severe ice/wet-snow storms for many years, were seriously impacted. Scientists believe that, as a result of climate change, similar events will be more frequent, more severe, and longer lasting in the near future [7][8].

To protect our power network, especially overhead transmission lines, from damage caused by ice/wet-snow storms, currently there are several research options, such as studies on the ice accretion mechanisms [9], failure mechanisms of iced outdoor insulation equipments [10], anti-icing and de-icing methods [11], on-line monitoring and diagnosis of icing [12], online evaluation, prediction and decision making of icing [13][14], establishment of an emergency response system against ice-snow disaster [15] etc. But up to now, most of these prevention and treatment methods focusing on different aspects in power outages, have not been systemized or standardized

[1] A version of this chapter has been accepted for publication. DeTao Mao, Jose R. Marti and K. D. Srivastava (2009), Mitigation Snow-Caused Power Outage along Cascading Pathways, *the 2009 IEEE International Conference on Technologies for Homeland Security (HST'09)*, Waltham, MA, USA, May 11-12, 2009.

for industry applications,

For instance, it will be challenging to adapt these Joule-effect-based de-icing and anti-icing methods, which have been applied in many countries before, to our modern large-scale power networks [11].

Different to these methods stated above, we propose a systematic approach to inhibit the development of similar disaster as well as to mitigate its propagation along these cascading pathways. This approach is based on our investigation of the 2006 power outage caused by a snow storm in Vancouver area (BC, Canada), where by analyzing the evolution processes and considering the changed climate, the root causes of this disaster and possible chain-reaction pathways have been carefully studied.

The content of this paper is organized as following. In Section 4.1, we give a short introduction on the background and a brief review of current research related to atmospheric icing issue in power systems. In Section 4.2, the power outage caused by the snow storm in Nov. 2006 at Vancouver is investigated. The root causes of this blackout and the effects of climate change are described, followed by an analysis on the dependency network containing these cascading pathways. In Section 4.3, based on analyzing the emergence mechanism of the disaster, systematic countermeasures for blocking these manageable cascading pathways, such as building an early warning system against snow storm and inhibiting wet-snow storm by artificial precipitation stimulation (APS) etc., are summarized. Finally, our study is concluded in Section 4.4.

4.2 Investigation on Vancouver's 2006 Snow-Caused Power Outage

On Nov. 27th, 2006, an unexpected heavy snow storm in the Vancouver area, including: Vancouver, North Vancouver, Lions Bay, Bowen Island, Surrey, Burnaby and Maple Ridge etc., resulted in a sustained power outage. It was reported that this power outage, was mainly caused by falling trees and snow-damaged power lines [3]. Contrast to the conclusion in [16], which states that this is a typical snow-caused power outage. By analyzing the development process of this disaster, especially the root conditions leading to the cascading failures, we discovered that climate change had played an importance role in this disaster.

4.2.1 Several Root Causes Introduced by Changed Climate

Compared to snow-caused large blackouts under normal circumstances, the Vancouver 2006 outage, caused by climate change as well the greenhouse effect, has some special characteristics, which can be summarized as follows:

The First Heavy Snow Date Was Early at Vancouver in 2006

Based on the data from [17], both the first snow dates and the first heavy snow dates in Vancouver B.C. from 1997 to 2007, are listed in Table 4.1. According to this table, it was about 10 days earlier than the average date. Moreover, the first snow and the first heavy snow (lasting over three days) happened at the same time in 2006. This early heavy snow brought forth some negative effects on local power networks. For instance, electrical load impacts, the falling probability of trees over transmission line; Otherwise, if it snowed several weeks later, these preconditions that had induced the power outage might become very rare, the reserved margin capacity in power systems would have been better prepared for winter load peak, and with less moisture and less foliage, the trees would be more resilient during this storm.

Table 4.1: Data on Vancouver 's Snow Dates (1997-2007)

First Snow Dates	**Annual Heaviest Snow**	**Interval**
Dec 18, 1997 (1 day)	Jan 1, 1998 (4 days)	14
Dec 21, 1998 (3 days)	Dec 21, 1998 (3 days)	0
Dec 14, 1999 (1 day)	Dec 31, 1999 (2 days)	17
Dec 14, 2000 (3 days)	Dec 14, 2000 (3 days)	0
Nov 29, 2001 (3 days)	Jan 17, 2002 (3 days)	49
Dec 24, 2002 (1 day)	Mar 7, 2003 (3 days)	102
Nov 22, 2003 (1 day)	Dec 30, 2003 (4 days)	38
Dec 6, 2004 (1 day)	Jan 6, 2005 (3 days)	31
Nov 28, 2005 (5 days)	Nov 28, 2005 (5 days)	0
Nov 25, 2006 (5 days)	Nov 25, 2006 (5 days)	0
Nov.26, 2007 (1 day)	Jan 7, 2008 (4 days)	41

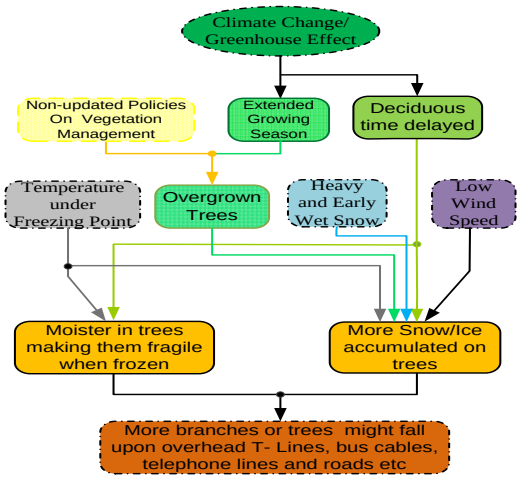

Figure 4.1: Synthesized effect of delayed deciduous time, extended growing season and unchanged policies on vegetation management upon the collapse probability of trees and branches.

The Deciduous Time Delayed by the Effect of Greenhouse

Another factor that had worsened the effect of falling trees, was trees' deciduous time. Since a tree with more leaves and larger canopy could catch more wet snow, and internal moisture might make trees much fragile when frozen. According to [18][19], the greenhouse effect has delayed the deciduous time of trees. Based on data collected across Europe, they found during the last 30 years, autumnal senescence has been delayed by 1.3 to 1.8 days per decade.

During an early and long lasting wet snow, this may highly increase the collapse probability of tree, especially when the temperature is below freezing point. The causal relationship/dependencies between climate change, temperature, and the collapse probability of trees is displayed in Fig.4.1.

The Growing Season of Tress has been Extended

Due to climate change, many woody and herbaceous plants in mid to upper latitudes are significantly advanced in spring bud break and similarly significantly delayed in autumn with leaf color change and leaf fall, resulting in an extension of the growing season. Remote sensing of vegetation using the normalized difference vegetation index shows a 12-day extension of the growing season in North America between 1982 and 1999 [21]. Thus for

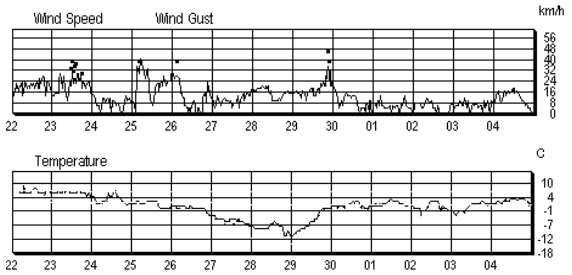

Figure 4.2: The temperature curve (upper figure) and wind speed curve (lower figure) during Nov 22th to Dec 4th 2006 in Vancouver area .

trees along essential transmission line and key roads, our previous frequency for pruning trees, usually once $4-8$ years [16], should be modified with the above facts in consideration.

4.2.2 Unchanged Policies of Vegetation Management by BC Hydro

According to [16], before 2006, factors such as climate change and greenhouse effect etc. are not considered by BC Hydro in its vegetation management. After the 2006 power outage, BC Hydro planned to invest more in vegetation management, but evaluation on effects such as extended growing season, new growing patterns and delayed deciduous time etc., which have been introduced by changed climate, were still not mentioned, let alone quantified and considered [16].

4.2.3 Related Weather Factors Affecting Ice Accretion on Overhead Wires

The snow storm lasted from Nov 25 until Nov 30, during which, the tendency of related weather factors are displayed in Fig.4.2. The maximum wind speed was less than 40km per hour, and averaged less than 24km per hour, and the local temperature was below the freezing point of water. Based on the conclusions in [9], these factors have induced and positively effected ice accretion on overhead wires. With snow accumulated on overhead lines, falling trees would highly increase the probability of snow-caused line fault.

4.2.4 Impacted Critical Infrastructure Networks

Low temperature following this unexpected early snow had made the customers turn on their air-conditioning equipment simultaneously, which impacted the power systems heavily. In some situations, power systems without enough reserved capacity, after such an impact maybe pushed beyond their stability margin.

Except the electric network, during this storm, there were several other related critical infrastructures that had contributed to the final blackout, such as the transportation network and the communication network, since their un-availabilities would hinder recovery from a power outage.

The transportation network was slowed down because of the slippery road surface caused by wet snow and freezing rain. Driving on roads became very dangerous, especially on curves and slopes. Bus-cable failures due to fallen trees or branches made situation worse. Since many buses were out of work, more private cars might jam the road.

As to the communication network, according to [22], quite a number of telephone lines were damaged by the fallen trees and atmospheric icing.

4.2.5 Dependency Network Representation for the Power Outage in Vancouver 2006

According to the above analysis in Section 4.2.3 and Section 4.2.1, as well as considering these hidden interdependencies unfolded during this disaster, a sequential diagram has been built to represent the causal relationship among these elements, in which each cascading pathway starts from the root causes, passing by affected events or objects, and finally reaching their common destination: "the blackout of Vancouver". The manageability of each pathway has been analyzed, classified and labelled. Mitigation treatments or prevention methods are only permitted along these manageable pathways.

The whole dependency network structure leading to this power outage can be seen in Fig.4.3, in which the related elements (in boxes) are connected by cascading pathways (solid or broken lines). These concurrent processes or preconditions are represented, which pinpoints the mechanism of this power outage and facilitates the finding of countermeasures that will be discussed below.

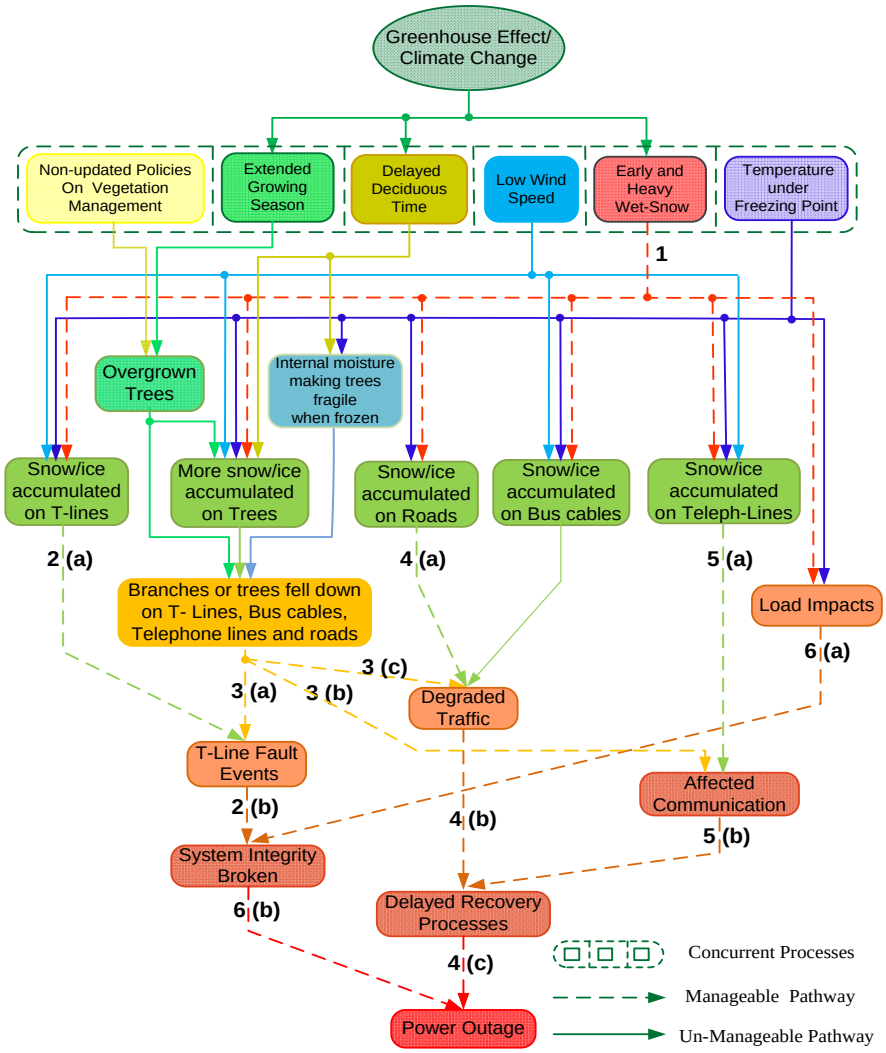

Figure 4.3: Dependency network for these cascading pathways unfolded during the power outage in Nov, 2006 at Vancouver area (B.C., Canada).

4.3 Countermeasures against Snow-Caused Power System Failure

In this section, we aim to develop a mitigation strategy or countermeasure along manageable cascading pathways (dotted lines in Fig.4.3) in order to isolate related events in a limited range, or mitigate the overall impact of

snow storm to a certain degree, thus reducing the probability and risk of power system failure.

According to our best knowledge, most of the current anti-icing and de-icing methods at power industry are not available for wide application, while the cost of building a transmission network which may tolerate any degree of snow storm would be extremely high. Based on our previous analysis of the Vancouver case, particularly the sequential diagram in Fig.4.3, a systematic solution against snow-caused blackout is proposed and described in two aspects:

- actively inhibit the development of ice/wet-snow storms;
- block cascading along manageable cascading pathways.

the detailed content will of them be explained below respectively.

4.3.1 Active Suppression on the Development Process of Atmospheric Icing

Much attention on Climate Change (CC) is directed towards mitigation measures for reducing greenhouse gas; However, the complexities and uncertainties in CC science and predictions, which warrant that investment in adaptation measures to manage climate risks may prove to be more certain and tangible benefits rather than just reducing CO_2[23].

According to Fig.4.3, meteorological factors globally affect all downstream events and objects. Once these meteorological processes emerge concurrently, atmospheric icing will come into being. Longer duration of precipitation of wet-snow, will result in more ice accumulating on trees, transmission lines, bus cables, roads, telephone lines etc., and increase the probability of a power system failure. Corresponding to the manageable cascading pathway 1 in Fig.4.3, an intuitive idea is to reduce its duration or at least inhibit the coexistence of preconditions that have induced the ice accretion process.

Based on the advancement of modern meteorological technologies and especially based on the feasibility studies of forecasting heavy snow storms[23][24], we propose some meteorology modification methods, such as artificial precipitation stimulation (APS). The effect of artificial precipitation stimulation (APS) can be seen in Fig.4.5. The decision making process for APS can be seen in Fig.4.4. Here the time threshold value t_1 can be calculated by the snow accretion model in [9][13]. As in[9], a formulae for determining the

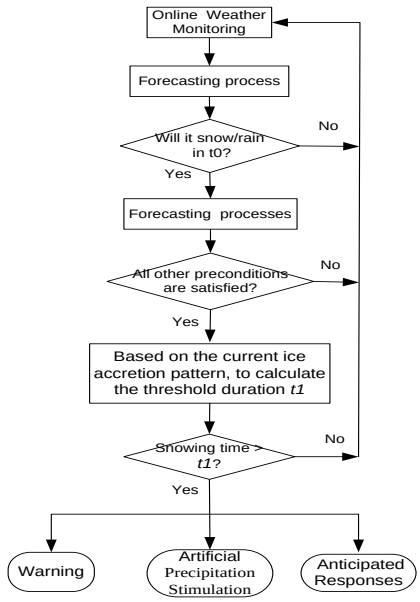

Figure 4.4: Decision making process for artificial precipitation stimulation(APS) action.

mass of accreted snow per unit length of wire can be expressed as

$$W = 4.5 \frac{e^{-6(T/T_0 - 0.32)^2}}{V_N^{0.2}} P_n t \tag{4.1}$$

where T denotes the surrounding temperature ($^\circ C$), T_0 is a threshold value for determining whether it is raining or snowing, V_N denotes wind speed (ms^{-1}), P_n is the amount of snow passing around the wire per unit time (gt^{-1}), t denotes time (s).

Other countermeasures along cascading pathway 1 includes building an early warning system (EWS) for adverse weather, this would give critical infrastructure networks more time for preparation, possibly improving the survivability of essential services as well as reducing the monetary losses.

4.3.2 Blocking the Propagation of Disaster along the Manageable Cascading Pathways

A manageable cascading pathway (**MCP**) refers a cost effective pathways, in which benefit of any feasible mitigation and/or countermeasure generally

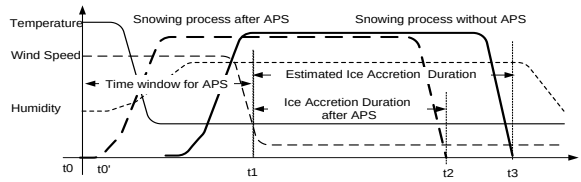

Figure 4.5: Active suppression of the development process of atmospheric icing by artificial precipitation stimulation. Where t_0 denotes present time, t_0' denotes the APS action time, t_1 denotes the beginning time of ice accretion, (t_1, t_2) denotes the ice accretion duration after APS, while (t_1, t_3) denotes the estimated ice accretion duration without APS.

prevails the associated costs, otherwise it is called an unmanageable cascading pathway (**uMCP**). In Fig.4.3, except pathway 1, there are in total 10 manageable cascading pathways left. Besides anti-icing and de-icing methods in [11], other related countermeasures or mitigation strategies will be discussed in the following subsections.

MCP $2(a)$ **and** $2(b)$

As shown in [26], the frequency of snow-caused outage is determined significantly by the geographical location of the transmission lines. During snow storms (or flood, hurricane and other adverse weathers), underground cable is more reliable than overhead cable, but it will be extremely costly to replace all these overhead lines [27]; Hence only locations with a higher frequency of line fault after a snow storm, and areas become inaccessible after the storm, should transmit electrical energy underground. Also as the reliability of a transmission line is mainly determined by its most vulnerable segment or weakest linkage, the load limits of these transmission-lines and supporting towers should also be evaluated, the weakest segments should be strengthened [28].

For instance, assume in Fig.4.6, there are n locations $A_1, \cdots, A_n$ which are vulnerable to snow storm, and the failure rate of an overhead transmission line at one of these locations is P_o during a snow storm, then the probability of transmission failure is:

$$P_1^{ss} = 1 - (1 - P_o)^{3n} \tag{4.2}$$

after replacing the overhead line with underground cable, assume the failure rate becomes P_u, the probability of transmission line after upgrade is P_2^{ss},

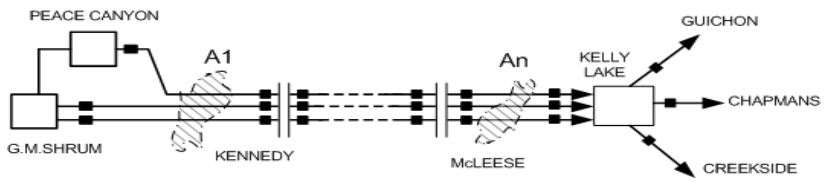

Figure 4.6: Vulnerable geographical locations under snow storm along the transmission lines in Northern British Columbia.

then the reliability comparison between the two cases is:

$$\frac{P_2^{ss}}{P_1^{ss}} = \frac{1-(1-P_u)^{3n}}{1-(1-P_o)^{3n}} \simeq (\frac{P_u}{P_o})^{3n} \tag{4.3}$$

MCP $3(a)$**,**$3(b)$ **and** $3(c)$

Each species of trees should be evaluated in terms of growing speed, falling probability, falling direction and possible falling range. According to [2], robust tree species should be planted beside roads and overhead lines instead of tree species which prone to fall under adverse weather condition.

Typically, very tall or fast-growing vegetation, such as hackberry or ash trees, should be removed from the right-of-way to ensure safety and reliability.

MCP $4(a)$**,**$4(b)$ **and** $4(c)$

For snow/ice accumulated on roads, instead of traditional methods, such as anti-icing by spreading salt, de-icing by snow removal program, priority for the transportation networks before, during and after snow etc. should be systemically considered and carried out according to the latest forecasting information[24]25].

MCP $5(a)$ **and** $5(b)$

For overhead telephone lines prone to snow-induced failure, 4.3.2 can be taken, for instance, they can be replaced by underground optical fibers. The communication infrastructure can also be strengthened by the installation of more wireless stations.

MCP 6(a)

Since a large part of electrical load is affected by weather factors, to reduce the load impacts under similar situation, previous plan for reserved generation capacity, maintenance schedule, transmission reliability analysis [26] etc. should be adaptive to new climate patterns [23], especially to these unexpected adverse weathers induced by climate change.

MCP 6(b)

Since these power outages were mainly and directly caused by faults on transmission lines, to keep the integrity of the whole power system, especially to keep these critical services or essential missions survive during adverse weathers caused by climate change, besides splitting strategy against cascading failures, risk de-centralizing generation options, such as mobility generators, distributed generation etc. should be considered in long term sense under the background of climate change.

4.4 Conclusion

As a result of climate change, adverse weather will be more frequent and more severe. In order to prevent snow caused power outages, we have investigated the power outage in the Vancouver area in November 2006, and discovered that climate change seriously affected this power outage. By considering all the related cascading processes during this disaster, a systematic solution has been proposed to suppress the development of the disaster as well as to block its propagation along cascading pathways. For similar future snow storms, we believe that, the probability of large-scale power outage can be highly reduced based on our solution.

4.5 Acknowledgment

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Chapter 5

Conclusions

After the September 11th New York attacks, modelling, identification and analysis of interdependencies among critical infrastructures was drawn increasing attention. Affected by a changing global climate, as well as by the advancements and changes in technologies, economics and policies, the organizational structure and relationship of infrastructures are greatly changing. Furthermore, the revolution in information technology has resulted in more interconnected infrastructure networks, with greater centralized instead of distributed control. In fact, the trend towards higher degree of infrastructure interdependency has accelerated these years. More effort should be devoted in studying the important role that interdependencies play in a changing environment, on the continuity and reliability aspects of infrastructure operation as well as on the increased security concerns and risks that might emerge given these hidden interdependencies.

As a system of systems, our interdependent critical infrastructure networks are facing many unexpected events, which may cascade to a large-scale disaster through those interdependency pathways. Various measures can be taken to reduce the frequency of such kind of failures. However, in our current stage, tracking all such interdependencies is too complex, the price of preventing all possible failures may be extremely high, investing on the survival of critical services is more feasible than preventing all large cascading failures. With the physical interdependencies represented by the generalized adjacency matrix (GAM), also based on our previous results [1][2][3], we have proposed a more practical approach—Interdependencies Control Strategy—to respond to a large disaster. This approach can help to manage the interdependencies among the critical infrastructure networks, and, therefore, can improve the survivability of any critical service as well as prevent potential large cascading failures. The proposed strategy is an effective means to reduce the inherent vulnerability of interconnected critical infrastructure networks and to increase their resiliency. For further research in this topic (accurately identifying, modelling and analyzing the complicated interdependencies of our critical infrastructures), information privacy will become the main bottleneck.

Also, as a result of climate change, adverse weather has a high probability to be more frequent, more severe and longer lasting. In order to prevent snow-caused power outages, we have investigated the power outage in the Vancouver area in November 2006 caused by a snow storm and discovered that unusual snow storm date, extended growing season and delayed deciduous time (all climate change related variables) had played an important role in affecting this power outage. By identifying the related cascading processes during this snow storm, a systematic solution has been proposed to stop the development of the disaster, as well as to block its propagation along cascading pathways. For similar future snow-caused power outages, we believe that the probability of large-scale power outage can be highly reduced by our proposed solution. Moreover, the analytical technique developed in this study can also be extended to analyze the 2003 blackout in North America.

The JIRRP team at UBC has taken an initial step in this direction by proposing an ontology and a simulator—I2Sim—to facilitate interdependencies research. But because of the strong nonlinearity and high complexity introduced by the connectivity among the infrastructure networks, interdependencies are still a very difficult problem to analyze. In the real world, many factors, such as interdependencies type, varying environment, coupling degree, response behavior, event type, and system operation state etc. may create complicated challenges to any solution under a specified context. For future study, these directions can be undertaken:

- Developing methods for optimizing the survivability index of an island (SII) according to both the global event spectrum and the interdependencies of local infrastructures;
- Identification of complicated cascading patterns by data mining [4];
- Detecting time-dependent hidden interdependencies with the help of formal verification methods.

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Appendices

Appendix A

Introduction on I2Sim

A.1 Conceptual Framework of I2Sim

One of the goals of JIIRP is to build a simulator on interdependent infrastructures (I2Sim), which is capable of capturing the complex dynamics occurring in a system of multiple infrastructures as cascading events develop during large disaster situations. In which the system modelling and solution approach implemented is based on a time-sensitive coordination of the delivery of tokens (these vital goods and services) required to maximize as well as to keep human survivability. I2Sim models the network of different infrastructures simultaneously.

I2Sim simulator consists of several basic components [1][4], which can be listed as follows:

- Tokens: Tokens are goods or services that are provided by some entity (e.g., manufacturer or distributor) to another entity that uses them.
- Cells: A cell is an entity that performs a function.
- External Sources: Resources brought into the system from outside the system.
- Reserves: Resources available at the cells location.
- channels: Channels are the means by which tokens flow from a resource cell(node) to a consuming cell(node).
- Distributor: A distributor divides the output of a cell to send it to other cells according to distribution factor.
- Aggregator: An aggregator adds up external inputs and internal inputs to produce a total input.

In our multiple infrastructures interdependency simulator (I2Sim), the components of the physical layer, tokens, cells, channels, external sources, reserves, distributors and aggregators etc. are integrated together by two

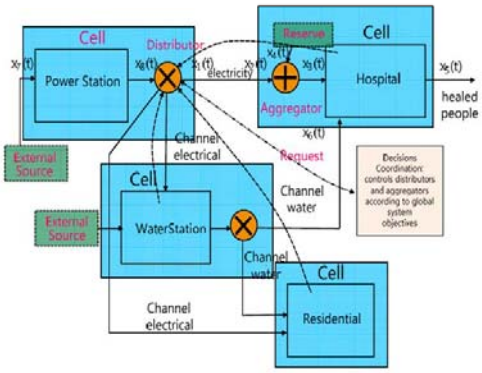

Figure A.1: Instance of cells, channels, reserve, external source, aggregators and distributors by UBC campus case.

layers of operating relationships. The first layer is the cell's functionality, where specific amounts of input tokens are needed to produce specific amounts of output tokens, and this functionality is abstracted from human readable table (HRT, which will be explained in detail in Chapter B). Another layer is the physical (inter)dependencies layer among different cells, since the tokens are delivered through channels from supplying cells and/or external sources to the consuming ones, the topological relationships and the channel characteristics (channel capacity and time delay) will give another set of conditions that must be satisfied. These two layers of functionality can deduce the matrix of transportation (Fig.A.2), where both the cell's operability equation and the global physical linkages are well quantified and represented.

A.2 Clustered I2Sim Integrated into a Single Machine

The previous version of I2Sim was implemented by the five PCs of the 16-machine PC-cluster at UBC power lab, whose topological structure can be seen in Fig.A.4. However, instead of using SCI communication in the pc-cluster distributed model [2](Fig.A.3), here a top system is created at the highest level, which includes the five cells as subsystems, data store memories [3] for global variables are applied to synchronize the five subsystems, and thus integrate the five cells into one single machine (Fig.A.5). This single machine prototype preserve the same properties and dynamical behavior as

$$
\begin{array}{c}
\\ p1 \\ p2 \\ p3 \\ w1 \\ w2 \\ w3 \\ r1 \\ r2 \\ r3
\end{array}
\begin{array}{c}
\begin{array}{ccccccccc} p1 & p2 & p3 & w1 & w2 & w3 & r1 & r2 & r3 \end{array} \\
\left[\begin{array}{ccc|ccc|ccc}
 & \text{Power} & & & & & & & \\
x & x & x & y & & & & & \\
x & x & x & & y & y & & & y \\
x & x & x & y & & & & & y \\
\hline
 & y & & x & x & x & & & \\
y & & & x & x & x & \text{Water} & & \\
 & & & x & x & x & & & \\
\hline
y & y & & & & & x & x & x \\
 & y & y & y & y & & x & x & x \\
y & y & & & y & & x & x & x \\
 & & & & & & & \text{Roads} &
\end{array}\right]
\end{array}
\left[\begin{array}{c} p1 \\ p2 \\ p3 \\ \hline w1 \\ w2 \\ w3 \\ \hline r1 \\ r2 \\ r3 \end{array}\right]
=
\left[\begin{array}{c} Sp1 \\ Sp2 \\ Sp3 \\ \hline Sw1 \\ Sw2 \\ Sw3 \\ \hline Sr1 \\ Sr2 \\ Sr3 \end{array}\right]
$$

Figure A.2: An instance of transportation matrix. Here x refers internal transmission link; y refers interdependency link; p_i (w_i, r_i) refers power (water, road) token value node i; Sp_i (Sw_i,Sr_i) refers power (water, road) source value node $i, i = 1, 2, 3$..

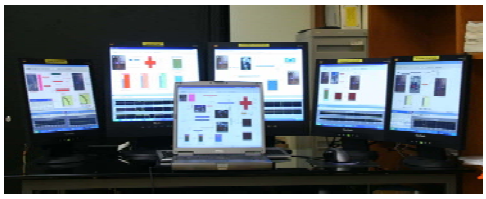

Figure A.3: I2Sim demo illustrated by PC cluster.

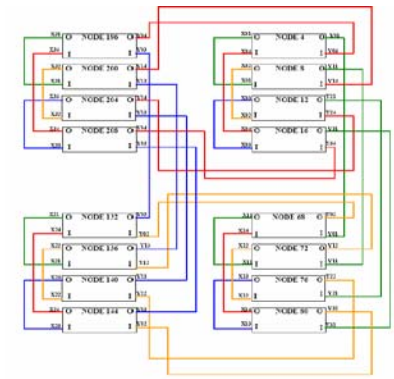

Figure A.4: Topological structure of the 16-PC cluster at UBC power lab.

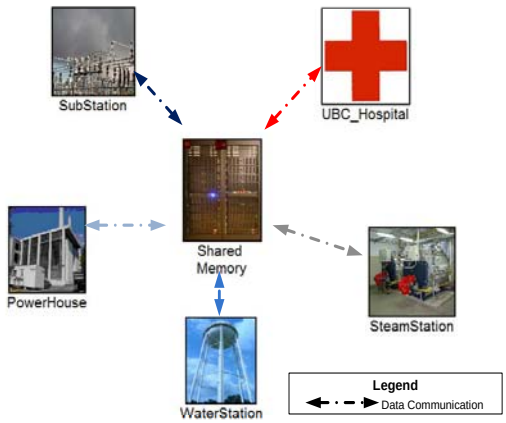

Figure A.5: UBC 5 cell cluster demo integrated into one single machine by global memory synchronization.

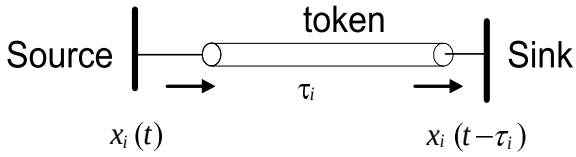

Figure A.6: A typical channel model with delay.

the cluster one, but the HRT table for hospital cell has been replaced by the abstracted function from it. This single machine prototype can conveniently display the design scenarios, with an interactive GUI added, human decision process and related activities can also be integrated in to the system, driven by different events created by human activities, the impacts and effects of human layer on these infrastructures will be unfolded dynamically.

A.3 Modelling Channels with Time-varying Delay

Mathematical Description for the Flow-type Channel: The equation for a typical channel with delay (Fig.A.6) can be expressed as $x(t) = Cx(t-\tau)$, usually $C = 1$. But for a flow-type delay, since in most cases, this type channel's capacity is defined as the volume of flow. Thus for the flow type

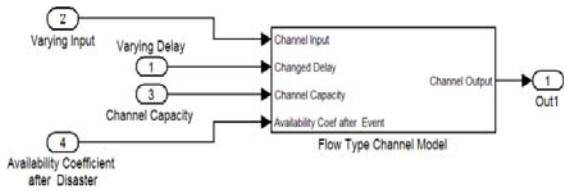

Figure A.7: Overview of the channel model with time-varying delay.

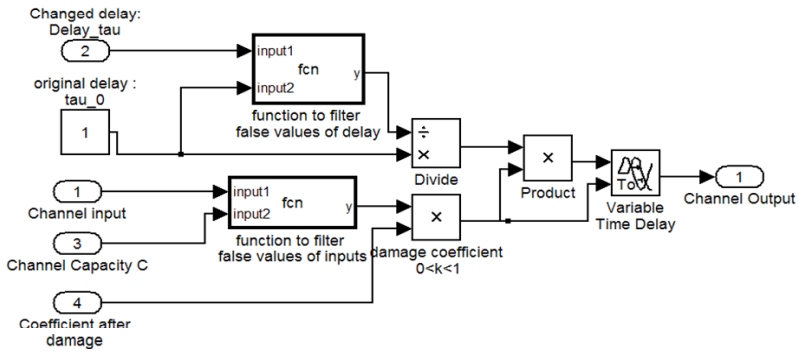

Figure A.8: Detailed internal structure of the channel model by MATLAB Simulink.

channel, the capacity under threshold is proportional to its speed, hence

$$C(\tau) = r.v = r\frac{L}{\tau} = \frac{L\tau_0}{\frac{\tau}{\tau_0}} = C(\tau_0)\frac{\tau_0}{\tau} \tag{A.1}$$

then its transportation equation can be expressed as

$$x(t) = C(\tau)x(t-\tau) = C(\tau)\frac{\tau_0}{\tau}x(t-\tau) \tag{A.2}$$

Where τ_0 is the minimum delay for the channel, as in usual situation $c(\tau_0) = 1$, therefore

$$x(t) = \frac{\tau_0}{\tau}x(t-\tau) \tag{A.3}$$

This channel model with time-varying delay has been implemented by Simulink in MATLAB, the top-level block can be illustrated in Fig.A.7, and detailed subsystem block can be illustrated in Fig.A.8. Where in Fig. A.7, the "Varying Input" block refers to the real time input for the chan-

nel; the "varying delay" block refers to the real time delay for the channel, but emphasis on the delay affected by global event, for instance snow storm that worsen the roads situation. the "Channel Capacity" block refers to the real-time capability of the channel, for instance, in transportation channel case, it refers to the volume of traffic flow; the "Availability coefficient after Disaster" block refers to the left capability of the channel after a damage or a disaster.

A.4 Bibliography

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(http://ieeexplore.ieee.org)

Appendix B

Introduction on HRT Method and GAM Representation

B.1 Continuous Function Representation for Complicated Cells Based on Human Readable Tables (HRT) Method

B.1.1 Introduction

For information privacy and security, for instance, to hide a cell's internal sensitive information that are not publicly accessible, or to protect its critical elements, Dr. Marti proposed the idea of human read tables (HRT) to model a cells' operability.

But for a complicated cell with multi-inputs from different infrastructure networks , in most situations, the interactions among these inputs cannot be modelled in an explicit way, also it is difficult to get enough data to construct a complete HRT. To get the cell's output for any continuously varying input, traditional linear interpolation methods are not applicable, as the data sample in the multi-dimension space is too sparse. To solve these problems, based on theoretical assumptions, I derived a multi-variable nonlinear function to represent the cell's functionality. This function is constructed from the HRT with limited information and it can approximate the cell's I/O behavior within an acceptable fitting gap.

B.1.2 Basic Assumptions and the Derived Formulae

In [1], Adam Smith observed that, without labor division, each pin-maker could make at most 20 pins a day, but with a proper division and combination of their different operations, ten pin-makers could make four thousand eight hundred pins in a day. For these cells with complicated internal struc-

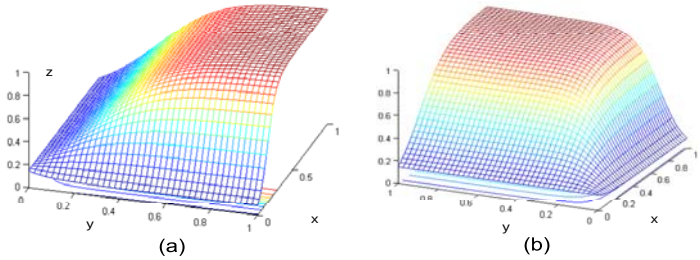

Figure B.1: The ideal multi-dimension fitting function in a 2-D subspace viewed from different angles.

ture and I/O relationship, such as hospital, the hospital cell can be seen as a pipeline from patients to healthy people, with many subsystems as division of labors, similar to the pin-making process, the hospital cell's operability will be improved exponentially as availability of utilities increases (Matthew effect). But because of these physical constraints, such as system scale and other hardware bottle necks (saturation effect), the final operability cannot be infinite, it can be seen as a set of equilibria, which demonstrates the compromised competition between two effects: Matthew effect and saturation effect.

Based on the above analysis, a nonlinear continuous function has been derived to represent the cell's I/O behavior, this function projected on one single dimension in the multi-dimension space can be expressed as

$$f(x, \alpha_0, K_1, x_0) = \frac{\alpha_0}{\alpha_0 + (1-\alpha_0) \cdot e^{-K_1 \cdot (x - x_0)}} \tag{B.1}$$
$$(0\% < x, \alpha_0, x_0, x - x_0 < 100\%).$$

When projected in a 2D subspace, this multi-Dimension fitting function can be seen in Fig. B.1. Where $\{x, y\}$ are inputs, z is the operability of a cell. For more information, the derivation details can be found in [5].

B.1.3 From HRT Data in I2DB to Represent Functions in I2Sim.

As shown in Fig.B.2, this multi-dimension function can be abstracted offline from HRT data, both the HRT data and the abstracted parameters are stored in I2DB, these parameters will be quarried online by the I2Sim simulator, as the function's form is fixed, thus it can easily be recovered by

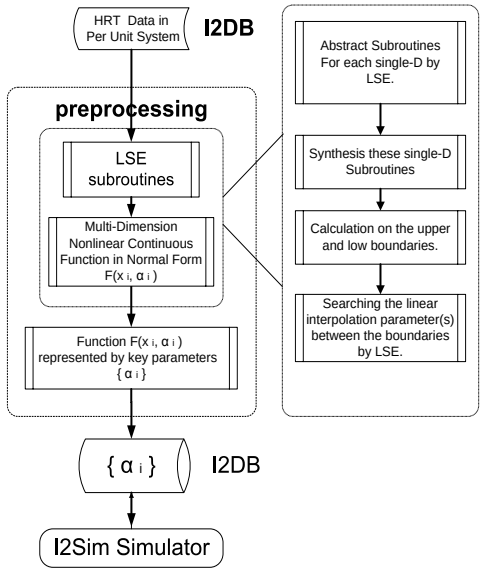

Figure B.2: Flowchart on data processing from I2DB to I2Sim.

the parameters. The simulator and the HRT data that has physical world information are totally isolate, which guarantees a high level of information security, and also improves the computing efficiency greatly.

B.1.4 Multi-dimension Function to Approximately Represent the Operability of Cells Based on HRT

the Multi-dimension efficiency function of hospital in a view of optimism

Usually a convex metric need to be constructed to synthesis these inputting utilities, but in this case, it is obvious that the hospital's efficiency is at least limited by the minimum value of these seven single-dimension functions:

$$E_{opt} = \min\{E(x^0_{doc}), E(x^0_{gas}), E(x^0_{med}), E(x^0_{ele}), E(x^0_{wat}), E(x^0_{stm}), E(x^0_{nurs})\}$$

That's to say, in an optimism view, we can see $E_{opt} = E_{min}$ as a metric of the multi-dimension function of $U_i, (0 \leq i \leq 7)$.

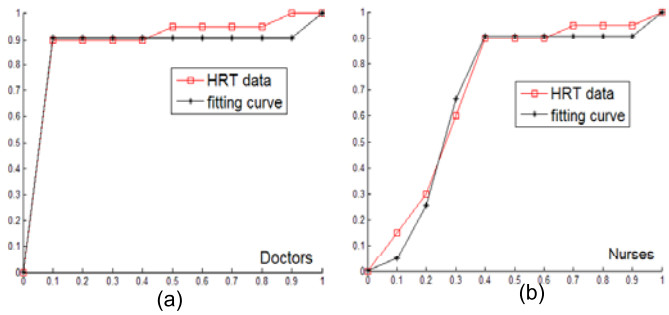

Figure B.3: For the multi-dimension function abstracted from the HRT data of UBC hospital, (a) is the fitted function projected on the nurse dimension; (b) is its projection on the doctor dimension.

B.1.5 Fitting Results for HRT Data from the UBC Hospital

Based on the HRT constructed by L.Liu in [1], a multi-dimension function is abstracted, its fitting results can be seen in Fig.B.3.

B.1.6 Other Aspects about Cell Modelling Based on HRT

- Based on HRT, the more data we get, the more accurate the model and the representing function will be, since these principal parameters can be adjusted in least square error (LSE) sense. But comparing with neural network method, our modelling method doesn't need a large volume of data and thus there is no training process required.(but it requires a minimum support set of data.)

- Assessments over the priority of these inputting utilities are evaluated in the HRT modelling process, it can supply us local vulnerability information for late global analysis.

- By variable reduction and dimension fusion, the dimensions or variables with the similar characteristics will be fused together, therefore this method can reconstruct the multi-dimension function with incomplete information.

B.2 Infrastructure Interdependencies and Their Representation by the Generalized Adjacency Matrix (GAM)

B.2.1 Introduction and Overview

To represent inter/intra interaction relationship through physical interface among these cells in the multi-layer infrastructure networks, so as to do some interdependency related analysis, such as vulnerability assessment and risk assessment etc., in this section, the conception of Semi-certain Adjacency Matrix (SAM), which is usually to represent undirected graph by Boolean variables $\{0, 1\}$ in graph theory, is generalized to represent multi-arc directed graphs (MDG) with loops(feedback graph) by a complex matrix. A physical interdependency or interaction between two cells can be seen as a link in graph theory, with this generalized SAM matrix, interaction can be represented by numbers in the complex field, where logic rules and algebraic operations are also redefined. In this thesis, all related interdependency analysis is based on this matrix representation. By introducing the concept of Strongly Coupled Components (SCC), further topological knowledge about MDG graph, can be calculated explicitly and efficiently. Based on the calculated results of the SCC, critical components, vulnerability assessment, sensitivity analysis can also be obtained. By SCCs identification, splitting strategies among these critical infrastructure networks can therefor be more convincible. Other possible applications based on GAM are also remarked.

B.2.2 Introduction on Interdependency Types

Dependency refers to a linkage or connection between two infrastructures, through which the state of one infrastructure inuences or is correlated to the state of the other. Interdependency refers to a bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other[3].

Interdependencies vary widely, and each has its own characteristics and effects on infrastructure agents. In the sections that follow, four principal classes of interdependencies: physical, cybertical, geographic and policy, will be defined. Although each has distinct characteristics, these classes of interdependencies are not mutually exclusive.

- Physical Interdependency: Two infrastructures are physically interdependent if the state of each is dependent on the material output(s) of

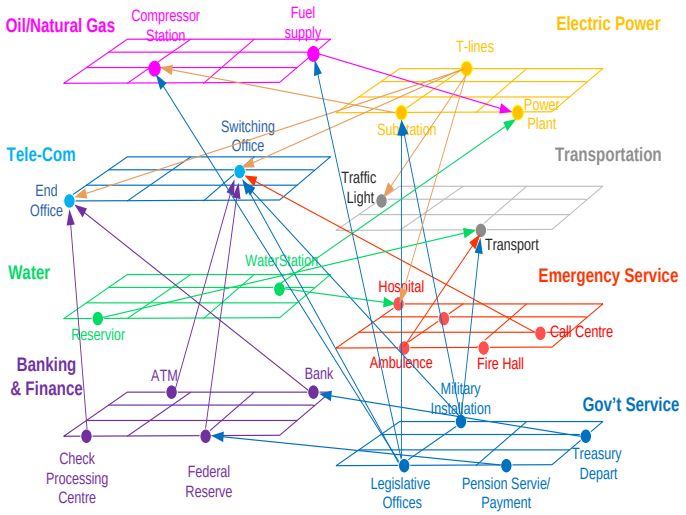

Figure B.4: Infrastructure interdependencies among those critical infrastructure networks.

the other.

- Geographic Interdependency: Infrastructures are geographically interdependent if a local environmental event can create state changes in all of them.
- Cyber Interdependency: An infrastructure has a cyber interdependency if its state depends on information transmitted through the information infrastructure.
- Logical Interdependency: Two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber, or geographic connection.
- Policy/Procedural Interdependency: An interdependency that exists due to policy or procedure that relates a state or event change in one infrastructure sector component to a subsequent effect on another component.

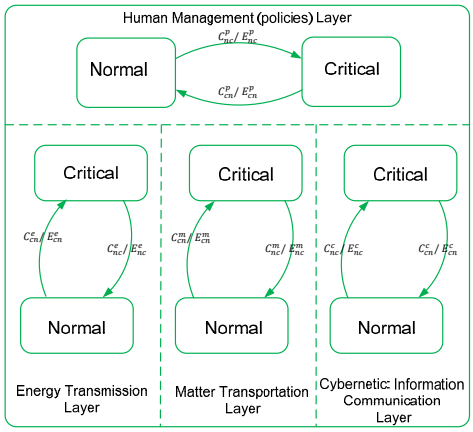

Figure B.5: EMIP: Study space of infrastructure Interdependency Analysis. Which includes four layers: Energy transmission, Matter transportation, Information communication, Policy management.

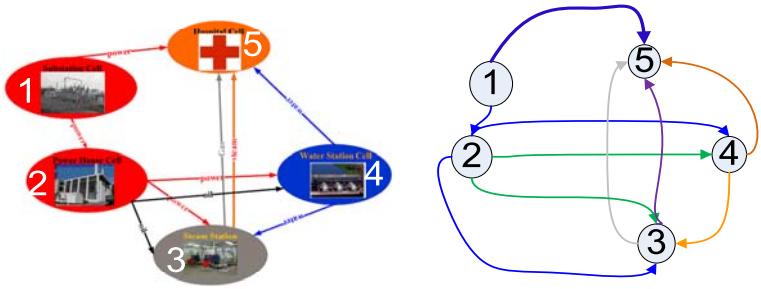

Figure B.6: UBC campus five cell model.

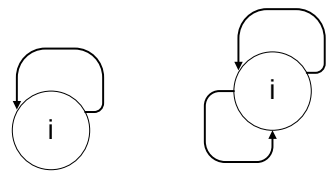

Figure B.7: Instances of self-loop or rings.

B.2.3 Multi-Arc Directed Graph Represented by GAM with Redefined Operation Rules

In Fig.B.6, five cells on UBC campus can be seen as an instance of Infrastructure Interdependency, which is also represented by the following matrix A_{GAM}.

GAM Representation

In a generalized SAM , the connectivity information between vertexes is represented by a complex number, with exiting degree as its real part and entering degree as imaginary part, thus a GAM matrix A_{GAM} is capable to imply that physical interdependency information among infrastructure components.

$$A_{GAM} = \begin{bmatrix} 0 & 1 & 0 & 0 & 1 \\ i & 0 & 2 & 2 & 0 \\ 0 & 2i & 0 & i & 2 \\ 0 & 2i & 1 & 0 & 1 \\ i & 0 & 2i & i & 0 \end{bmatrix}$$

Though it can be presented mathematically by the corresponding diagonal element, self-loop(s) (as in Fig. B.7) of each elements is not practically significant, it is not permitted here, for instance, for order $n = 1$, by definition, diagonal elements of matrix A should be zero, $a_{ii} = 0 (i = 1, \cdots, n)$.

Algebraic operation and logic rules for GAMs

Since the logic rules for the operation on SAM cannot be adopted here directly, I have defined the **multiply operator** $\otimes$ of generalized SAM,

$$B = A^2 = A \otimes A$$
$$b_{ij} = \sum_{k=1}^{n} a_{ik} \cap a_{kj}$$

here b_{ij} is the element of B, and $\sum$ is algebraic "sum" in regular sense. $\cap$ is logic "and" (&) but has a generalized definition as fellows:

$$x \cap y = re(x) \cdot re(y) + i \cdot img(x) \cdot img(y) \tag{B.2}$$

here $re(x)$ denotes the real part of variable x, and $img(x)$ the imaginary part of x. variables like x and y are complex numbers whose real part and imaginary part are all non-negative integers.

Flow chart of the algorithm for searching and compressing SCCs

A directed graph is called strongly connected if for every pair of vertices $\{u, v\}$, there is a path from u to v and a path from v to u. The strongly connected components (SCCs) of a directed graph are its maximal strongly connected subgraphs, that form a partition of the graph B.8. The reason we introduce the conception of SCC here is to reduce the computing complexity of directed graph with pathway cycles in it. When all these cycles are reduced to SCCs, the structure of these different orders of matrix will become simple, and the interdependency relationship between different components or vertices can be more clear and obvious. Otherwise, for the graph with pathway cycles in it, the number representing the length of the pathway can become very large, since the loop in the pathway can repeat itself for arbitrary times.

By finding all these pathways between any pair of components or vertices, GAM can identify or detect the whole possible correlated or affected domain for any components in the system, since all these types of interdependencies can be modelled into GAM. And it is also an exhaustive analysis method instead of a "what if" analysis depended on a certain set of preconditions, theoretically it can supply us more reliable, global and complete results.

By analysis with GAM, for a disaster triggered by a certain type of event, for these infrastructure components that have a higher priority of protection, the index of cascading impact can tell us all the relationship to other in-

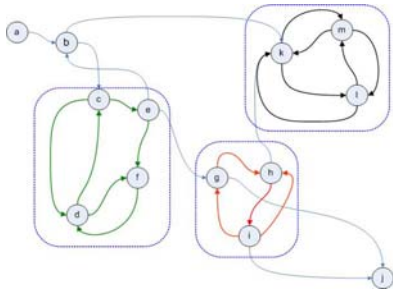

Figure B.8: Graph with strongly connected components (SCCs) marked.

frastructure components, which may give us essential information on where to buffer the cascading failures with the minimum cost. Also for a detailed local interdependencies model, GAM can tell us all these unexpected weaknesses. For instance, during the ice storm in 1998 at NW Canada, a GAM model on this multi-layer infrastructure networks may inform the decision makers the locations of these most vulnerable vertices or which linkage has the highest probability of collapse[2].

The flow chart for the algorithms on searching and compressing SCCs is described in Fig. B.9. An instance for previous algorithms will be displayed in Fig.B.10and B.11.

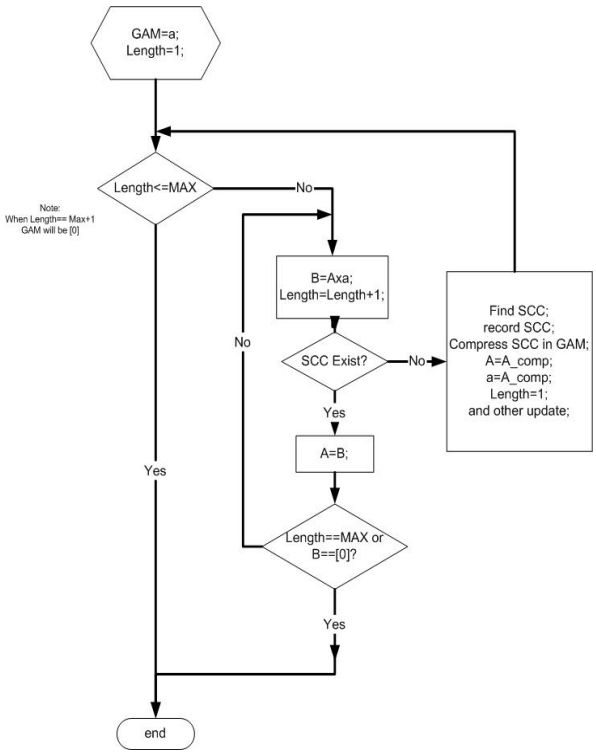

Figure B.9: Flowchart on the searching and compressing algorithm for SCCs.

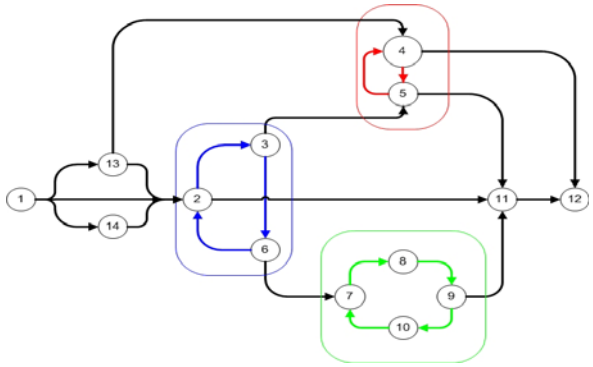

Figure B.10: Strongly connected components (SCCs) identified by GAM computing algorithm.

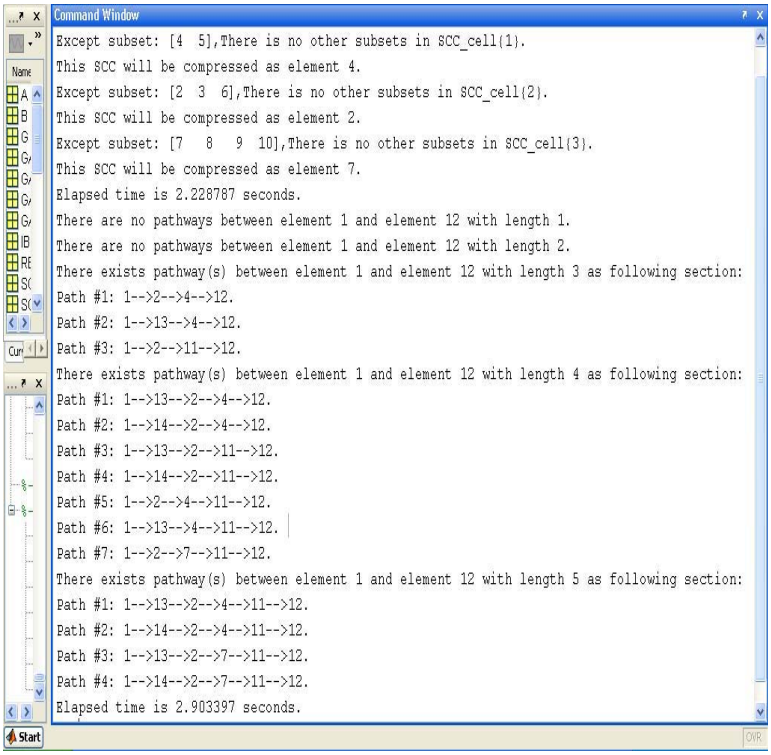

Figure B.11: SCCs and pathways found between vertex 1 and vertex 12 in Fig. B.10.

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Appendix C

Matlab Code for the Library on the Operators of GAM

C.1 A Library of Functions for GAM Operation

Based on the new-definited GAM matrix operation, a library of functions coded in MATLAB has been developed.

Table C.1: Library of Functions for GAM Operation

Function Name	Description
gc_and.m	Generalized "and " for two scalar variables.
gc_multiply.m	Generalized "multiply" for two matrixes.
gc_RC.m	Generalized "multiply" for a two vectors.
Check_SCC.m	Check the existence and identify the SCCs.
setdiagonal.m	Set the diagonal elements to zeroes.
SCC_Compress.m	Compress SCC after calculating them out.
Set_Minus.m	Subtraction between two SCCs and theri subsets.
checkGAM.m	Check whether a matrix is a GAM.
findout_SubSet.m	Find a subsets of SCCs.
Get_subset_SCC.m	Find out all the subsets of SCCs.
Display_SCC.m	Display the subsets of SCCs.
check_GAMcomp.m	Verify the compressed GAM.
Pathway_Finder.m	Find out all the pathways between two elements.
Display_Paths.m	Display all the pathways between two elements.
mainSCC.m	Main program for finding, compressing and displaying both SCC and pathways.
GAM2Lap.m	To convert GAM into Laplacian matrix.
Number_of_Paths.m	To find out how many paths in one connectivity.
InfDomain_of_Cell.m	To find out whole influence domain of a cell.
InfDomain_of_Link.m	To find out whole influence domain of a channel.

C.1.1 Generalized "And"

Description: Generalized "and" for two scalar variables.
Code:

```
function y = gc_and(x1,x2);

if nargin ~ = 2;
        error('Wrong number of input arguments!');
end;

if((round(real(x1)) =real(x1))—(round(real(x2))~=real(x2)));
        error('Error with X1 or X2,one or both of the real parts are not
integer,out of definited value range!');
end;

if((round(imag(x1))~=imag(x1))—(round(imag(x2))~=imag(x2)));
        error('Error with X1 or X2, one or both of the imag parts are not
integer, out of definited value range!');
end;

if (real(x1)<0) | (real(x2)<0) | (imag(x1)<0) | (imag(x2) < 0);
        error('Error with X1 or X2,one or both of the real parts are not
integer,out of definited value range!');
end;

y=real(x1)*real(x2)+i*imag(x1)*imag(x2);
```

C.1.2 Generalized "Multiply" for Matrixes

Description: generalized multiply for two matrixes.
Code:

```
function y=gc_multiply(A,B);

[na,ma]=size(A);
[nb,mb]=size(B);
```

```
if (na~=ma)|(nb~=mb)|(na~=nb)
      error('The matrixs are not square!');
 end;

for i=1:1:na;
        for j=1:1:nb;
              y(i,j)=gc_RC(A(i,:),B(:,j));
        end;
end;
```

C.1.3 Generalized "Multiply" for Vectors

Description: generalized multiply for two vectors.
Code:

```
function y=gc_RC(z1,z2);

    if nargin ~= 2;
         error('Wrong number of input arguments');
    end;

    if (length(z1)~=length(z2))|(length(z1)==0);
        error('Error, they are not equal length column and row!,or null vari-
able!');
     end;

    y=0;

    for i=1:1:length(z1);
         y=y+gc_and(z1(i),z2(i));
    end;
```

C.1.4 SCC Checking and Detecting

Description: Check the existence and identify the SCCs.
Code:

```
function [exist_SCC,SCC]=Check_SCC(A);
```

```
[na,ma]=size(A);
if (na~=ma)|na==1
    error('The matrixs are not square!');
end;

SCC=[ ];
Diag_A=diag(A);
SCC=find(Diag_A);
 [na,nb]=size(SCC);

if na>nb
     SCC=SCC';
end;

[na,nb]=size(SCC);

if (na==1)&(nb>1);
    exist_SCC=1;
else
    exist_SCC=0;
end;
```

C.1.5 Diagonal Elements Resetting

Description: set the diagonal elements to zeroes.
Code:

```
function y=setdiagonal(X);

if nargin ~=1;
    error('Wrong number of input arguments');
end;

[m,n]=size(X);

if (m~=m);
    error('Error with X, it is not a square matrix!');
end;
```

```
for i=1:m;
    X(i,i)=0;
end;

y=X;
```

C.1.6 Compressing SCCs

Description: compress SCC after finding them out.
Code:

```
function y=SCC_Compress(A,SCC)

SCC=SCC(1:end-2);
index=find(SCC~=0);
SCC=SCC(index);
n=length(SCC);

for i=2:n;
    A(:,SCC(1))=A(:,SCC(1))+A(:,SCC(i));
    A(SCC(1),:)=A(SCC(1),:)+A(SCC(i),:);
    A(:,SCC(i))=0;
    A(SCC(i),:)=0;
end;

A(SCC(1),SCC(1))=0;

    y=A;
```

C.1.7 Substraction between SCCs

Description: substraction between two SCCs and their subsets.
Code:

```
function y=Set_Minus(A,B);
```

```
[x1,y1]=wcommon(B,A);

if sum(x1)~=length(x1)
     error('B is not a subset of A.');
end;

position_B=find(y1==1);
A(position_B)=0;
[v,w]=find(A~=0);

    y=A(w);
```

C.1.8 GAM Matrix Checking

Description: Check whether a matrix is a GAM.
Code:

```
function [y, size_A ]=checkGAM(A);

[row, column]=size(A);

if row~=column
      y=0;
 else
      size_A=row;
     y=A-i.*A';
     [n1,n2]=find(y~=0);

    if length(n1)*length(n2)==0
          y_sym=1;
     else
          y_sym=0;
     end;

    realA=real(A);
    imagA=imag(A);
    [n1,n2]=find(realA<0);
    [n3,n4]=find(imagA<0);
```

```
    if length(n1) * length(n2) > 0 | length(n3) * length(n4) > 0
        y_degree=0;
    else
        y_degree=1;
    end;

    if y_sym*y_degree==0;
        y=0;
    else
        y=1;
    end;
end;
```

C.1.9 Subset Detection of a SCCs

Description: detect a subset of a SCC.
Code:

```
function y=findout_SubSet(SCC,path_length,G);

[na,nb]=size(SCC);

if (na =1)&(nb =1)
    error('this is not a SCC.');
end;

if na>nb
    SCC=SCC';
end;

index_nonzero=find(SCC =0);
SCC=SCC(index_nonzero);
y=SCC(1);
length_SCC=length(SCC);

for j=1:length_SCC;
for i=1:length_SCC;
    [n1,m1]=size(find(y==SCC(i)));
    [n2,m2]=size(find(y==SCC(j)));
    if (i =j)&(Circle_Check(SCC(j),SCC(i),path_length,G))& ···
```

```
(Circle_Check(SCC(i),SCC(j),path_length,G)) &(m1==0)&(m2>0)
            y=[y,SCC(i)];
        end;
    end;
end;

    [nr,nc]=size(y);

    if nr>nc
        y=y';
    end;
```

C.1.10 Find Subsets of SCCs

Description: find out all subsets of a SCC.
Code:

```
    function [number_SCC,SCCM]=get_subset_SCC(SCC,path_length,G);

    [na,nb]=size(SCC);

    if na>nb
        SCC=SCC';
    end;

    lengthSCC=length(SCC);

    if length(SCC)==path_length;
        SCCM=[SCC,0,path_length];
    else
        i=0;
        while length(SCC)>2;
            i=i+1;
            subSCC=findout_SubSet(SCC,path_length,G);
            z=[ ];
            l=lengthSCC-length(subSCC);
            z(1:l-1)=0;
            SCCM(i,:)=[subSCC,z,0,path_length];
            SCC=Set_Minus(SCC,subSCC);
```

```
            number_SCC=i;
        end;
end;
```

C.1.11 Display SCCs

Description: display all subsets of a SCC.
Code:

```
function Display_SCC(SCC_cell);

    Length_SCC_cell=length(SCC_cell);

    for k=1:Length_SCC_cell;
        SCC_Matrix=SCC_cellk;
        last_bit=SCC_Matrix(1,end);
        SCC_Matrix=SCC_Matrix(:,1:1:end-2);
        [rn,cn]=size(SCC_Matrix);

        if rn>1;
     str=['There are ',num2str(rn), ' subsets in SCC_cell',num2str(k),'.'];
     disp(str);
        for m=1:1:rn;
            sub_SCC_m=SCC_Matrix(m,:);
            index_nonzero=find(sub_SCC_m =0);
            subSCCm=sub_SCC_m(index_nonzero);
            str=['The No.',num2str(m) ,' Subset of SCC_cell',num2str(k),'
is: [',num2str(subSCCm),'].'];
            disp(str);
            str=['This subset of SCC will be compressed as element ',num2str(subSCCm(1)),'.'];
            disp(str);
        end;
     else
        sub_SCC_m=SCC_Matrix;
        index_nonzero=find(sub_SCC_m =0);
        subSCCm=sub_SCC_m(index_nonzero);
        str=['Except subset: [',num2str(subSCCm),'],There is no other sub-
sets in SCC_cell',num2str(k),'.'];
        disp(str);
        str=['This SCC will be compressed as element ',num2str(subSCCm(1)),'.'];
```

```
        disp(str);
        end;
    end;
    sprintf('\n');
```

C.1.12 Compressed GAM Verification

Description: verify the compressed GAM.
Code:

```
function [no_ring,G,G_ pages]=check_GAMcomp(GAM_comp);

run=1;
path_length=0;
G(:,:,1)=GAM_comp;
A=GAM_comp;

while(run==1);
    B=gc_multiply(A,GAM_comp);
    path_length=path_length+1;
    G(:,:,path_length+1)=B;
    [exist_SCC,SCC]=Check_SCC(B);

    if exist_SCC>0;
        run=0;
        no_ring=0;
     else
        run=1;
        no_ring=1;
    end;

     RB=real(B);
     IB=imag(B);
     [rrb,rcb]=size(find(RB>0));
     [irb,icb]=size(find(IB>0));

     if (rcb*rrb)==0 & (icb*irb)==0;
        run=0;
     end;
```

```
    A=B;
end;

    G_ pages=path_length;
```

C.1.13 Find Out All Pathways

Description: find out all the pathways between two elements.
Code:

```
    function [exist_path, paths]=Pathway_Finder(element_i,element_j,path_length,GAM_record);

    [cn,rn,pn]=size(GAM_record);
    exist_path=real(GAM_record(element_i,element_j,path_length));

    if exist_path==0| path_length<0 | path_length>pn ;
         exist_path=0;
         paths=[ ];
         disp(['There are no pathways between element ',num2str(element_i),...
' and element ',num2str(element_j),' with length ',num2str(path_length),'.']);
     else
        exist_path=1;
        disp(['There exists pathway(s) between element ',num2str(element_i),...
' and element ',num2str(element_j),' with length ',num2str(path_length),' as
below:']);
     end;

    if path_length==1
        exist_path=real(GAM_record(element_i,element_j,path_length));
        path=[element_i,element_j];
    end;

    while (path_length>1);
         Ics=find(real(GAM_record(element_i,:,path_length-1))>0);
         element_j_temp=[];
          [rn1, cn1]=size(element_j);

         if rn1*cn1>0;
          [rn,cn]=size(element_j(:,1));
```

```
 end;

    if (rn1*cn1>0)&(rn*cn>0);
     for k=1:1:rn;
         Jcs_k=find(real(GAM_record(:,element_j(k,1),1))>0);
        Jcs_k=Jcs_k';
    if length(Jcs_k)>0;
     common_element_position=wcommon(Ics,Jcs_k);
     common_elements=Ics(common_element_position);
     z=[];
     for l=1:length(common_elements);
         z=[z; common_elements(l),element_j(k,1:end)];
     end;
    element_j_temp=[element_j_temp; z];
     end;
  end;
element_j=element_j_temp;
end;
path_length=path_length-1;
end;

  [rn,cn]=size(element_j);

  element_ii=ones(1,rn)*element_i;

  paths=[element_ii; element_j']';
```

C.1.14 Display All Pathways

Description: display all the pathways between two elements.
Code:

```
  function Display_Paths(paths,GAM);

  [rn,cn]=size(paths);
  str=[ ];
  for i=1:rn;
     for j=1:cn
         if j==1;
```

```
                head=(['Path ♯ ',num2str(i),': ',num2str(paths(i,j))]);
                str=[str,head];
            else if j==cn;
                str=[str,'->',num2str(paths(i,j)),', '];
                    else str=[str,['->',num2str(paths(i,j))]];
            end;
        end;
    end;

   numb_path=Number_of_Paths(paths(i,:),GAM);
    str=[str,'totally ', num2str(numb_path), ' paths.'];
    disp(str);
    sprintf('\ n');
    str=[ ];
    sprintf('\n');
    sprintf('\n');
end;
sprintf('\n');
```

C.1.15 Main Function

Description: Main program to find, compress and display SCCs and pathways.

Code:

```
    tic;
    clear;
    clc;
    format rat;
    global GAM;
    GAM=
            [0,1,0, 0,0,0, 1,0,0, 0,0;
            j,0,1, 0,j,0, 0,0,0, 0,0;
            0,j,0, 1+j,0,0, 0,0,0, 0,0;
            0,0,1+j, 0,1,1, 0,0,0, 0,0;
            0,1,0, j,0,0, 0,0,0, 0,0;
            0,0,0, j,0,0, 0,j,0, 1,0;
            j,0,0, 0,0,0, 0,1+j,1, 0,0;
            0,0,0, 0,0,1, 1+j,0,1+j, 0,0;
            0,0,0, 0,0,0, j,1+j,0 0,0;
            0,0,0, 0,0,j, 0,0,0, 0,1;
```

```
            0,0,0, 0,0,0, 0,0,0, j,0;];
[GAM_criteria,sizeA]=checkGAM(GAM);

    if GAM_criteria==0;
        error('The matrix is Not a GAM!');
    end;

    run=1;
    element_number=sizeA;
    path_length=1;
    A=GAM;
    a=GAM;
    GAM_comp=A;
    G(:,:,1)=a;
    SCC_counter=0;

    while (run==1)&(path_length¡element_number);
        B=gc_multiply(A,a);
        path_length=path_length+1;
        G(:,:,path_length)=B;
        RB=real(B);
        IB=imag(B);
        [rrb,rcb]=size(find(RB>0));
        [irb,icb]=size(find(IB>0));

       if (rcb*rrb)==0 & (icb*irb)==0;
            run=0;
        end;
       [exist_SCC,SCC]=Check_SCC(B);

       if exist_SCC>0;
           SCC_counter=SCC_counter+1;
            [number_SCC_SubSet, SCCM]=get_subset_SCC(SCC, path_length,G);
           SCC_cellSCC_counter=SCCM;
           SCCM_subset_no=0;

           while number_SCC_SubSet>=1;
               SCCM_subset_no=SCCM_subset_no+1;
               GAM_comp=SCC_Compress(GAM_comp,SCCM(SCCM_subset_no,:));
                number_SCC_SubSet=number_SCC_SubSet-1;
```

```
            end;

            a=GAM_comp;
            A=GAM_comp;
            path_length=1;
            G=[ ];
            G(:,:,1)=GAM_comp;
            else
                A=B;
            end;
        end;

        Display_SCC(SCC_cell);

        [no_ring,GAM_record,path_length]=check_GAMcomp(GAM_comp);

        for p=1:path_length;
        [exist_path, paths]=Pathway_Finder(1,11,p,GAM_record);

        if exist_path;
            Display_Paths(paths);
        end;
    end;
toc;
```

C.1.16 GAM Converter

Description: covert GAM matrix to Laplacian matrix.
Code:

```
function y=GAM2Lap(x);

[isGAM,size_A]=checkGAM(x);

if isGAM
     error('The matrixs is not a GAM!');
end;
y=x;
```

```
for i=1:1:size_A;
    for j=1:1:size_A;
        c=find(x(i,:) =0);
        y(i,c)=-1;
       y(i,i)=length(c);
    end;
end;
```

C.1.17 Pathway Number

Description: find out how many paths in one connectivity.
Code:

```
function y=Number_of_Paths(path,GAM);
if length(path)<2;
 y=0;
   else if length(path)==2;
     y=GAM(path(1),path(2));
     y=abs(y);
    else if length(path)>2;
        la=path(1:1:end-1);
        lb=path(2:1:end);
        y=1;
    for i=1:1:length(la);
        y=y*GAM(la(i),lb(i));
     end;
     y=abs(y);
    end;
end;
end;
```

C.1.18 Cell's Domain

Description: find out the influence domain of a cell.
Code:

```
function cell_set=InfDomain_of_Cell(cell_i,GAM_record);
```

```
[rn,cn,page]=size(GAM_record);
cell_set=[];

for i=1:1:page;
    A=GAM_record(cell_i,:,i);
    c=find(A =0);
    cell_set=union(cell_set,c);
end;
```

C.1.19 Channel's Domain

Description: find out the influence domain of a channel.
Code:

```
function cell_set=InfDomain_of_Link(cell_i, cell_j, GAM_record);

link=GAM_record(cell_i,cell_j,i);

if real(link)>0
    cell_i=cell_j;
end

    [rn,cn,page]=size(GAM_record);
    cell_set=[ ];

for i=1:1:page;
     A=GAM_record(cell_i,:,i);
     c=find(A =0);
     cell_set=union(cell_set,c);
end;
```

Appendix D

Publications

[1]Detao Mao, Peng Zhang, Hafiz Abdur Rahman, and Jose R. Marti, "Nonlinear Oscillations Caused by Periodic Disturbance between Inter-area Power Systems", *Electric Power Conference, 2008. EPEC 2008. IEEE Canada*, Vancouver, B.C., Canada, Oct, 2008.
(http://ieeexplore.ieee.org)

[2]Hafiz Abdur Rahman, Mazana Armstrong, DeTao Mao, and Jose R. Marti, "I2Sim: A Matrix-partition based Framework for Critical Infrastructure Interdependencies Simulation", *Electric Power Conference, 2008. EPEC 2008. IEEE Canada*, Vancouver, B.C., Canada, Oct, 2008.
(http://ieeexplore.ieee.org)

[3]DeTao Mao, Mandana Sotoodeh, Kafui Monu, Jose R. Marti, and K. D. Srivastava, "Interdependencies Control—Compensation Strategies on the Inherent Vulnerability of Critical Infrastructures ", *the IEEE 2nd Climate Change Technology Conference (CCTC 2009)*, CANADA. (accepted)

[4]DeTao Mao, Jose R. Marti, and K. D. Srivastava, "Mitigating Snow-caused Blackouts on the Cascading Pathways", *2009 IEEE International Conference on Technologies for Homeland Security (HST '09)* (accepted)

[5]DeTao Mao, Jose R. Marti, and K. D. Srivastava, "Survival from Disaster by Interdependencies Management", *International Journal of Emergency Management* (to be submitted)