AN INFORMATION MODEL FOR INFRASTRUCTURE INTERDEPENDENCIES

by

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Bachelor of Computing, Queen’s University, 2005

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MASTER OF SCIENCE

In the School of
Interactive Arts and Technology

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ABSTRACT

One of the key problems in critical infrastructure (CI) interdependency visualization is that the interdependency information from different resources needs to be shared and understand as a whole, so it is necessary to support a visual common ground from interaction across all CI organizations, managers and planners.

The objective of this thesis is to propose a comprehensive information model for developing shared visualization of CI interdependencies. In the Infrastructure Interdependencies Coordination (I2C) project of the Joint Infrastructure Interdependencies Research Program (JIIRP), this information model aims to support the graph-based dependency view of the Infrastructure Interdependencies Simulation (I2Sim) system. The University of British Columbia (UBC) five-cell test case is used as the example problem. A walkthrough of the 2006 UBC campus power shortage scenario demonstrates how the information model might be applied to support practical problems from three user perspectives: planning, analysis and reaction.

Keywords: critical infrastructure interdependencies, interdependency visualization, knowledge capture, I2C JIIRP.
To my family!
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CHAPTER 1: INTRODUCTION

1.1 Background

Critical infrastructures (CI) are defined as the “physical and information technology facilities, networks, services and assets” that provide critical support to “the health, safety, security or economic well-being” of a nation (Public Safety Canada, 2009). In modern societies, critical infrastructure sectors such as electricity, water, telecommunication, transportation and medical services are highly interconnected and mutually dependent. Disruption of one infrastructure sector can be felt widely and interact with many other infrastructure sectors. Eventually these disruptions can cause large-scale damage.

On August 14, 2003, a massive power outage occurred throughout most of the Northeastern and Midwestern regions of the United States and Canada. In the province of Ontario, Canada, traffic lights, subways and streetcars were shut down. Large numbers of factories and businesses were forced to close or reduce production. Food, water, and fuel supply and distribution were delayed. Communication, banking and government services were interrupted. All hospitals shifted into emergency response mode. Surgeries were cancelled and health services were scaled down. According to Public Safety Canada, about 50 million people were affected during this power failure (Public Safety Canada, 2006).

“The relationship of influences that an element in one infrastructure impacts upon another infrastructure” is also known as critical infrastructure interdependencies.
(Dudenhoeffer, Permann & Manic, 2006, P480). Recent natural and man-made disasters, such as the September 11, 2001 terrorist attacks, the 2003 northeast blackout, the Asian tsunami as well as Hurricane Katrina, have made the protection of critical infrastructures a pressing challenge in emergency management. People in emergency management have realized that failure to understand the dynamics underlying the different infrastructures will result in ineffective responses, poor coordination, and the mismanagement of both resources and rescue teams. Therefore, it is crucial to identify, understand and manage infrastructure interdependencies for the preparation of the response and recovery phases of emergency management.

There are two major difficulties in understanding CI interdependencies. CI interdependencies are often “unintended and unplanned” (Martí, Hollman, Ventura & Jatskevich, 2006a). They can be influenced by a variety of factors, including the physical condition of a system, resource allocation, information flow and human activity. Some of them are hidden from apparent view and hard to predict, and some of them are not discovered until afterwards. For example, most critical infrastructure sections have backup generators in case of power breaks, so during the 2003 blackout, the assumption was that they were fine. However, it turned out that the power outages disrupted the transmission of fuel to the generator because the fuel pumps or the transportation systems had broken down. Had the power blackouts continued, it would have been a big problem. As emergency management often requires timely and close coordination across different infrastructures, unexpected or hidden interdependencies ignored by emergency planners and infrastructure managers can cause emergency response plans to fail to function properly and effectively.
Another problem is knowledge sharing between different infrastructures. In a disaster, stakeholders are always coming from different industrial and professional areas of expertise. They have very different and sometimes incomplete understanding of the situation because of their domain specific knowledge and experience backgrounds, such as data formats and representations, concerns and priorities, vocabularies and visual lexicons (Bartram & Pottinger, 2007).

In recent years, a large number of exercises and research efforts have been undertaken to deal with this problem. Approaches include the development of comprehensive modeling and simulation systems to study the impact of decision making across infrastructures (Pederson, Dudenhoeffer, Hartley & Permann, 2006), the development of conceptual models – ontologies – to improve semantic interoperability between infrastructures for emergency management (Kruchten et al., 2007; Mendonca & Wallace, 2007; MacEachren et al., 2006), as well as emergency operation exercises to enhance coordination and formalize emergency procedures across critical infrastructures, and government and non-government organizations (Zerger, 2003; UBC EOC exercise plan, 2005). While these approaches provide the necessary steps to improve the communication flow and identify interdependencies between different infrastructures, the resultant interdependency information gathered from different resources is not easily shared and understood as a whole. Since different representations greatly affect people's understanding and their ability to communicate effectively across different infrastructures, it is necessary to support a visual common ground for interaction across all CI organizations, planners and managers. What is truly needed is a common set of
information criteria that can be shared and understood across multiple infrastructures, rather than simply a combination of every stakeholder’s input and details.

As a result, I am interested in addressing the problem of knowledge sharing in emergency management from the perspective of CI interdependency visualization. I propose a comprehensive information model to assist in the development of CI interdependency visualization tools, which can then support the formation of shared understanding across different infrastructures.

This motivation for the study of CI interdependency visualization to support knowledge sharing in emergency management was derived from the development of the Infrastructure Interdependencies Simulation (I2Sim) system within the Joint Infrastructure Interdependencies Research Project at the University of British Columbia (JIIRP at UBC, also called I2C).

1.2 Overview of JIIRP at UBC (I2C)

The Joint Infrastructure Interdependencies Research Program (JIIRP) was funded by the Natural Sciences and Engineering Research Council (NSERC) and Public Safety Canada (Department of Public Safety and Emergency Preparedness). Six Canadian universities participated in this program. The research project conducted by the University of British Columbia is called the Infrastructure Interdependencies Coordination (I2C). It is a multidisciplinary project that investigates systematic approaches to modeling critical infrastructure interdependences in order to assist emergency managers in making better decisions.
One of the main focuses of the I2C project was to develop the software simulator I2Sim to achieve both time-domain simulation and visualization of disaster scenarios affecting large scale systems of infrastructure. The simulator was developed by the I2C engineering team. They used a cell-channel model approach to model multiple physical infrastructures (Martí et al., 2006b). I2Sim comprehensively simulates the conditions of each infrastructure component (cells, channels, input and output tokens) within disaster scenarios. Users of the simulator, such as emergency planners and infrastructure managers, will be able to watch the simulation through an user interface and explore how disruptions or decisions can affect the entire infrastructure network.

A number of subgroups work together to support the functionality of the I2Sim simulator, which includes I2DB (integration of the simulator with the database), I2VIS (visualization), I2Dam (damage assessment), and I2GIS (integrated GIS system for damage and trace back visualization).

The UBC Campus case is a small scale dataset currently used by the I2C team to build the I2Sim simulator prototype. The modules are shown in Figure 1-1.
1.3 Objectives of this Thesis Research

This thesis research is part of the I2VIS research work. In the I2C project, the I2VIS team is responsible for designing the external user interface and solving CI interdependency visualization problems associated with the modeling and simulation system. The objective of this research is to study how interdependencies between critical infrastructure systems can be represented in a way that facilitates communication among infrastructure managers and emergency planners and helps them make better decisions. A comprehensive information model is proposed for developing a shared visualization of CI interdependencies among multiple critical infrastructures under the UBC test case scenario setting.
1.4 Research Questions

My research questions are:

1) What kinds of CI interdependency information should be visually represented to facilitate knowledge sharing?

2) What visualization requirements should be introduced in this information model in order to support shared visualization of interdependencies?

The I2C's approach is to support CI visualization with both graph based and geospatial based representations. In this thesis, the research efforts are focused on the information model of the graph based view.

1.5 Thesis Structure

The rest of the thesis is organized as follows. Chapter 2 provides a background review of emergency management, infrastructure interdependency and related research areas on dependency visualization. Chapter 3 presents the motivation and goal of my research. The design of the information model is described in Chapter 4. Here, I define the data dimensions of CI interdependency for the UBC test case, and then analyze the visualization requirements for the graph based dependency view. I discuss the important features of the dependency view with both design considerations and implications. In Chapter 5, I walk through a real user case to show how the information model extends to the typical simulation model in the UBC test case. In Chapter 6, I further discuss how the information model might support emergency management work from three user perspectives: planning, analysis and reaction. The research contribution, limitations and future work are summarized in Chapter 7.
CHAPTER 2: BACKGROUND

2.1 Introduction

This chapter will first provide an overview of emergency management by focusing on the requirements of emergency response. Then, I will introduce the basic concept of critical infrastructure interdependency. This chapter will also discuss issues related to the visualization of infrastructure interdependency.

2.2 Emergency Management

Emergency management is "the discipline and profession of applying science, technology, planning and management to deal with extreme events that can injure or kill large numbers of people, do extensive damage to property, and disrupt community life" (Drabek & Hoetmer, 1991). In the past six decades, the practice of emergency management has changed from an essentially reactive and response focused civil defence approach to a more comprehensive and integrated approach. Comprehensive emergency management refers to "the responsibility and capability of a political component (nation, state, and local area) to manage all types of emergencies and disasters by coordinating the actions of all relevant players" (Britton, 2001). The "comprehensive" aspect refers to four major phases of emergency management cycle: mitigation (or risk reduction), preparedness (readiness), response and recovery (Perry 1985; Britton 1999, 2001; Haddow & Bullock, 2003).
According to Perry (1985), the activities in the four phases are described as follows:

**Mitigation** – Deciding what to do where a risk to the health, safety, and welfare of society has been determined to exist; and implementing a risk reduction program;

**Preparedness** – Developing a response plan and training first responders to save lives and reduce disaster damage and the development of necessary agreements among responding agencies, both within the jurisdiction and with other jurisdictions;

**Response** – providing emergency aid and assistance, reducing the probability of secondary damage, and minimizing problems for recovery operations; and

**Recovery** – providing immediate support during the support system to minimum operation levels, and continuing to provide support until the community returns to normal. (Perry, 1985, p.3)

Disaster management stakeholders are people who have direct involvement in responding and dealing with emergency situations (Montoya-Morales, 2002). Emergency management usually requires that all essential services and utilities coordinate in real-time to reduce death, injuries and damage to communities. The decision-making often involves expertise in a variety of backgrounds (such as policy, operations, engineering, and command control) and from all aspects of the society (nongovernmental organizations, government agencies and private sectors). (Britton, 1999; Abdalla, 2006).

### 2.2.1 Emergency Response

Emergency managers and first responders need to act decisively within tight time schedules, often with incomplete information and/or with too much data from which it is difficult to extract relevant information. At the same time, they often have to overcome diversity in the knowledge and background of participating stakeholders as well as cooperate with stakeholders from other domains. This means that individuals within the
emergency management system are under more pressure to: “absorb information rapidly; judge its sense, its meaning, its relevance, and its reliability; decide what the options for action are and make effective decisions; and deal with plans that were prepared with little knowledge of the reality” (Carver & Turoff, 2007, p. 34). Practical and research exercises have shown that effective information systems that provide timely access to comprehensive, relevant, and reliable information are critical (Van de Walle & Turoff, 2007), and that the human role in emergency response systems must be considered (Carver & Turoff, 2007).

Research on emergency response information systems goes back several decades. The first emergency response system, EMISARI (Turoff, 2002), was designed as a communication system and used for the 1971 Wage Price Freeze crisis. Over the next ten years, EMISARI was used for assorted crisis events such as strikes, energy source shortages and natural disasters. Ever since then, the use of information and communication technology (ICT) has progressed in all phases of emergency management; however, “the objectives remain the same in crises: providing relevant communities collaborative knowledge systems to exchange information” (Turoff, 2002, p.29). Due to experiencing and learning from recent disasters, many researchers have become aware of the importance of the human factor in emergency management systems.

Carver and Turoff (2007) discuss the design challenges for human-computer interaction in emergency management systems. The authors point out the importance of having a user-centered, systematic approach with a major emphasis on user requirements. They conclude that the human role in emergency response information systems should not be neglected: “the human is part of the system, the computer is part of the team, and
both the computer and the human work with other people and other computer systems in other agencies, sharing information and working together to manage the crisis, mitigate its effects and to support the victims after the event” (Carver & Turoff, 2007, p. 38).

2.3 Infrastructure Interdependency

2.3.1 Critical Infrastructures

Canada’s critical infrastructures are those physical and information technology facilities, networks, and assets, which, if disrupted or destroyed, would have a serious impact on the health, safety, security or economic well-being of Canadians, or the effective functioning of governments in Canada. The ten major infrastructure sectors in Canada identified by Public Safety Canada (2009) are:

1) Energy and Utilities (e.g., electrical power, natural gas, oil production and transmission systems)
2) Communications and Information Technology (e.g., telecommunications, broadcasting systems, software, hardware and networks including the Internet)
3) Finance (e.g., banking, securities and investment)
4) Health Care (e.g., hospitals, health care and blood supply facilities, laboratories and pharmaceuticals)
5) Food (e.g., safety, distribution, agriculture and food industry)
6) Water (e.g., drinking water and wastewater management)
7) Transportation (e.g., air, rail, marine and surface)
8) Safety (e.g., chemical, biological, radiological and nuclear safety, hazardous materials, search and rescue, emergency services, and dams)
9) Government (e.g., services, facilities, information networks, assets and key national sites and monuments).
10) Manufacturing (e.g., chemical industry)
2.3.2 Infrastructure Interdependency Taxonomies

Advances in science and technology have made critical infrastructures increasingly automated and interconnected. “The relationships or influences that an element in one infrastructure imparts upon another infrastructure” are known as *infrastructure interdependencies* (Dudenhoeffer, Permann & Manic, 2006, p. 480). In order to clarify the interrelationship among multiple infrastructures, researchers have been trying to identify and describe the interdependencies between different categorizations:

2.3.2.1 Interdependency Type

Interdependencies can be very different, and each has its own characteristics and effects on infrastructures. Several taxonomies have been proposed to categorize the types of interdependencies.

Rinaldi, Peerenboom, and Kelly (2001) describe interdependencies in terms of four general categories:

- Physical – a physical reliance on material flow from one infrastructure to another;
- Cyber – a reliance on information transfer between infrastructures;
- Geographic – a local environmental event that affects components across multiple infrastructures due to physical proximity; and
- Logical – a dependency that exists between infrastructures that does not fall into one of the above categories.

Dudenhoeffer, Permann and Boring (2006) propose a slightly different categorization of infrastructure interdependency types:

- Physical – direct linkage between infrastructures as from a supply/consumption/production relationship;
• Informational – a binding or reliance on information flow between infrastructures;

• Geospatial – co-location of infrastructure components within the same footprint; and

• Policy – a binding of infrastructure components due to policy or high level decisions.

Bartram and Pottinger (2007) expand the taxonomy developed by Rinaldi et al. (2001). Consideration of the impact from human activity and the flow of resources is included:

• Physical - elements of the physical environment that depend on other elements (e.g. power lines, water mains, substations, communication towers).

• Resource - goods/services that are needed.

• Information - decisions depend on having the right information from other sources.

• Role - coordination of decisions depend on the right people being in the right place.

• Activity/event - this refers to the situation where actions/events cannot take place until another action/event has occurred.

The “geographic” type is not included in this categorization, since Mendoca, Lee and Wallace (2004) have presented a more comprehensive categorization to describe interdependency conditions.

2.3.2.2 Interdependency Criteria

Bühne et al. (2003) define the following dependencies through the discussion of dependencies in feature modeling for use cases.

• Requires-dependency – the binding of one object implies the need of another object, e.g., a required following;
• Exclusive-dependency – the binding of one object excludes the selection of another object;
• Hints-dependency – the binding of one object has some positive influence on another object;
• Hinders-dependency – the binding of one object has some negative influence on another object.

Mendoca et al. (2004) define the criteria for determining whether an interdependency exists: an infrastructure is interdependent on one or more infrastructures if any of the following four conditions hold:

• Input - the infrastructure requires one or more services as input from another infrastructure in order to provide a service;
• Shared - some physical components and/or activities of the infrastructure used in providing the service are shared with one or more infrastructures;
• Exclusive-or - either the infrastructure or some other infrastructure (but not both) can be in use during provision of the service;
• Co-located - two or more infrastructures’ physical components or activities are co-located within a prescribed geographical region.

2.3.2.3 Domain and Interdependency Direction

McNally, Lee Yavagal, and Xiang (2007) classify interdependencies according to their domains and directions. An interdependency can be intra-domain or cross-domain, and can be uni-directional or bi-directional, and direct or indirect.

• intra-domain interdependencies: interaction within a critical infrastructural system;
• cross-domain interdependencies: interactions among multiple infrastructures
• Unidirectional: A depends on B
• Bi-directional: A depends on B and B depends on A. (Unidirectional functional interdependency can turn into bi-directional during a catastrophic event.)
• Direct: object A immediately relies on B, and/or B immediately relies on A;
• Indirect: there are one or more mediating objects in between object A and B

2.3.2.4 Dimensions of Infrastructure Interdependency

Including the types of interdependency, Rinaldi et al. (2001) conceptualize the interrelated factors and system conditions of critical infrastructure interdependencies in terms of six dimensions:

1) Types of Interdependencies
2) Infrastructure Environment
3) Coupling and Response Behaviour
4) Type of Failure
5) Infrastructure Characteristics
6) State of Operation

A summary of the different categorizations proposed by Rinaldi et al. (2001) and other researchers is presented below.
<table>
<thead>
<tr>
<th>Categorization Criteria</th>
<th>Sub-components</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of Interdependencies</td>
<td>Physical; Cyber; Geographic; Logical</td>
<td>Rinaldi et al. (2001)</td>
</tr>
<tr>
<td></td>
<td>Physical; Informational; Geospatial; Policy</td>
<td>Dudenhoeffer et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Physical; Resource; Information; Role; Activity/event</td>
<td>Bartram and Pottinger (2007)</td>
</tr>
<tr>
<td>Infrastructure Environment</td>
<td>Economic and business; Public policy; Legal and regulatory; Health and safety; Technical, Security; Social and political</td>
<td></td>
</tr>
<tr>
<td>Coupling and Response Behavior</td>
<td>Adaptive; Inflexible; Loose; Linear/complex</td>
<td>Rinaldi et al. (2001)</td>
</tr>
<tr>
<td>Type of Failure</td>
<td>Cascading; Escalating; Common cause</td>
<td></td>
</tr>
<tr>
<td>Infrastructure Characteristics</td>
<td>Organizational; Operational; Temporal; Spatial</td>
<td></td>
</tr>
<tr>
<td>State of Operation</td>
<td>Normal; Repair/Restoration; Stressed/Disrupted</td>
<td></td>
</tr>
<tr>
<td>Interdependency Criteria</td>
<td>Requires-dependency; Exclusive-dependency; Hints-dependency; Hinders-dependency</td>
<td>Bühne et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Input; Shared; Exclusive-or; Co-located</td>
<td>Mendoza et al. (2006)</td>
</tr>
<tr>
<td>Domain</td>
<td>Intra-domain and cross-domain</td>
<td></td>
</tr>
<tr>
<td>Direction</td>
<td>Unidirectional and bi-directional; Direct and indirect</td>
<td>McNally et al. (2007)</td>
</tr>
</tbody>
</table>
2.3.3 Critical Infrastructure Interdependency Model and Simulation

Recently, various innovative approaches have been taken to develop models that accurately simulate critical infrastructure behavior and identify interdependencies and vulnerabilities. In 2006, a survey of the U.S. work as well as international work on critical infrastructure interdependency modeling was completed by the researchers of the U.S. Technical Support Working Group and the Idaho National Laboratory (Pederson et al., 2006). This survey identified and described ongoing research in the area of infrastructure interdependency modeling and analysis. These modeling approaches included agent-based modeling, effects-based operations (EBO) models, input-output models, models based on game theory, mathematical models, models based on risk.

The cell-channel model adopted by the I2Sim simulator of the UBC JJIRP project is based on the idea of service token delivery to different infrastructure entities (Martí et al., 2006a; Martí, 2007). The system space is conceptualized in terms of the following basic components (Figure 2-1).

- Cells (Production components): an entity that requires inputs and produces outputs (e.g., a substation, a hospital).
- Tokens: resources or services that are provided by one entity to another entity that uses them (e.g., water, power, medicines).
- Channels (Transportation components): the means by which tokens flow from the output of a cell to the input of another cell (e.g., water pipes carry water from the water station to the hospital).
- Nodes: a cell or a group of similar cells separated by time or distance
- Dispatching components (Decision components): determine resource allocation during scarcity.
The I2Sim simulator simulates the conditions of each infrastructure component (cells, channels, input and output tokens) of large disaster scenarios to help support decision making as well as to mitigate the disaster effects.

2.4 Visualizing Interdependencies

CI interdependencies are complex networks across multiple infrastructures. A well-designed visual representation of CI interdependencies will help users better understand problems and identify vulnerabilities. Therefore, while the modeling and simulation work provides the initial step for establishing an underlying functional model of the interdependency network, how people operate these systems is crucial to visualize the network effectively.

Generally, with relationships among data elements, interdependencies can be classified as spatial connections and logical connections. CI interdependencies such as
the physical and resource types are spatial connections while the information, role and activity/event types are logical connections.

There are two main categories of representations in interdependency visualization: geo-spatial and graph. Geo-spatial representation is often used to model spatial connections, such as roads and pipelines in maps and GIS. Graph representation can be used for both spatial and logical connections. It is widely used in a variety of domains, such as the logical dependencies in software visualization as well as both spatial and logical connections among entities in knowledge visualization. Because the field of infrastructure interdependency is fairly new, graph visualization approaches and techniques have rarely been systematically studied for use in representing infrastructure interdependency. In this section, I will review graph visualization models that are applicable to representing interdependencies, as well as the tools and approaches that have been used to model interdependencies in related fields.

2.4.1 General Graph Visualization Models

Dependencies are typically represented in a graphical form such as a dependency diagram. As a popular output format generated by many software tools, dependency diagrams are essentially directed graphs where each node in the graph represents some element or aspect of a system whereas an edge from one node to another signifies a dependency of the first element on the second.

In graph theory, there are two standard ways to represent a graph $G = (V, E)$: as a collection of adjacency lists or as an adjacency matrix. Either way is applicable to both directed and undirected graphs (Cormen, 2001).
**Adjacency list** - Each vertex has a list of which vertices it is adjacent to.

**Adjacency matrix** - An N by N matrix, where N is the number of vertices in the graph. If there is an edge from vertex x to vertex y, then the element $M_{x,y}$ is 1, otherwise it is 0.

The adjacency-list representation requires a small memory space. It is usually preferred for *sparse* graphs, where $|E|$ is much less than $|V|^2$. An adjacency-matrix representation provides faster search of edges but requires a large memory space, so it may be preferred for *dense* graphs, where $|E|$ is close to $|V|^2$.

![Diagram](image)

(A) directed graph G having six vertices and eight edges. (b) An adjacency-list representation of G. (c) The adjacency-matrix representation of G.

Figure 2-2 Two representations of a directed graph (Cormen, 2001)

In the next section, general graphical based layout and navigation techniques will be reviewed in order to understand possible models for representing infrastructure interdependency.
2.4.1.1 Graph Layouts

In graph visualization, a dependency diagram might be displayed through a variety of layouts. The structure could be hierarchical or arbitrary. Because CI interdependencies often involve loops and multiple links among objects, the structure is more likely to be arbitrary. Layouts such as tree-based structures that only represent hierarchy are not ideal choices for CI interdependencies.

2D Layout

1) Radial Layout

With radial layout, the view of a graph is determined by the selection of a single node as the center of interest, or focus. The focus node is usually placed at the center of the display, with the other nodes spreading out around it. The straightforward method, such as the "radial drawing" in (Di Battista et al., 1999) arranges nodes on concentric rings around the focus node. Each node lies on the ring corresponding to its shortest network distance from the focus. Immediate neighbors of the focus lie on the smallest inner ring, their neighbors lie on the second smallest ring, and so on.

Even if a graph is small enough to display everything at once, it can be difficult to understand all of the relationships from only a single view. The advantage of a radial layout is that it provides an interactive exploration of sub-regions of the graph. The ability to interactively view a graph from different perspectives can yield new insights.

2) Manhattan Layout

The Manhattan layout (Sander, 1996) is also called the orthogonal layout. In Manhattan layouts, all edges consist of sequences of line segments which have a strict
horizontal or vertical orientation. It is widely used in VLSI design. The Manhattan layout helps reduce edge crossings while keeping the drawing looking organized.

3) Spring layout

Spring layout refers to all nondeterministic layout techniques, and is also called Force-Directed Methods. It was first proposed by Eades (1984) in a graph drawing. Spring layout models nodes and edges of a graph as physical bodies tied with springs. It has been used successfully to produce well balanced layouts for graphs. In some cases, it can help to minimize edge-crossing without any supplementary efforts (Frick, Ludwig and Mehldau, 1994). In general, however, spring layouts may be highly unpredictable. Two different runs of the algorithm on identical graphs might produce different layouts. This makes them less interesting for visualizing CI dependency since unpredictability could be a large drawback for interaction.

4) Edge bundles

Edge bundles (Holten, 2006) can be used in conjunction with existing tree visualization techniques. It provides an intuitive and continuous way to control the strength of bundling and helps to reduce visual clutter.

3D Layout

Compared to 2D, 3D displays have advantages when displaying large structures. The extra dimension makes it possible for user to navigate and find a view without occlusions. To display graphs in 3D, the simplest approach is to generalize classical 2D layout algorithms for 3D, such as the 3D radial tree and the information Cube (Rekimoto & Green, 1993). However, 3D also brings new problems: objects in 3D can occlude one
another and it is not always easy to find the best view in the 3D space. Therefore, enough visual cues, such as transparency, depth queuing, etc, must be included in the display.

Although some graph layout techniques such as the cone tree (Robertson, Mackinlay & Card, 1991; Carriere & Kazman, 1995) and navigating systems such as the Perspective wall (Robertson, Card & Mackinlay, 1993), VizNet (Fairchild, 1993), Vitesse (Nigay & Vernier, 1998), and Web book (Card, Robertson and York, 1996) have been developed directly for 3D, 3D graph visualization still has significant difficulties. According to Herman, Melancon and Marshall (2000), the main reason is the inherent cognitive difficulties (Ware, 2004) of 3D navigation in our current system. Perceptual and navigational conflicts are caused by the discrepancy of using 2D screens and 2D input devices to interact with a 3D world, combined with missing motion and stereo cues. Limited 3D interaction, such as the ability to rotate an object for inspection without getting closer to it, may provide 3D interaction that doesn’t cause disorientation. Some of these difficulties may be solved by using advanced VR–like systems such as Workbench, CAVE, or large tiled displays. However, such facilities are not widely available and are still too expensive to serve as a basis for most information visualization applications.

2.4.1.2 Techniques for Representing Context

The problem of large sized graphs in visualization cannot be solved simply by graph layouts. Navigation and interaction facilities help to reveal the structure of a graph.

Zoom and Pan

Zooming is the “increasing magnification of a decreasing fraction of a two-dimensional image under the constraint of a viewing frame of constant size” (Spence, 2001, p.130). Panning is the “smooth movement of a viewing frame over a two-
dimensional image of greater size" (Spence, 2001, p.130). Panning offers the viewer a transmission of the location being viewed and zooming offers the ability to see the details. Together, they provide users the choice of navigating between local details and a global overview (Spence, 2001).

Focus + Context

If there are too many objects and relationships among data elements, visually representing the information all at once may create a complex graph that is impossible to read. Focus+context graphs are designed to relieve the load on working memory by linking overview with detailed information. To make the graph simple, only some key pieces of information are presented on the global view. When the user is focusing on a specific object, contextual information around the object of primary interest is presented in full detail. According to Herman et al. (2000), a well-known problem with zooming is that while zooming to a specific area, contextual information is often lost. With a separate window open, it is possible to keep the context visible, but the connection between contexts is often weak. Such a loss of context can become a considerable usability obstacle. The focus+context technique does not replace zoom and pan, but it helps viewers to focus on detail without losing the context.

Focus+context techniques have been implemented and explored by researchers in different directions. Fisheye distortion is one of the most popular approaches. It imitates the well-known fisheye lens effect by enlarging an area of interest and showing other portions of the image with successively less detail. Some techniques, such as the Continuous Zoom (Dill et al., 1994; Bartram et al., 1995) distort a data representation, giving more room to the points of interest and decreasing the space given to the region
away from those points. Elements of the graph are dynamically repositioned and resized based on the point of interest selected by the user. Selected nodes are expanded to show their contents, while unselected nodes are shrunk or clustered. CZWeb (Fisher et al., 1997) is a web application developed based on this idea of Continuous Zoom. It creates a fish-eye view that allows viewers to see details of partitions without losing the surrounding context.

Clustering

Clustering improves the clarity of a layout by reducing the number of visible elements being viewed. Various “abstraction” and “reduction” techniques can be applied to clustering. Most of them are structure-based clustering, which uses only structural information to perform clustering. Content-based clustering uses semantic data associated with graph elements, and it requires application-specific data and knowledge.

There are many ways to represent clustered elements, such as ghosting, hiding or grouping (Herman et al., 2000):

- Ghosting: deemphasizing nodes, or relegating nodes to the background.
- Hiding: simply not displaying the unselected nodes. This is also referred to as folding or eliding.
- Grouping: grouping nodes under a new super-node representation.

Figure 2-3 Different schematic views of a tree: (a) ghosting, (b) hiding, and (c) grouping (Herman et al., 2000)
2.4.2 Software Dependency Visualization

In software visualization, dependency diagrams appear in many different forms including module structure charts, call sequence diagrams, entity-relationship diagrams, flow charts, finite state machines, menu trees and Petri nets. According to the research survey of Koschke (2003), graphs are the dominant way used in software visualization when conveying information.

In recent years, many commercial and research graph layout tools have been developed, but most of them address the problem of graph layout only. The major problem of dependency visualization is not about graph layout, but how to represent the semantic meaning of nodes and edges, and how to support interactive functions which provide appropriate user control over the observation and analysis process.

One of the few studies that focus specifically on this area is by Smart (1994). The author points out that a major problem of software dependency visualization is that dependency diagrams carry semantic information that cannot be captured in a purely graph theoretical model. This is because the information associated with each node and the meaning implied by each edge can only be assigned and interpreted within the context of the system at hand.

2.4.2.1 A-Vu model

The A-Vu mode (Smart, 1994) is a software dependency visualization model. The model is constructed as a unified model for effectively capturing complex system dependency information in a manner which is conducive to visualization. The foundation of the model is the directed graph representation of dependencies. Each system element is represented as a node and each dependency as an edge. Visualization mechanisms, such
as layout and visualization space, are built upon the graph representation. The layout defines the position of each node on a graph and the visualization space defines the positions of each node and edge in a design space. Visualization space in this model can be continuous, discrete or hybrid. The introduction of visualization space enables users to examine the dependency structure in a variety of new ways, breaking away from strictly planner-based organizations. The domain, semantic information is incorporated in the graph diagram through the modeling of node attributes (e.g. procedural, implementation, visible), auxiliary node attributes (e.g. name, location, contents), edge attributes (e.g. implied, restricted, inherited) and auxiliary edge attributes (e.g. parameters, rules), graphically represented with various predefined types, shapes and sizes of nodes and edges. To reduce the number of nodes in a graph, the A-Vu model allows collections of graph nodes to be collapsed into a single composite node. This process can be recursively applied with multiple levels of nesting. The concept of composite configuration is introduced to address the inheritance of attribute configuration within composite nodes.

The A-Vu model supports a series of user controls over complex system explorations. The seven functional operation groups are: initialization, editing, selection, arrangement, reduction, compaction and archival. Some of these groups are also applicable to visualizing the dependencies of critical infrastructures, such as:

- Relationship selection: select all nodes based on the relation (dependent nodes or the nodes dependent upon, directly or indirectly) to the specified set of nodes
- Attribute selection: locate a specific set of elements given an attribute associated with the nodes and edges
- Degree selection: locate nodes which possess a specific value of degree (numbers of dependencies associated with the node).
• Arrangements: Process hierarchical, layered, breadth-first, depth-first, or horizontal layouts over a set of nodes and edges.
• Reduction: simplify the graph by hiding or compositing nodes and edges.
• Compaction: adjust current visualization space to make nodes located in close proximity.
• Archival: allow a configuration specification to be stored for later access or loaded from previous access.
• Data display of the A-Vu model can be processed from a variety of perspectives, such as filtering and defining viewing parameters.

2.4.2.2 SHriMP

SHriMP (Simple Hierarchical Multi-Perspective) (2008) is a sophisticated graph layout toolkit designed for visualizing and exploring software architecture and other information spaces. SHriMP supports navigation from various perspectives, such as call graph, package dependency via method call, class hierarchy, etc, to support different requirements of exploration. Users can also customize a view based on any of the predefined views.

SHriMP provides three zooming modes for navigating software structures: zoom mode (geometric), magnify mode (semantic) and fisheye mode. Users can easily click buttons to switch between these modes while they browse the details of each software’s hierarchy. Under the magnified zooming mode, the particular zoom-in view being displayed depends on the configuration of the selected node. For example, if the focused node represents a java package, the node may display its children (packages, classes, interfaces). A node representing a class or method may display the corresponding source code. Different graph layouts, such as radical, tree, and treemap can be applied to the sub-components of a selected node on any hierarchy levels. This feature takes advantage
of graph layouts in displaying and organizing dependencies, while minimizing the problem of a large graph size by zooming into the particular area that interests the user. This forward and backward function allows users to undo or redo previous operations. Under a call graph or hierarchy view, selecting a node will also highlight all the in-coming and out-coming links connected to this node. This feature is very useful when the graph size is large. Functions associated with a node or edge, such as hide/show, group/ungroup, can be selected from the menu shown by right clicking. SHriMP provides the ability to manually group nodes into composite nodes (which can be labeled and documented accordingly) and to filter node and arcs based on type and other selection criteria.

2.4.2.3 Tom Sawyer Analysis

Tom Sawyer Analysis (2008) is a commercial JAVA toolkit for developing graph analysis applications. The applications provide various clustering, graph traversal, path, dependency, impact, root cause, and network analysis tools. Users can choose parameters such as start and finish node, range, desired flow, and more. Results can be displayed in different modes (e.g. cost, capacity or flow) by showing the value associated with a path. A combination of color and width of path is used to represent the capacity value. Animation effects are applied to show the direction of flow.
2.4.3 Knowledge Visualization

2.4.3.1 Concept Mapping

A concept map is a knowledge model used to summarize a body of knowledge on a topic. Typically, each node represents a concept, and an arc between two nodes represents a relationship between two concepts. There have been many concept map based tools, such as CmapTool (2008), SMARTideas (2008), Mindmanager (2008), Analyst’s Notebook (2008) and ConceptVista (2008) Among them, Mindmanager is for text based and tree structured data; Analyst’s Notebook are mainly for visualizing connections; and ConceptVista is an advanced ontology based on concept map tools.

Concept mapping is a tangible way to visually represent an idea, process, and the relationships between concepts. Concept map tools with collaborative features usually contain both individual view and group view options. Users can either work individually or collaboratively on their knowledge construction. Work completed in the individual
view can be selectively posted to the group view. This function provides experts with a common ground for constructing and sharing their knowledge from different backgrounds. It is ideal for the brain-storming and pre-planning stages of collaborative tasks. Unfortunately, current concept mapping tools are still restricted to being concept map editors only. They seldom provide dynamic functions such as filtering and path tracing; therefore, they cannot fulfill the need of visualizing infrastructure interdependency.

2.4.3.2 Causal maps

Causal maps are the most traditional way to represent cause-effect relations. A causal map is a directed diagram in which ideas and actions are causally linked with one another through the use of arrows. Causal concepts are represented as the nodes in the network, and causal relationships are represented as the arrows between the nodes. Bayesian causal maps are advanced causal maps which combine causal maps and Bayesian network techniques to add dynamic features to causal maps (Figure 2-5). Recent research shows that causal maps can be used as feasible tools to represent the domain knowledge of decision-makers (Ackermann & Eden, 2005; Chaib-draa, 2002; Darais, Nelson, & Reich, 2002; Nelson, Nelson, & Armstrong, 2000).
2.5 GIS and CI Dependency Visualization

Geographic Information Systems (GIS) play an increasingly important role in emergency management because of its ability to manage and display large volumes of assessment and geospatial data, and assist in planning emergency operations (Martí et al., 2006b). Geospatial information is a fundamental component of CI dependency visualization. Most physical infrastructure dependencies, such as roads, water lines, and power lines, are represented as lines on maps. For visualizing infrastructure data, GIS supports robust functions for layering and displaying physical dependencies with a geospatial reference, such as scale, terrain and environment information. GIS also provides a planning base for collaborative decision making among stakeholders, because
the unique geospatial references help to avoid decision making ambiguity (Zerger and Smith, 2003).

In spite of the above advantages, impediments still exist with the practical utilization of GIS in emergency events. Zerger and Smith (2003) conducted a field study on the application of GIS, based on a real-time emergency management disaster scenario held in Mackey City, Australia. Results from observations and interviews showed that crisis managers still prefer to discuss emergency tasks around large paper maps (made by GIS analysts prior to real events) rather than computer-based map displays. In response to an emergency situation, emergency managers were more concerned with temporal resolution (e.g. general movement of people and vehicles) than spatial resolutions (e.g. spatial precision and high spatial resolution). For regional scale decision making, computer displays can not provide regional views with necessary local scale details due to the restriction on screen size. User perceptions and comments from the survey have depicted desktop-based crisis management GIS as “cumbersome or difficult to be used by decision-makers directly”, “incapable of answering questions in acceptable time-frame”, “lack of spatial and temporal relevancy”, and “difficult to share information with others”.

These findings revealed a major problem in emergency management: a lack of understanding of “the unique operational constraints on human interaction with geospatial information inherent within the context of crisis response” (Cai, Sharma, MacEachren, Rauschert, & Brewer, 2006). To solve the problem, a comprehensive framework for human-computer interaction must be developed to bridge the gap between our knowledge about human constraints, and technological solutions (Cai et al., 2006, Muntz et al., 2003).
Cai et al. (2006) proposed a framework with three principle constraints for understanding human interactions with geospatial information: immediacy, relevancy, and sharing. **Immediacy** refers to the timeless constraint of crisis response. System-generated information must be provided in a timely manner to assist emergency management work. **Relevancy** is concerned with how well the content and form of presented information fit the needs of decision-makers. **Sharing** refers to the needs of group members when they share workspace and awareness and deal with complex emergency situations and coordinating actions. It is an extremely challenging task to fulfil all three requirements in one design solution.

MacEachren et al. (2006) defined the role of visual signification in supporting group work with geospatial information. Visual signification can be used as: shared *objects to talk about* (as the object of collaboration), shared *objects to think with* (as components of group knowledge and thinking), and shared *objects to coordinate perspectives and actions* (to coordinate group activity).

DAVE\_G (Dialogue-Assisted Visual Environment for Geoinformation) (Cai et al., MacEachren & Cai, 2006) is a prototype GIS environment with a large screen display which allows risk managers to interact with a GIS map display through dialogue and gesture. DAVE\_G uses the three roles of visual signification: the GIS map on the large screen as the shared view of the situation, to talk about and think with, and the dialogues and gestures to coordinate group activity.

The geocollaboration application (Schafer, Ganoe & Carroll, 2009) also supports coordination of emergency planning with a shared view. The system interface consists of a public team view and a role-specific individual view (Figure 2-6). The map on the left
is the public team view, which displays the mouse cursor locations of others. The map on the right is a role-specific environmental view with two floodplains and a river highlighted. Private work on individual views can be selectively posted to the public view. On the public view, users can collaboratively edit the map data and immediately see updates from each other.

Figure 2-6 A geocollaboration application (Schafer, Ganoe & Carroll, 2009)

GeoTime (Kapler and Wright, 2004; GeoTime, 2009) is a 3D GIS platform for temporal analysis of geo-referenced data. The platform integrates temporal and spatial visualization into one visual space. Events are constructed within an X,Y,Z coordinate space (Figure 2-7). The X,Y plane represents geographic space and the vertical Z axis
represents time. As time moves forward, individual frames of movement are transferred into an animation of events in the 3D space. GeoTime enables the visualization and tracking of movements, events and relationships over time and space in a single view, which helps analysts gain insight into data, reveal interconnections between data, and indentify patterns of behaviors.

![Figure 2-7 GeoTime 3D space](image)

### 2.6 Visualization Techniques in Current Research on Infrastructure Interdependency

#### 2.6.1 Chajrabarty and Mendonca’s Visual Model

Chajrabarty and Mendonca (2004) proposed a graph-based visual model of CI interdependencies, which intended to help infrastructure managers optimize restoration, allocate resources and trace disruption impact. This model represents infrastructure systems as a network of nodes and links. Nodes represent infrastructure components of demand, supply or transhipment (such as a telephone pole, power generation plant or a switching station). Links represent channels which deliver service or products (such as a power line). Properties of nodes include locations, temporal behaviours, physical characteristics, status and organizations. Properties of links include the direction of
transfer, rate of transfer, duration, capacity and content. The authors suggested denoting the properties of nodes and links with various visual codes (such as shape, color, darkness, etc). Figure 2-8 and Figure 2-9 shows an example of using this model to visualize interdependencies between telecommunication and power infrastructures.

Figure 2-8 Model visualization (normal state) (Chajrabarty and Mendonca, 2004)
Figure 2-9 Model visualization (after disruption) (Chajrabarty and Mendonca, 2004)

Figure 2-8 depicts the normal state. Shapes of nodes are used to represent different unit functions: square – transmission service, circle – utilization, hexagon – monitoring units. Icons denote the infrastructure sectors, e.g. a lighting symbol as power. The bar below a node indicates the current operating level. The number on the right of the bar represents the capacity of the unit. The style of line ends are assigned based on the interdependency criteria: arrows for input, dots for exclusive-or and bullets for shared. Figure 2-9 depicts the state of the system after a power disruption. The effected nodes are all colored black (100% dark scale) to help users trace the source of problems. The authors also suggested using a sound or flashing node as alarms to alert the decision makers when a certain failure happens.
2.6.2 CIMS

Critical Infrastructure Modeling System (CIMS) (Dudenhoeffer et al., 2006) is a modeling and simulation framework which supports 3D interactive visualization for infrastructure interdependency analysis. The nodes and edges of the infrastructure network are geo-referenced by latitude, longitude, and altitude and displayed as spheres and lines in the 3D visualization. Colors are assigned according to the state or characteristic of infrastructure elements. Cascading effects of infrastructure disruptions can be observed through multiple views. Figure 2-10 shows a CIMS model of infrastructure components surrounding a facility. The first view shows the consequence of losing a power breaker in the infrastructure network. The second view shows a diametric view of the structure. The affected components are colored with yellow in these views.
Loss of one of the main breakers at an electrical distribution substation, resulting in a loss of power to half the facility.

Figure 2-10 Multiple views of CIMS model visualization (Dudenhoeffer et al., 2006)

The interactive environment of CIMS also supports “what if” analyses. The user can choose to modify the state of specific nodes or edges to see the domino effect, e.g. shut down a substation or disable a power line. Through creating a baseline script, the user can also combine multiple events to observe and analyze the result.
2.6.3 IME

Integrated Modeling Environment (IME) (Tolone et al., 2004) is a framework that provides an analysis of impact across multiple infrastructures. Features of IME visualization are GIS environments supported by ArcGIS and an intelligent agent-based system. Users can issue a “what if” analysis by modifying infrastructure features and viewing the impact through the GIS visualization. Figure 2-11 presents an example of a “what if” analysis. The user initiates the simulation by disabling a small segment of the power distribution. The disabled section is highlighted on the display (Figure 2-11 (a)). The impact of the change is simulated by the system and rendered by the GIS network. Figure 2-11 (b) shows the downstream impact on power distribution, and Figure 2-11 (c) shows the cross-infrastructure impact on gas distribution. Figure 2-11 (d) shows the downstream gas distribution.
Figure 2-11 An example of IME "what if" analysis (Tolone et al., 2004)

The GIS environment of IME also supports elevated rendering of multiple infrastructures with the disabled sections extruded on the top. Figure 2-12 presents a three-dimensional, extruded rendering of three infrastructures (gas, electrical power and transportation – top to bottom).
Figure 2-12 IME three-dimensional, extruded rendering (Tolone et al., 2004)

Figure 2-13 shows an ArcScene-based IME display of infrastructure network layers. The disabled sections are extruded and the vertical links represent the cross-infrastructure interdependencies.

Figure 2-13 ArcScene-based IME display (Tolone, 2006)
2.6.4 IEISS

The "Interdependent Energy Infrastructure Simulation System (IEISS)" (2009a) is designed to assist interdependency analysis of energy infrastructures. Visualization facilities of IEISS include both 2D and 3D GIS displays (Figure 2-14). Figure 2-15 shows an IEISS 3D view. Colors and layers are assigned to different infrastructures. The horizontal links represent inner-infrastructure connections and the vertical links represent cross-infrastructure connections.

Figure 2-14 IEISS user interface (Interdependent Energy Infrastructure Simulation System (IEISS), 2009b)
2.6.5 Summary

The GIS map is the most commonly used technique for CI visualization. Different infrastructure sectors are often represented via layers of color, and 2D and 3D maps are generated with displays of statistical results. In a graph display, flow or capacity is usually represented with the width of the link. Dependency type is represented with colors, and nodes are assigned a combination of color and shape to represent different infrastructure components.

2.7 Collaboration and Common Ground

Because of the complex interdependency between major infrastructures, the planning, response and recovery phases of crisis management normally require collaboration between the work of people from different infrastructures. This
collaboration, to a large extent, depends on the communication among the different stakeholders. In order to capture the flow of communication, researchers have put large efforts into modeling the interdependences amongst critical infrastructures. However, in some cases, the linkages and interdependences are unintended and unplanned (Martí et al., 2006a), which can hardly be fully modeled; some expert knowledge remains only in the mind and cannot be explicitly documented with data and procedures. The diversity of domain expertise also causes communication impediments. In an actual disaster, different stakeholders often have very different and incomplete understandings of the situation. The truth is, planners and managers from different infrastructure usually only work with their own people: they have different concerns and priorities, they use different visualization tools to process and represent data, and they have different terminologies and visual conventions. To bridge the gap and capture interactive knowledge amongst infrastructure domains, a common ground for interaction is required to show a common context between stakeholders across different infrastructures (Bartram & Pottinger, 2007).

The concept of “common ground” has been explored in many disciplines including linguistics and online social environments. It is “the context created by collaborators due to their mutual awareness of each other’s experiences, expertise and knowledge, and current cognitive, emotional, and physical states”, and it “includes one’s ongoing activities, including the people and objects with which one is interacting” (Chuah & Roth, 2003). This concept is also applicable to the field of collaborative visualization. Chuah and Roth suggested that collaborative visualization systems could help people communicate and coordinate their activities by establishing common ground.
CoMotion (Chuah & Roth, 2003) is a collaborative visualization environment for creating information analysis and decision-supporting applications. Figure 2-16 shows an example of the CoMotion desktop. The left side is a commander view where the commander can assign key questions and task areas, as well as check each member's progress. The triangles and rectangles represent intelligence sightings and units. The diamonds denote the assertions added by team members. This view can be shared with team members to show the intention of the commander. The right side of the desktop is a set of frames showing the workspaces shared by each of the team members.
Figure 2-16 An example of the CoMotion desktop (Chuah & Roth, 2003)
Based on their research with CoMotion, Chuah and Roth summarized a set of common ground features:

- **Explicitly shared objects and events**: the central focus of a communication which people can directly refer to;
- **Implicitly shared objects and events**: surrounding physical cues that people can jointly perceive in physical spaces but are often missing from electronic spaces;
- **Goals for analyzing objects and events**: people’s task and interests;
- **Interpretations and thoughts**: The meaning and patterns perceived by the collaborators;
- **Level of attention on the objects**: people have different attentional focus. Awareness of others’ attention helps to reveal additional information such as priorities and changes;
- **History of objects**: who created them, who else is aware of them, whose expertise has contributed to their interpretation and whose goals and tasks are served;
- **People’s emotional reactions and personal characteristics**.

Chuah and Roth suggested that collaborative visualization should not only support sharing of explicit data, but should also try to make other elements of common ground visible.

**2.8 Issues of CI Interdependency Visualization**

As discussed in the previous section, to understand CI interdependency and to evaluate and seek useful content, emergency planners and infrastructure managers need visual tools to bridge the gaps in information sharing. Previous research focused mostly on system control and individual domains. The idea of using interdependency visualization to support the sharing of understanding and decision making needs further exploration.
2.8.1 Layout

Critical infrastructure is a complex network of highly interconnected and mutually dependent components. Visualizing the interdependencies between these components is firstly a problem of viewing a large space of information (complex network) on a small screen, which is not only a problem in dependency visualization but also a key issue in graph visualization. Besides that, the scope of infrastructure domains and the hierarchical structure of CI components create even higher requirements for CI visualization. CI visualization integrates data from many different infrastructure sectors into a shared visual space. The shared representation of CI interdependencies must be easily understood by different infrastructure managers, and must provide overview, directions and start points the moment users want to access details in certain infrastructures. In other words, the visualization must provide an overview as well as a level of detail according to their needs.

Graph layout is the most widely used format for representing dependency. Software visualization models such as SHriMP and Tow Sawyer Analysis provides users with a choice of different graph layouts. The knowledge visualization tool, ConceptVista (2008), uses a spring layout to minimize edge-crossing when displaying complex networks of ontologies. These approaches make the layout more flexible according to various inputs of data as well as user preferences, but they also make the output layout highly unpredictable. For CI dependency visualization, unpredictability is a large drawback, because knowledge sharing requires a stable interaction between users and the information space.
Geographical layout is another layout technique often used in infrastructure modeling or simulating approaches. The geographical display supported by GIS provides some robust functions for layering and displaying physical dependencies with geospatial reference. The problem is that the interdependencies that can be represented by the current GIS are often restricted to physical links and elements. Additionally, not all the important physical components are modelled in the current GIS. They are often only detailed in regards to objects such as buildings, but do not further include important components within a building. Traditional graph representation is more flexible in representing this kind of detailed information, but how to integrate these two representations and have them dynamically refer to each other still remains a problem.

2.8.2 Multiple links with different types of interdependencies

Representing multiple linkages with different types of interdependency is another challenge of CI visualization. Previous researchers have applied different classifications to interdependencies, but little research to date has been focused on how to represent different content and the restrictions associated with multiple links. Chakrabarty and Mendonca’s visual model (2004) proposed using line ends to denote the type of interdependency, but they do not address the problem of how to represent multiple linkages and avoid overlay.

2.8.3 Interdependency analysis: tracking the flow of decision impact

Supporting decision-making is the most important task of CI visualization. Before emergency managers make decisions about an infrastructure component, it is necessary for them to understand how this component is related to other infrastructure, so the
impact of the decisions across infrastructures will be taken into account. Although current simulation and modeling tools have been applied to model the relationships within an interdependency matrix, human readable table or dependency graph, this does not mean that the users can easily figure out the impact of their decision by simply checking the table or tracing the graph. Existing dependency tools do not ideally support the representation of decisions and their impact. Most of them are only capable of showing the path according to the connectivity of the dependency links. GeoTime is able to support spatial time tracks of events and movements; however, it is restricted to georeferenced data.

Besides the connectivity between infrastructures components, the impact of decisions is restricted by many other factors, such as time, threshold and the shared or exclusive relations between interdependencies. Without enough visual cues, it will be very difficult for users to uncover these restrictions together with the temporal pattern in decision change flows.

2.8.4 Common visual language

To support shared visualization, it is necessary to have a visual convention which can be accepted across domains. Emergency managers of different infrastructures usually follow different rules and conventions on their individual work, in areas such as procedures, signals, colors, icons, and ways to raise alarm. The diversity of the conventions can cause misunderstandings in communication. However, currently, there is no defined visual language that can be shared across different infrastructures.
CHAPTER 3: MOTIVATION AND GOALS

3.1 Research Context and Motivation

The JIIRP research conducted by the University of British Columbia - the Infrastructures Interdependencies Coordination (I2C) project - is a multidisciplinary project that researches CI interdependencies and emergency management. One of the main focuses of the project is to develop the infrastructure interdependency simulator (I2Sim). I2Sim aims to comprehensively simulate the conditions of each infrastructure component (cells, channels, input and output tokens) with disaster scenarios and help decision makers explore how disruptions or decisions affect infrastructure networks. The research team chose the UBC campus as the test case due to its geographical location, diversity of stakeholders, complex infrastructure, and accessibility to complex data.

Overall, this thesis research is one part of the research of I2Vis. I2Vis studies CI interdependency visualization problems associated with I2Sim. The focus is on exploring ways to visualize interdependencies between critical infrastructures and to establish a shared understanding between both emergency and infrastructure managers under the I2Sim UBC test case scenario setting.

3.1.1 I2C's approach to the external user interface I2UI

I2UI is the user interface of the simulator, which provides a visualization of CI interdependencies as well as helps to enable knowledge sharing and knowledge capture. In the beginning stages of the research, the plan was to support I2UI with a GIS
representation for the purpose of aiding the visualization of CI interdependency and increasing the sharing of information. As the research work went further and into more detail, limitations of our original approach became apparent.

3.1.1.1 Restriction of the Cell-Channel Model

The I2C’s cell-channel model is restricted to modeling interdependencies which are physical or resource connections across infrastructures, e.g., water pipes and other water resources. Interdependencies related to information flow and human behaviour, such as roles or activities/events (Bartram and Pottinger, 2007), are not as easily modeled. The problem is that these interdependencies are often just logical connections between infrastructures, and thus, they can be hard to plan for and measure spatially and quantitatively.

Furthermore, some of these interdependencies might only be discovered over time. Through interviewing campus facility managers and emergency planners, the I2C research team collected and summarized some of the information flow between infrastructures at the UBC campus over a longer term of time (Figure 3-1). There is also a great deal of knowledge that can be difficult to identify and model, such as experiences that remain in the mind rather than get documented, or certain reactions that only occur during specific events.
3.1.1.2 Restriction of Geo-spatial Representation

For visualizing CI interdependency, GIS representations have the following advantages and disadvantages.

Advantages

Maps are widely used in emergency management. GIS displays objects with geospatial-referred information and provides a planning base for collaborative decision making among stakeholders. In the UBC JIIRP project, using the campus as a guide, both physical infrastructure layers and building assessment data are modeled in the GIS.

Disadvantages
In existing GIS systems, representations are often only detailed for objects such as buildings. Detailed, important components, such as generators in a power house, pumps in a water house, or a backup system in a hospital, are usually not modeled. Besides that, existing GIS systems are unable to model information that is non-spatializable, such as logical conditions, e.g. A cannot access the system until B talks to C and then gives permission to A, and thus, interdependencies such as logical information, event/activity, and role cannot be modeled by GIS.

3.1.1.3 Improved approach to I2UI: Graph-based view + GIS-based view

In order to help infrastructure managers capture the knowledge that is missing from physical and resource models, we have to make an explicit place in the model to collect this as it occurs, such as logical information that is discovered after events. Thus, the I2UI should be capable of showing not only spatial connections but also logical connections. Also, tools should be available to help users record and collect their thoughts, comments and suggestions.

The improved approach of I2C to I2UI is a multi-view design of both the graph-based dependency view and the GIS based spatial view. The central idea is to support CI visualization with both graph and geo-spatial representations and to have them complement each other. Graph representations are capable of showing both spatial and logical connections, while GIS representations are restricted to spatial connections but have the advantage of displaying objects with geo-referred information. With the multi-view design, the graph-based dependency view represents all of the interdependencies that exist, such as physical resources and information resources. The GIS based spatial view represents the interdependencies that are modelled in the GIS database. Most of
them are physical interdependencies. The two views are best visualized with multi-monitor screens, so the user can easily switch attention and refer to information between screens.

3.1.2 Common ground: What is to be shared?

In the UBC JIIRP project, the purpose of the CI simulation and visualization is to establish a common ground that can assist with information sharing. Although the goal is to represent interdependencies, both the scope and content of “common ground” still remains to be defined. What do users want to see and how much information do they need? What do they like to share and how much are they able to contribute? One straightforward way is to share everything — each user sees the same complete view of all the interdependencies that can be modeled and captured. However, this is not practical due to the following three reasons:

1) Showing too much information may overwhelm users’ perceptions. In a simplified testing case with only five components, we tried to represent all the available interdependencies with a graph. Even before the information updates were added into the display, the display was already overcrowded because too many dependency links needed to be drawn in one limited space. Information overload can obviously be a problem if a large case with a lot more interdependencies needs to be completely represented and shared among multiple users.

2) Users of the system are experts in different infrastructure domains. As such, they have different concerns and different priorities when solving problems. On the other hand, it is not necessary for each of them to see every detail and update of
the interdependencies. For example, the power manager may only need to understand “there is a water supply line running between the stations”, but it might not be necessary to know “the water supply is 10L/second” and “the maximum capacity is 15L/second”. They only need to see the part of the overall system that is related to their work. Besides that, due to the diversity of tools and data formats that are being used in different infrastructures, currently there is no common protocol (vocabulary and visual lexicons) that could be universally shared among different infrastructures.

3) In the real world, due to the restrictions of government policy and/or industrial regulations, many organizations have constraints and concerns over releasing internal information.

3.2 Goals

The research focus in this thesis is the graph-based dependency view. Our research goal is to establish requirements for the dependency view and to develop an enriched information model that will include elements which are not explicitly provided in the simulators, but are important to CI managers. Throughout this research, I have explored ways to visualize interdependencies across multiple, critical infrastructures and to establish a set of practical guidelines for the design of a graph-based dependency view that supports decision-making and shared understanding under the I2Sim UBC test case scenario setting.

In the previous chapter, I stated the general issues of interdependency visualization: Layout, multiple links, tracing and common visual language. In response to these issues, I identified my research questions as follows:
What kinds of CI interdependency information should be visually represented to facilitate knowledge sharing? The dimension of interdependency needs to be further defined. Requirements for visualization systems should also be considered. As a result, a data model to structure meaningful dependency attributes and to support visual functions is proposed, according to the problem scope of the UBC test case.

What visualization requirements should be introduced in this information model in order to support interdependency visualization, knowledge sharing and knowledge capture? These challenges are explored from three user perspectives: planning, analysis and reaction.

This thesis covers the following steps of this approach:

1) Define the target users and major dimensions of CI visualization data for the dependency view.
2) General user and requirement analysis to understand user’s needs.
3) Information model design, analysis and discussion.
4) Describe the UBC test case data set.
5) Low-fidelity prototype of the model using the UBC test case scenario
6) Discuss design implications and user perspectives.
CHAPTER 4: INFORMATION MODEL DESIGN

4.1 Target User

This research considers infrastructure managers who come from different domain backgrounds as well as managers of the EOC who closely monitor the system, as the characteristic users of the visualization system supported by the information model.

4.2 Three User Perspectives

The information model is expected to aid in problem-solving from three user perspectives:

- Planning Perspective (What – if): This perspective discovers the possible impact of decisions during the planning stages of an emergency exercise.
- Analysis Perspective (Why did that happen?): This perspective tries to investigate the cause of a problem and find out how to handle a similar event in the future.
- Reaction Perspective (What’s going on?): This perspective tries to find out “what information do I need to make decisions? And what actions should I take?

4.3 Data Dimension

The foundations of this dimension are both the interdependency criteria and the interdependency type. In the example problem, interdependencies are defined according to the criteria proposed by Mendoca et al. (2006). Mendoca indentified four circumstances, and the appearance of any one of them makes an interdependency.

- Co-located - two or more infrastructures’ physical components or activities are co-located within a prescribed geographical region.
• Input - one infrastructure requires one or more services as input from another infrastructure in order to provide a service;

• Shared - some physical components and/or activities of one infrastructure used in providing a service are shared with one or more other infrastructures;

• Exclusive-or - either the infrastructure or some other infrastructure (but not both) can be in use during the provision of the service;

In this criteria, we assume that co-located is represented by the GIS view, and the other three categories should to be represented by the dependency view.

Interdependency types are classified according to the definition of Bartram and Pottingers (2007).

• Physical - elements of the physical environment that depend on other elements (e.g. power lines, water mains, substation, communication tower).

• Resource - goods/services that are needed.

• Information - decisions depend on having the right information from other sources.

• Role - coordination of decisions depend on the right people being in the right place.

• Activity/event - this refers to the situation where actions/events cannot take place until another action/event has occurred.

This classification of interdependency types is based on a summarization of definitions proposed by Rinaldi et al. (2001) and Dundenhoffer et al. (2006) and the research discovered in the I2C project. Considerations of resource flow and human factors are included in this classification.

Concerned with the interdependency data available in the UBC campus data set as well as the requirements of visualizing the data, I decided to include four categories of interdependency data in my consideration: identification information, dependency
information, situation awareness information and additional information. Identification information contains the unique ID of an interdependency element on both the graphical view and the GIS view (as a node or link on the graphical view or as a map object on the GIS view). It is the link between the two different representations of the same object.

Dependency information describes the type, direction and content of interdependency. Situation awareness information includes priority, alert and annotation. Priority measures the importance of interdependency, which suggests which interdependency should be dealt with ahead of others. Users will be able to filter interdependencies based on the priority. Alert is the emergency alert which shows a conflict that needs to be solved immediately. The annotation helps to collect extra, situational comments from users.

Additional information may include any useful information that users would like to further refer to or research.

Table 4-1 is a summary of the major dimensions of interdependency information data along with an explanation and examples.
### Table 4-1 Interdependency Data Dimensions

<table>
<thead>
<tr>
<th>Category</th>
<th>Data Dimension</th>
<th>Description/Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identification information</td>
<td>Element ID</td>
<td>P100</td>
</tr>
<tr>
<td></td>
<td>Name</td>
<td>Power line 100</td>
</tr>
<tr>
<td>Dependency information</td>
<td>Infrastructure Sector</td>
<td>Power, water, gas, medical etc.</td>
</tr>
<tr>
<td></td>
<td>Interdependency Type</td>
<td>Physical, resource, role, information or activity/event</td>
</tr>
<tr>
<td></td>
<td>Interdependency Criteria</td>
<td>Input, shared, exclusive-or, or co-located</td>
</tr>
<tr>
<td></td>
<td>Target</td>
<td>ID or name of another element</td>
</tr>
<tr>
<td></td>
<td>Source</td>
<td>ID or name of another element</td>
</tr>
<tr>
<td></td>
<td>Content</td>
<td>Capacity/current value/control information/activity information</td>
</tr>
<tr>
<td>Situation Awareness information</td>
<td>Priority</td>
<td>High, middle, low</td>
</tr>
<tr>
<td></td>
<td>Alert</td>
<td>Emergency alerts, conflicts that need to be solved immediately</td>
</tr>
<tr>
<td></td>
<td>Annotation</td>
<td>Comments and notes left by users of the system</td>
</tr>
<tr>
<td>Additional Information</td>
<td>Reference Information</td>
<td>URL, documents, etc.</td>
</tr>
<tr>
<td></td>
<td>Contact information</td>
<td>Tom Lee, water facility manager, 604-123-4567</td>
</tr>
</tbody>
</table>

### 4.4 User Requirement Analysis

For the purposes of emergency management, a visualization system should be able to fulfill the requirements of infrastructure managers from the following five aspects.

#### 4.3.1 Understand the Structure of CI dependency

The most important aspect of CI visualization is the structure of CI dependency. The planners and managers of disaster management are usually domain experts from different infrastructures. They are experienced in certain domains, but often lack a complete understanding of situations in other domains. As a planner and manager of disaster management, it is very important to see an overview of all related infrastructure dependencies, so one can have a complete understanding of the situation across all the related infrastructures. A visualization tool should support this from three aspects:

- It should support an overview shared by different infrastructure managers. With this, if the managers are located in different places and they want to discuss the
situation through the tool, they will have common objects to refer to and talk about.

- The tool should also allow managers to explore the structure of dependency with different levels of detail; so when they are interested in understanding a certain part in the overall display, they will be able to see an enlarged view containing structure specifics and internal components.

- Since maps have been widely used in disaster planning and management, the tool should allow an infrastructure manager to see the CI components and links in a map format. This is applicable to most of the physical and resource components and links. With the help of a map display, it should be easy to identify the geographical distribution and environment of the infrastructure components.

4.3.2 Interdependency Analysis

In addition to knowing the overall structure of the CI dependency, it is also important to see how certain infrastructure components are related to each other. As well, it will help CI managers get a better idea of who should they talk to and what will be affected before they make decisions. A visualization tool should provide interdependency analysis functions in five ways:

- The type of interdependency: As mentioned in the literature, different types of interdependencies function differently across infrastructures. In many cases, it is possible that two CI components will be associated with each other by having multiple types of interdependencies. For example, the interdependencies between a water station and a hospital may be:
  - a physical interdependency: the water pipe;
• a resource interdependency: the water flow within the pipe;
• an information interdependency: the water control information.

A visualization tool should allow an emergency manager to visually identify different interdependencies easily.

- The content of the interdependency: Different types of interdependencies yield different dependency information, especially with the properties of the content associated with the "flow" between the two. With the above example, a water pipe has its capacity, water flow has the value of current flow, and the water control information has the details of how the water is being controlled. This information is essential to emergency managers while they make decisions, so the tool should display the information in a reasonable way.

- Contact and reference information: In some cases, an emergency manager does identify a problem across infrastructures, but does not know who to talk to in other infrastructure departments. The visualization tool should have important contact information associated with the CI display. It is also recommended that some extra information related to CI components is made available through online resources and documentation; the visualization tool should provide users with the option of accessing these references.

- Prioritizing interdependencies: An emergency manager usually has to face a large number of interdependencies. An effective way to identify potential problems is
to categorize interdependencies according to their importance. The visualization tool should support this function by visually displaying the interdependencies according to the priority.

- Trace the interdependency: One of the most important tasks of CI visualization is to help emergency managers understand the cause of a problem and the impact of a decision; for example, what makes the capacity of ER beds go to 0? And what will happen if I take this power line out? To answer these kinds of questions, it is necessary for an emergency manager to be able to trace the interdependency with a tool. Forward tracking should be able to show all the trickle-down effects as well as all the results of a certain operation impacting the dependency. Backward tracking should be able to show all the possible sources of a dependency.

4.3.3 Modifying Interdependency

In a given time period, it is possible that an interdependency no longer exists, or that a new interdependency is captured by users. In these cases, the tool should allow users the ability to modify interdependencies and its associated properties. The tool should also be able to remind other users of recent changes with visual cues.

4.3.4 Annotating Messages

While exploring CI interdependencies, emergency managers may wish to write down their understanding of a situation for the purpose of a future review with colleagues.
The tool should remind emergency managers of the existence of the annotations with visual markings, and help them identify and view the message easily.

4.3.5 Querying and Filtering

In some cases, emergency managers may want to identify interdependencies or a certain problem area with a specific range of associated property; for example, all buildings with damage > n or all buildings connected to line A. A tool that supports a querying and filtering function should be able to highlight the results on the output display, so that users can quickly identify areas of interest.

4.5 Design Considerations

In the following sections, I will discuss how the information model should support CI visualization with the dependency view from five aspects: layout, attribute arrangement, information updates and interdependency analysis. I am interested in establishing a set of guidelines that people can follow to design the end user interface.

4.5.1 Layout Technique on the Dependency View

In the dependency view, the interdependency components are represented as a network of nodes and edges. Compared to the dependency visualization of other domains, the CI interdependency layout has several unique characteristics:

Large Size: Due to both the scope and complicated structure of critical infrastructures, the representation of a real-world interdependency network may contain large numbers of objects and complicated relationships among the objects.
Complicated structure: The representation of CI interdependencies is conceptualized from the real-world network, so it has to follow certain organization structures of the real world. For example, CI interdependencies cannot be simply represented with tree structures, such as in fixed parent-child relationships. The objects of the network cannot be randomly distributed. Some of them may have to follow hierarchical or geographical relations determined by certain industries.

Multi-user: Users of the CI interdependency system are experts from different infrastructure domains. While they explore interdependencies, each of them may have their own interests regarding the scope and details of the data, so the display should be very flexible when fulfilling different needs.

Layout techniques for the dependency view should be able to support the following features:

- Representing multiple interdependencies
- Supporting appropriate details according to users’ interests.

As I discussed in Chapter 2, various layout techniques have been used in other domains to represent dependency. However, current dependency layout techniques all have some drawbacks when applied to CI interdependencies. The tree layout is a widely used layout in knowledge visualization and software visualization for representing relations among objects, but it is strictly restricted to fixed parent-child relationships. Because CI interdependency graphs may contain loops and crossings, the tree layout is not an ideal choice. ConceptVISTA (2008) uses radial layout to arrange concepts, which provides interactive exploration based on user’s interests. However, the force directed feature of radial layout can be very confusing while multiple users try to collaborate and
share information. Since two different selections of a single node on identical graphs might produce different layouts, the visualization space becomes highly unpredictable, and users may find it difficult to locate shared objects while they work in a collaborative environment based on this display. The Manhattan layout is often used to represent circuit lines and pipe lines. In the I2sim research, many diagrams of a physical model also use this layout. The Manhattan layout arranges all the links with highly organized, vertical and horizontal lines. However, this also makes the graph inflexible to structural changes, and which could be a problem if people need to constantly adjust details in certain parts of the display.

The Continuous Zoom algorithm (Dill et al., 1994; Bartram et al., 1995) is a multi-focus fisheye zooming technique. Research in applications such as CZWeb (Fisher et al., 1997) and CZTalk (Lam, Fisher & Dill, 2005; Wong, 2005) shows that Continuous Zoom has the advantage of displaying hierarchically organized 2-D networks. For instance, Continuous Zoom represents an upper level component as a container node and the subcomponents as nodes contained. Throughout the navigation, users control the amount of detail by opening or closing a container node, while at the same time the structure and high level context of the graph are preserved. This helps to support detailed views of various points of interests without losing the larger context of the entire system.

Inspired by Continuous Zoom, a suggested approach for the layout is to apply the focus + context technique and hierarchical container structure of Continuous Zoom to the dependency diagram. In the diagram, a node can be an infrastructure organization, service or building, such as a hospital, a power house or an emergency control center. A node may contain several levels of sub-nodes, which represent important sub-components.
under the infrastructure organization, service or building. Directed links between nodes represent interdependency links, such as a road, a water line, or a control command. Users can zoom out to obtain an overview or zoom into a sub-node to explore detailed information.

4.5.2 Attribute Arrangement and Display

As I introduced in the previous section, CI interdependency contains multi-dimensional information (Table 4.1). Relations among infrastructure components can be represented with a graph, but the visualization of the information associated with the graph is a difficult problem. In software dependency visualization, a similar problem was pointed out by Smart (2004). Smart commented that a purely graphical theoretical model cannot capture the semantic information carried by dependency diagrams. In his prototype software visualization model A-Vu, the semantic information is incorporated into the graph diagram through the modeling of node attributes and edge attributes. On the display, the information is graphically represented with various predefined types, shapes and sizes of nodes and edges.

The visual model proposed by Chakrabarty and Mendonca (2004) uses visual vocabulary and grammar to describe the state of an infrastructure system. In this model, the researchers use icons to denote infrastructure sectors, line ends to denote infrastructure criteria (dots for exclusive-or and bullets for shared), and bars to denote the current operating level in regards to system capacity. They also suggest using a sound or flashing node to represent alarms in order to gain the user's attention. Their model introduces an effective way to visualize the attributes of the information associated with
the interdependencies; however, one major problem of the model is that only physical interdependency types were considered.

The interdependency data dimensions identified in this research (Table 4.1) are more complicated than Chakrabarty and Mendonca’s model, which contains not only multiple types of interdependencies but also more information attributes. Because users’ perceptions may be quickly overwhelmed if too much information is being displayed at once, multiple dimensions of data should be organized and shown with different levels of details. One reasonable approach is to arrange them by their importance. Data exploration is supported by the focus + context navigation technique.

4.5.2.1 Infrastructure Sector and Infrastructure Type

A problem to represent multiple links with different sector types is that it generates many links between the nodes. For example, in Figure 4-4, if there are three supply lines: power, water and gas, running between the stations, each of the links then contain three interdependencies types:

- a physical interdependency: e.g. the power line;
- a resource interdependency: e.g. the power delivered through the line;
- an information interdependency: e.g. the power control information.
I would have to draw nine links between the nodes. The display space can be terribly overcrowded if the interdependency network contains many similar supply lines. However, because the interdependency type originates from the detailed internal information of a specific infrastructure, it is not necessary to display it to all the users. For example, a power manager may only need to understand “there is a water supply line running between the stations”, not necessarily to know “the water supply is 10L/second” and “the maximum capacity is 15L/second”. To simply the representation and save space, the context-in-detail technique should be applied to the link visualization; that is, all interdependency links are distinguished by sectors, by default. The types will be visible only when the user zooms-in and clicks the link.

4.5.3 Information Updates

The dependency view should be able to support time-based visualization, so the user can roll back to a predefined state and thus re-visualize previous updates. When the information is updated, how should it show up on the display? According to Roberts et al. (2000), there are three strategies: replacement, overlay and replication to show parameter updates in interactive visualization. Overlay and replication provide explicit comparisons between each update, but overwhelming displays may become a problem when the amount of updates gets too large, therefore I suggest replacement as the strategy to represent updates.
4.5.4 Interdependency Analysis

4.5.4.1 Forward and backward trace

The forward and backward trace is to help emergency managers understand the cause of a problem and the impact of a decision; for example, what makes the capacity of ER beds go to 0? And what will happen if I take this power line out? Forward tracking should be able to show all the trickle-down effects and results of a certain operation impacting the dependency, and backward tracking should be able to show all the possible sources of an interdependency. The results of a trace are a list of dependency paths. The issue for a display is to make them stand out from all others while maintaining the original characteristics of the display.

4.5.4.2 Filtering

Filtering as a visual technique has been used in software visualization and GIS. The Node Filter and Arc Filter in SHriMP (2008) are based on types, and other selection criteria. Users can choose to enable, disable or combine multiple filtering functions. Filtering can be used for priority and alert status to help users identify interdependencies or problem areas by giving them a certain range of choices.

4.6 Summary

This chapter described the design of the information model. The dimension of the information model was defined according to two considerations: data dimension of CI interdependencies and requirements for visualization systems. Design considerations were discussed from five aspects: layout, attribute arrangement and display, information updates and interdependency analysis.
CHAPTER 5: WALKTHROUGH OF UBC TEST CASE

In this chapter, I discuss how the information models extend the simulation models in the UBC test case. To demonstrate this, I walk through a user case to illustrate how this model supports visualization of CI interdependency from three user perspectives.

5.1 Introduction to the Scenario Data Set

5.1.1 I2sim 5-cell test case

I2sim 5-cell test case is a reduced scale test case model of the UBC campus test case. This reduced scale test case was used by the I2C team to test the prototype simulator. The 5-cell test case includes five cells: substation, powerhouse, water station, steam station and hospital, which represents the electricity, water and medical infrastructures on campus.

Physical and resource interdependencies

The I2C engineering team modeled the physical and resource interdependencies. Figure 5.1 shows the cell-channel model of the five cells. Figure 5.2 shows the internal components of each cell and the physical and resource connections between them.
Figure 5-1 12sim Reduced Scale UBC Test Case Model (Liu, 2007)
Figure 5-2 I2sim 5-cell test case physical and resource connection diagram (Adapted from I2Sim architecture - CC cell model, I2Sim Team, 2007)
Information Interdependencies

Information interdependencies are not included in the cell-channel model, but they do exist in the infrastructure management work of the campus. Through interviewing campus facility managers and emergency planners, the I2C team noticed that the information flow across infrastructures is often important but easily ignored by decision makers, because it is usually formed by rules and/or experience, and it is invisible to the physical and resource network, e.g., UBC Campus & Community Planning requires information from the GVRD (Greater Vancouver Regional District) and BC Hydro to provide an external water supply plan to the UBC utilities. In case of an emergency, UBC Campus & Community Planning needs to examine the situation at the fire station and the hospital before allocating water resources. The knowledge interdependency diagram in Chapter 3 (Figure 3-1) shows how important information flows over a longer term of time.

Combining the physical and resource interdependencies with the information interdependencies

From the knowledge interdependency diagram, I chose the information interdependencies among the five cells (Figure 3-1) and combined them with the physical interdependency in Figure 5.2. Figure 5.3 is a diagram of the combined interdependencies.
Figure 5.3 Five cell physical, resource and information interdependencies
5.2 Scenario Background

The campus power shortage scenario below was used by the I2sim team to verify the simulation on the 5-cell test case. This scenario is based on actual disaster events during a 2006 power outage at the UBC campus.

On November 19, 2006, a Pacific storm brought 90mm of rain and strong winds to coastal B.C. Then a weather warning was issued, with an Arctic ridge over the BC interior, combined with a Pacific low-pressure system over the southwest of B.C. The result was that on November 26, 20-40 cm of heavy snow fell across Greater Vancouver, Victoria, and the rest of the South Coast. On November 27 and 28, the Arctic front spread across the Lower Mainland and temperatures dropped as the skies cleared (-12° C in Vancouver). The weight of the heavy snow brought branches and trees down on power lines (PSEPC, 2006; Ministry of Public Safety and Solicitor General, 2006; BC HYDRO, 2007). As a result, the impact of the snowstorm and the power outage caused by falling branches and trees affected UBC campus, and on November 27, the whole campus was closed. The campus power outage lasted for about 12 hours. (Liu, 2007, p.61)

5.3 Scenario Description

5.3.1 Events and Timeline

The analysis of this scenario involves six campus facility departments: campus planning, power, water and steam, hospital, fire station, and ambulance service. In this scenario, the power supplies to the water station and hospital were damaged one after another. The decrease in power supply caused a series of changes in the water, steam and medical services. Facility managers from the following six areas were involved in this scenario:

- Campus planning manager
- Power manager
- Water/steam manager
- Hospital facility manager
- UBC Station fire fighters
- First responders

Five major events happened during the snowstorm’s power outage which had a direct influence on UBC campus utilities, e.g.:

- Initial state: \( t_0 = 1:00 \)
  - The whole system runs in normal state until \( t_1 = 1:20 \)am;
- \( t_1 = 1:20 \)
  - A power outage occurs because fallen trees bring down the transmission lines sending power to the UBC Substation;
- \( t_2 = 1:40 \)
  - The water pipe linking the water station to the hospital bursts;
- \( t_3 = 3:20 \)
  - Hospital long term service is closed due to power and water outage;
- \( t_4 = 13:40 \)
  - The water pipe is fixed;
- \( t_5 = 14:20 \)
  - The power is restored.

*Figure 5-4 Timeline of the scenario*
These events happen in power and water infrastructures, but, in this case, both its direct and indirect influence spread out to all other campus facilities including campus planning, medical services and the fire department, due to the interdependencies among the campus infrastructures.

In this section, I assume that the players of the scenario (facility managers, firefighters and first responders) are located in different locations. I walk through the scenario from time $t_0$ to $t_5$ to show how an interface based on my prototype information model and visualization solution may help facility managers obtain critical updates of interdependencies, share information across domains, adjust to changes, and make decisions. At each moment of time, the individual views of the power, water and medical infrastructure managers are demonstrated one by one with paper mock-ups.
### 5.3.2 Legends

#### Table 5-1 Legends for the illustrative figures

<table>
<thead>
<tr>
<th>No.</th>
<th>Legend</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Line color</td>
<td>Power link</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Water link</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Steam link</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Medical link</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Oil link</td>
</tr>
<tr>
<td>6</td>
<td>Line style</td>
<td>Physical</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Resource</td>
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<tr>
<td>8</td>
<td></td>
<td>Information</td>
</tr>
<tr>
<td>9</td>
<td><img src="image" alt="Critical alert" /></td>
<td>Critical alert</td>
</tr>
<tr>
<td>10</td>
<td><img src="image" alt="Problem" /></td>
<td>Problem</td>
</tr>
<tr>
<td>11</td>
<td><img src="image" alt="Broken link" /></td>
<td>Broken link</td>
</tr>
<tr>
<td>12</td>
<td><img src="image" alt="Failure (0 flow)" /></td>
<td>Failure (0 flow)</td>
</tr>
<tr>
<td>13</td>
<td><img src="image" alt="Limited service" /></td>
<td>Limited service</td>
</tr>
<tr>
<td>14</td>
<td><img src="image" alt="Annotation" /></td>
<td>Annotation</td>
</tr>
<tr>
<td>15</td>
<td><img src="image" alt="Non-active backup unit" /></td>
<td>Non-active backup unit</td>
</tr>
<tr>
<td>16</td>
<td><img src="image" alt="Active backup unit" /></td>
<td>Active backup unit</td>
</tr>
<tr>
<td>17</td>
<td><img src="image" alt="Pop-up information" /></td>
<td>Pop-up information</td>
</tr>
</tbody>
</table>
| 18  | ![Shared Interdependency](image) | Shared Interdependency  
(B and C share supply from A) |
| 19  | ![Exclusively shared Interdependency](image) | Exclusively shared Interdependency  
(Either B or C has priority to get supply from A) |
Please note that the above legends including the styles and colors of the nodes and edges are only used in this scenario case to demonstrate the underlying design idea. Since each infrastructure domain has its own conventions and restrictions on symbols, shapes, and colors, this detail is not to be defined in this research.

5.4 Scenario Walkthrough

This walkthrough illustrates how the shared visualization of CI interdependencies can help to solve problems and support the three user perspectives.¹

Figure 5-5, 5-6, 5-7 are the views for each of the different domain managers. The managers can look at the details in their own domains and also be aware of a larger connection to other critical infrastructures.

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¹ A step by step walkthrough of the scenario is presented in Appendix A.
Figure 5-6 Water view at time 0
Figure 5-7 Hospital view at time0
At time0, campus infrastructures are in their normal state. What happens when things go wrong?

At time1, the power line is broken. On the power view (Figure 5-8), this yellow node with orange links shows that the power station is using a backup for external resources, and the power manager is trying to understand the impact. He can issue a forward trace and check the water details (Figure 5-9) and the hospital (Figure 5-10). It turns out the water station and the hospital both have backup power, but the water supply to the hospital is restricted. How will this affect the hospital?
Figure 5-8 Power view at time1
Figure 5-9 Power view at time1 – after clicking the water node
Figure 5-10 Power view at time1 – after clicking the hospital node
The hospital manager notices that there is no power and that water is restricted (Figure 5-11). He can issue a backward trace to find the source of the problem, and check with the power manager and decide whether he should reduce services. Here the hospital manager decided to stop taking new patients because of the restriction on water input. He can post an annotation (Figure 5-12), and the water and power manager should be able to see it. Now that the power manager can see if the power is off, there is an impact on the hospital because of the water restriction.
Figure 5-11 Hospital view at time - A
Figure 5-12 Hospital view at time 1 - B
At time 2, the water pipe breaks. The hospital manager’s question is “what do I do with respect to finding backup water?” On Figure 5-13, the active “BK water pump” shows that the hospital requires backup water from an external emergency water supply, the swimming pool. New interdependency links in grey pop out, showing that the emergency water resource is shared between the hospital and the fire station, and campus planning is responsible for providing this sharing plan, so the hospital manager knows that he can not make the assumption that he gets the emergency backup. He has talk to the UBC campus planner.

At time 2, the hospital decides to close long term services. Several information interdependency links appears between “hospital” and “campus planning”, and between “hospital” and “first responders”, which suggests that the hospital would inform the campus planning and first responders about the reduced operations.
Figure 5-13 Hospital view at time 2
At time 3 (Figure 5-14), the interdependency links connected to the "Long term service" disappear, and the "Long term service" node is closed and shrank. The interdependency link between the "Short term/emergency" and "Pool" turns blue, which indicates that the hospital gets access to the backup water.
At time4 (Figure 5-15), the water supply has recovered, but the water supply is still restricted.

Figure 5-15 Hospital view at time4
At time5 (Figure 5-16), backup power nodes turn grey, which indicates that the backup power is no longer active and the power service is back to normal.

Figure 5-16 Hospital view at time5
CHAPTER 6: DISCUSSION

In the previous chapter, I proposed an information model and demonstrated the model with a real user case. In this chapter, I state the significance as well as the implications of the information model and further discuss how it is expected to support the three user perspectives, with particular examples from the UBC test case.

6.1 Achieved Goals and Design Implications

In this research, an information model is proposed, to support the design of the graph-based dependency view of the 12Sim simulator. The I2sim simulator models the interdependency network and simulates data updates on the backend. While the user runs the simulation, a series of dynamic updates are displayed on the dependency view on the front end. In line with my research goal, I expect the information model to support shared visualization of interdependencies with the following four major features:

Represent multiple interdependencies

Here the multiple interdependencies carry two meanings: multiple interdependency types and multiple interdependency links.

- Interdependency types are the following: physical, resource, information, role and activity/event, which include both spatial and logical connections. This information model supports both spatial and logical connections with the graph-based representation.
Since the interdependencies between infrastructure components often involve multiple interdependency types and infrastructure sectors, the layout of the graph needs to be flexible enough to show multiple links between the nodes. The suggested technique for this information model is as follows: focus + context technique, with the hierarchical container structure of Continuous Zoom able to support multiple links.

**Support appropriate details**

The information model enables the interdependency information to be explored at different levels of detail. This is firstly supported by the hierarchical structure of the interdependency network and the focus + context navigation technique. Also, the interdependency information display can be arranged according to importance. For example, in the walkthrough, the interdependency information is arranged into three levels:

- On surface: The most important information showing the overview of the situation, such as: interdependency nodes, links and icons.
- Pop up: Summarization of interdependency information. The information is accessed by mouse clicks and displayed in a pop-up window.
- Further exploration is supported by zooming to a sub-node or sub-link.

This feature helps to maintain a visual overview of interdependencies. Users are able to locate and access desired information quickly and easily. It also helps individual users explore detailed interdependency information based on their domain interests.

**Support time-based visualization**
The I2sim simulator runs a time-domain simulation of infrastructure components within a disaster scenario. Time-based visualizations of the simulation helps users explore how disruptions or decisions affect the overtime of the infrastructure.

Capture missing knowledge

Capturing interdependency information from what has been modeled to what could be visualized on the interface is the initial step for establishing the common ground for information sharing. The information model organizes the available interdependencies into an information structure that can be easily navigated and understood by emergency planners and infrastructure managers from different domains. The dependency view supported by this model is supposed to be added as a supplement to current emergency management systems such as the GIS system in the I2C project. It also helps infrastructure managers remind or indentify critical dependencies in regards to other infrastructures, while they work with specific management systems in their domains. It should also help them share their experiences, suggestions and questions, which may assist in revealing hidden interdependencies.

6.2 User Perspectives

The dependency view support by the information model is expected to help solving problems from three user perspectives: planning, analysis and reaction. In this section, I will discuss how these perspectives are supported using examples from the UBC test case.
6.2.1 Planning Perspective (What – if)

This perspective tries to discover the impact of a decision during the planning stages of an emergency exercise. For example, the power manager’s view in the user case is actually a planning perspective problem: a UBC power manager needs to know “what will happen if I take the power line from BC Hydro out?” The considerations include: Which critical client will be affected? How long will they be able to use their backup resources? The power manager needs to issue a forward trace. Then, the result will be simulated and played back on the interface. During the playback, critical clients who are directly affected by the power being cut-off, including the power station, hospital and water station, should stand out on the display, so that the power manager will be able to notice them quickly and easily (Figure 6-1).
Figure 6-1 What if I take the power line from BC Hydro out?
If any backup system is being used, showing the status of the backup storage will help the power manager compare the priorities for service recovery. In Figure 6-2, the power station, water station and hospital are all operating on backup power. The hospital has its own backup power, but the water and steam services depend on the water station and steam station. The water station has its own backup power, but the services of the steam station depend on the water station and power station. When allocating access to the power supply, which client should have higher priority? While the power manager is making decisions, it is necessary to take into consideration knowledge about the backup fuel consumption, storage, and delivery status of each client.
Figure 6-2 Priority of service recovery
6.2.2 Analysis Perspective (Why did that happen?)

This perspective is used to investigate the cause of a problem and find out how to handle a similar event in the future. For example, a hospital manager wants to know “What makes the water input go down to 20%”? Considerations include: How serious is the problem? How long will the current service last? Who should I talk to for further information? The hospital manager needs to issue a backward trace to track the source of the problem. In the following case (Figure 6-3), there is a power breakdown between BC Hydro and the power substation. As a hospital manager, he may not necessarily know exactly where the line is broken, but he needs to find out if the problem is with the power section, which will in turn cause the power to be cut-off to both the hospital and water station. The hospital has its own power backup, but the hospital manager has to know how long the water and steam supply will last.

To identify the problems, the hospital manager firstly issues a backward trace on the water link. The result shows that the problem can be traced back to the power house, which means the water station is probably running with backup power, therefore, the hospital manager should consider confirming the availability of the water supply with the water station. Besides, since the steam service is supported by both power and water, the hospital may have to contact the power manager for further details. If it turns out that any of the services may not be recovered in the short run, then the hospital manager will probably make a decision to reduce or suspend hospital service.
Figure 6-3 Why did that happen?
6.2.3 Reaction Perspective (What’s going on?)

This perspective tries to find out “what information do I need to make decisions?” For example, in the user case, at time t2, a hospital manager considers using backup water because there is no water supply from the water station. Before making the decision, the hospital manager needs to consider two important dependencies. First of all, the external water backup – the pool water – is also an emergency backup for the fire department. Secondly, campus planning is in charge of the emergency sharing plan. Since these dependencies only exist under emergency conditions, they may be easily ignored by the hospital manager. Therefore, in my design, I try to remind users of the hidden interdependency. For instance, when the water backup is triggered, these hidden interdependencies will appear on the display (in Figure 6-4, as an exclusively-shared interdependency between the hospital and the fire department, as well as the information flow between hospital and campus planning).
Figure 6-4 What's going on?
6.3 Common Ground Features

The research of CoMotion, Chuah and Roth (2003) suggested that collaborative visualization environments should try to take advantage of virtual information spaces and provide common ground features. The proposed information model in this thesis is capable of supporting most of these common ground features:

- **Explicitly shared objects and events**: In CI interdependency visualization, these are the objects and updates of both the infrastructure component and interdependency graph, as well as the attributes which can be represented by different kinds of visual cues. They are the central focus of the visualization which people can directly refer to.

- **Goals for analyzing objects and events**: Showing broken interdependency links, priorities and alarms helps infrastructure managers identify potential problems and be aware of others’ interests.

- **Interpretations and thoughts**: The meaning and patterns perceived by the infrastructure managers can be shared by posting annotations attached to infrastructure components.

- **Level of attention on the objects and history of objects**: These two features are supported by the time-based visualization with annotations and backward and forward traces. The users can issue a backward trace to see what causes the problem and who else is affected. They can re-visualize previous updates of the simulation to see how certain objects are affected over time. They can also check the annotations for others’ suggestions and questions.
The implicit shared objects and events, as well as the people's emotional reactions and personal characteristics, are also the common ground features proposed by Chuah and Roth (2003). The proposed information model is unable to make these elements visible at the current stage. Are these features necessary to CI interdependency visualization? How do we visualize them in a CI interdependency visualization? The above two questions should be continually studied in the future.
CHAPTER 7: CONCLUSION

7.1 Introduction

This chapter provides a summary of the research. I review the thesis in the light of the I2C project and the design of the information model. Finally, I will summarize the contributions of this research and the recommendations for future studies in CI interdependency visualization.

7.2 Review of the Research

7.2.1 Problem and Motivation

Identifying, understanding and managing infrastructure interdependency is a crucial but difficult problem in emergency management. The visualization of CI interdependency is an effective way to facilitate the understanding of interdependencies across infrastructures. However, because CI managers are always coming from different expertises and industries, they sometimes have different and limited understanding of a set situation. To support the shared visualization of CI interdependencies, what is needed first is a common set of information that can be shared and understood across multiple infrastructures.

This motivation for this research was derived from the development of the I2Sim simulator system in the I2C JIIRP research project. The I2C’s approach to the user interface, I2UI, is a multi-view design involving a graph-based dependency view and a GIS based spatial view. The goal of this thesis is to propose a comprehensive information
model for developing shared visualization of CI interdependency, and to establish requirements for the graph-based dependency view.

### 7.2.2 Research questions revisited:

Objectives for this research have been twofold:

First, to define the data dimension of CI interdependency visualization. Two aspects were considered:

- Interdependency dimension: infrastructure type and interdependency criteria.
- Requirements for the visualization system: The interdependency data available in the UBC test case was considered.

The data dimension of the CI interdependency visualization was classified into four categories: identification information, dependency information, situation awareness information and additional information (Table 4-1).

Second, to establish visualization requirements in this information model, and in order to support interdependency visualization in the dependency view, I explained the design considerations from five aspects: layout, attribute arrangement and display, information updates and interdependency analysis.

To demonstrate the information model, I walked through the 12sim 5-cell test case using the 2006 UBC campus power shortage scenario (to illustrate both problems and solutions). From there, I further discussed how the information model would support the shared visualization of interdependencies with the following four major features: representing multiple interdependencies, supporting appropriate details, supporting time-based visualization, and capturing missing knowledge. I also explained how the
information model might support emergency management work from three user perspectives: planning, analysis and reaction.

7.2.3 Projected Use

The purpose the information visualization model is to support shared visualization which helps CI managers conduct emergency management work. The information model might be useful in the following circumstances:

- **Training**: Training CI managers to conduct collaborative work in a critical situation.
- **Simulation**: Running scenarios to assist CI managers in making decisions.
- **Analysis**: Tracing the interdependencies to figure out problems or vulnerabilities in the associated infrastructure entities.
- **Knowledge capture**: Collecting information from CI managers’ comments, suggestions and possible reactions in emergency scenarios.

7.3 Limitations and Future Work

The design of the visual model in this thesis is based on a research study of CI interdependency within the UBC campus area. I only touch upon some of the basic needs of the UBC campus emergency planners and infrastructure managers of the EOC. The visual model was drafted from my ideas, which will need to be put into practice and evaluation. Most of the design ideas need to be polished and adjusted through prototypes and user studies. The objective of the I2C JIIRP is to assist in information sharing and knowledge capture among emergency managers through CI interdependency simulation and visualization. The visual model is a very initial step to CI interdependency visualization, and many other research efforts need to be followed to reach the overall research goal.
7.3.1 Common Visual Language

In the walkthrough, I used colors, line styles and icons to denote interdependency information, but the specific colors, line styles and icons are only for the demonstration of the basic design idea. It is a good way to use visual language in shared visualization, but this may be constrained by what people are already using, therefore, the visual convention in CI interdependency visualization requires further user study. Currently, there is no defined or shared common visual language among managers from different backgrounds. Emergency managers of different infrastructures usually follow different rules and conventions on their individual work, in areas such as procedures, signals, colors, icons, and ways to raise alarm. The diversity of the conventions can cause misunderstandings in communication. Establishing a visual convention which can be accepted by all the infrastructure managers is fundamental in supporting the “common ground” of CI visualization.

7.3.2 Flow of Backup Information

Backup resources play a crucial role in a crisis management system. The backup systems/resources are often directly related to the availability of a service during an emergency situation, thus, it is a major concern for infrastructure managers during a service blackout. Information on a backup system could be represented in different ways, such as availability, storage, or remaining time. How this information should be passed across different infrastructures is an interesting point for future research.
7.3.3 Implementation of the Visual Model

The external user interface needs to be implemented based on the visual model. More interface details should be added into the interface design according to the user’s requirements, such as a command menu, toolbars, etc. I suggest implementing the focus + context navigation technique with the Continuous Zoom algorithm (Dill et al., 1994, Bartram et al., 1995). This will help support detailed views in various points of interests, without losing the larger context of the entire system.

7.3.4 Representation of Interdependency Impact

In this thesis, I did not explore how to represent the result of forward and backward trace on the display. The trace could be represented with various visual effects, and it is closely related to how people understand an interdependency impact. It is an interesting and important point to be further studied in the visualization of causality.

7.4 Conclusion

This research explores ways to visualize interdependencies of critical infrastructures and support shared understanding between infrastructure managers. As one part of the visualization research in the I2C JIIRP project, it contributes to the field of CI interdependency visualization by proposing a high level information model for supporting interdependency visualization and knowledge sharing. In this thesis, the model is demonstrated and discussed with the I2sim 5-cell test case and the 2006 UBC campus power shortage scenario. This research work is a first step to designing the user interface for the JIIRP I2Sim simulator, with the final goal being to develop a simulation
and visualization system which can assist infrastructure managers in emergency management training and planning.
APPENDICES
APPENDIX A: STEP BY STEP SCENARIO WALKTHROUGH

A.1 Time t0: Normal state

<table>
<thead>
<tr>
<th>Time</th>
<th>Events and Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0 1:00</td>
<td>Power</td>
</tr>
<tr>
<td></td>
<td>Normal state (Figure A-1)</td>
</tr>
</tbody>
</table>

Power view

At t0, the power view (Figure A-1) contains the power interdependencies among the off-campus power provider, the UBC power house, and the power consumers in the campus. To simplify the diagram, I use to represent a group of power links and campus buildings. On the power view, the power manager has access to all the detailed information within the power units, but by default, he has only high level overviews to the water, hospital and other buildings unless he asks to see the details. The grey “BK Power” node indicates that the power house has a power backup but it is not currently active.
Figure A-1 Power view at time \( t_0 \)
**Water view**

The water view (Figure A-2) contains the water and steam interdependencies among the resource provider, the UBC water house, and the water and steam consumers on campus. Compared to the power view, the water view contains less detail about the power house but more detail about the water house. The power links between the power house and the water house are kept on the water view because the regular operation of the water house is directly related to the power input from the power house.
Figure A-2 Water view at t0
Hospital view

On the hospital view (Figure A-3), the hospital facility manager has access to the details of power, water and medical interdependencies within the hospital. The external providers of power and water are represented as a high level overview of “UBC utilities” by default. The “Pool (Emergency BK Water)” is located outside of the “Hospital”, which indicates that the swimming pool is an external emergency water backup to the hospital. The grey color of the “pool” node indicates that the emergency backup is currently not in use. The interdependency link between the “Pool” and the “Hospital” will not show up until the hospital requires a water supply from the emergency backup.
Figure A-3 Hospital view at t0
## A.2 Time t1: Power breakdown from BC Hydro

### Table A-2 Events and actions at t1

<table>
<thead>
<tr>
<th>Time</th>
<th>Power</th>
<th>Water</th>
<th>Hospital</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>(Figure A-4) The power line (BC hydro -&gt; UBC substation) was broken.</td>
<td>(Figure A-8) The hospital power backup started. The water manager clicked the &quot;BK Power&quot; node for the status and volume of backup power.</td>
<td>(Figure A-10) The hospital power backup started. The hospital manager clicked the &quot;BK Power&quot; node for the status and volume of backup power.</td>
</tr>
<tr>
<td></td>
<td>Power from UBC substation to hospital = 0; Power from UBC substation to power house = 0; Power from power house to water station = 0. Power house backup started to provide limited power supply to the water station.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Figure A-5) Power manager zoomed in to the &quot;water&quot; node and tried to figure out how the power break might affect the water station. Power manager zoomed in the &quot;hospital&quot; node and tried to figure out how the power break might affect the hospital. Power manager checked problem links and alerts for detail information.</td>
<td>(Figure A-9) The water manager checked the detail physical and resource information of the input power links. The water manager zoomed into the &quot;Hospital&quot; node to check the alerts at Hospital.</td>
<td>(Figure A-11) Hospital manager zoomed into the &quot;UBC Utilities&quot; node and tried to figure out the source of the problem.</td>
</tr>
<tr>
<td></td>
<td>(Figure A-13) Updates showed the annotation from the hospital manager</td>
<td>(Figure A-14) Updates showed the annotation from the hospital manager</td>
<td>(Figure A-12) Hospital manager added in an annotation</td>
</tr>
</tbody>
</table>
Power view:

On Figure A-4, the \(\rightarrow\) on the power link (BC hydro -> UBC substation) indicates that the power line is broken. The \(\F\) symbol indicates the power supply to the hospital and the power house is down to 0. The \(\I\) symbol indicates the power supply to the water station is having a problem. The “BK Power” node turns from grey to yellow together with the oil dependency link showing up on the display, which indicates that the power house is currently operating with backup oil. The external oil dependency shows that the oil resource is from off campus, so the operation of the power house actually depends on the storage of the backup and the transportation of the fuel from an off-campus resource.

The \(\I\) symbols on the water and the hospital indicate critical problems in these areas. If the power manager wants to figure out how the power breakdown might affect the water station and the hospital, he can zoom in to access the details in the "Water" and the “Hospital” nodes (Figure A-5)
Figure A-4 Power view at t1 - A
Alert ID: 001
Time: 1:20 am
Power Outage from BC hydro is seriously Damaged.

Power line: p1
Capacity: 10
Condition: Damaged
Time: 1:20 am

Backup Status: on.
Time left: 15hrs

Figure A-5 Power view at t1 - B
On Figure A-4, while the water node is clicked and extended, the connected dependency link is also extended:

Water node before clicking

Water node extended after clicking. The interdependency links connected to the node are also extended

Figure A-6 Water node before and after clicking
Detailed information of the interdependency type can be accessed by clicking a dependency link. The following broken power interdependency link contains a physical interdependency and a resource interdependency, and the problem is with the physical interdependency because the pipe is damaged.

Before clicking

After clicking

Figure A-7 Interdependency link before and after clicking
Water view:

At t1, the water station no longer receives power from the power house, and the steam station receives only limited power input. On the water view (Figure A-8) the “BK Power” turns from grey to yellow and the oil dependency link appears on the display, which indicates that the water station is currently operating with backup power. Similar to the power view, the external oil dependency shows that the oil resource is from outside campus, so the operation of the water station depends on the storage of the backup oil and the transportation of oil from the off-campus resource. The water manager can click the "BK Power" node for the status and volume of backup power.

At this moment, another problem is knowing how long the power supply to the steam station will last. This information is related to the backup storage of the power house. The water manager may not have access to the internal details of the power house, but the storage information will be passed by the link, so the water manager can click the restriction symbol or the link to see the status of the power input (Figure A-8; Figure A-9). Note that the broken link is now a common reference between the water and the power manager.
Backup Status: on.
Supply left: 15hrs

External Oil

Power Station

Limited supply with backup power
Flow: 20%

Figure A-8 Water view at t1 - A
Figure A-9 Water view at t1 - B
**Hospital view:**

At t1, the hospital is operating with internal backup power, limited external water and limited external steam supply. To make decisions on reducing or suspending part of the medical services, the hospital facility manager needs to know how long the power, water and steam supply will last (Figure A-10). The hospital manager may also want to trace back to the source of the problem by requiring more details from UBC utilities (Figure A-11).
Figure A-10 Hospital view at t1 – A
Figure A-11 Hospital view at t1 – B
After evaluating the overall situation, if the hospital manager suggests reducing service by stopping the acceptance of new patients, he can add in annotations with the title "reduced service" to the display as shown in Figure A-12. The title of the annotation will be updated on the power view and the water view. The power manager and water manager can click the icon to see more details in the node (Figure A-13, Figure A-14).
Figure A-12 Hospital view at t1 - C
Figure A-13 Power view at t1 - C
### A.3 Time t2: Water pipe burst

Table A-3 Events and actions at t2

<table>
<thead>
<tr>
<th>Time</th>
<th>Events and Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Power</strong></td>
</tr>
<tr>
<td>T2</td>
<td>1:40</td>
</tr>
<tr>
<td></td>
<td>(Figure A-19) Updates showed the annotation from the hospital manager</td>
</tr>
</tbody>
</table>

**Water view**

At t2, the water pipe linking the water station to the hospital burst. On the water view (Figure A-15), the pipe broken symbol appears on the link (water station -> hospital). Water supply to the hospital is down to 0.
Power view

Similar to the water view, on the power view (Figure A-16), the pipe broken symbol appears on the link (water station -> hospital).

Hospital view

On the hospital view (Figure A-17), the active “BK water pump” shows that the hospital is requiring backup water from an external emergency water supply, the swimming pool. New interdependency links in grey pop out, showing that the emergency water resource is shared between the hospital and the fire station, and campus planning is responsible for providing the sharing plan. The hospital decides to close long term services. Several information interdependency links appears between “hospital” and “campus planning”, and between “hospital” and “first responders”, which suggests that the hospital informed campus planning and first responders about the reduced operations.

On the hospital view, the hospital manager adds in annotation what the water breakdown means: closing the long term services (Figure A-18). This information is updated on both of the power view and the water view (Figure A-19, Figure A-20).
Figure A-15 Water view at t2 - A
Figure A-16 Power view at t2 - A
Figure A-17 Hospital view at t2 - A
Figure A-18 Hospital view at t2 - B
Figure A-19 Power view at t2 - B
Figure A-20 Water view at t2 - B
A.4 Time t3: Hospital long term service is closed

Table A-4 Events and actions at t3

<table>
<thead>
<tr>
<th>Time</th>
<th>Events and Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>Power</td>
</tr>
<tr>
<td></td>
<td>(Figure A-23) Updates showed that the hospital is in emergency state with backup power and water. Power manager checked the current storage of the backup power.</td>
</tr>
<tr>
<td></td>
<td>Water</td>
</tr>
<tr>
<td></td>
<td>(Figure A-22) Updates showed that the hospital is in emergency state with backup power and water.</td>
</tr>
<tr>
<td></td>
<td>Hospital</td>
</tr>
<tr>
<td></td>
<td>(Figure A-21) Hospital started to function with backup water. Long term service was closed</td>
</tr>
</tbody>
</table>

Hospital view

On the hospital view (Figure A-21), the interdependency links connected to the "Long term service" disappear, and the "Long term service" node is closed and shrank. The interdependency link between "Short term/emergency" and "Pool" turns blue, which indicates that the hospital has started to function with the backup water from the swimming pool.
Figure A-21 Hospital view at t3

Water view

On the water view (Figure A-22), updates show that the hospital is in emergency state operating with backup power and water.

Power view

On the power view (Figure A-23), updates show that the hospital is in emergency state operating with backup power.
Figure A-22 Water view at t3
Figure A-23 Power view at t3
A.5 Time t4: The water pipe is fixed

Table A-5 Events and actions at t4

<table>
<thead>
<tr>
<th>Time</th>
<th>Events and Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Water</td>
</tr>
<tr>
<td>T4 13:40</td>
<td>(Figure A-26) The water pipe was fixed. The water station replaced the backup water to provide water supply to the hospital, but the water flow was still restricted.</td>
</tr>
</tbody>
</table>

On the water view (Figure A-24) and hospital view (Figure A-25), the broken pipe symbol and the backup water interdependency link disappear, which indicates that the water supply from the water station has been recovered. The hospital is no longer using the backup water, but the water supply from the water station is still restricted. This update about the fixed water pipe is also shown on the power view (Figure A-26).
Figure A-24 Water view at t4
Figure A-25 Hospital view at t4
Figure A-26 Power view at t4
A.6 Time t5: Power is restored

Table A-6 Events and actions at t5

<table>
<thead>
<tr>
<th>Time</th>
<th>Events and Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5 14:20</td>
<td>(Figure A-27) Power restored. All back to normal</td>
</tr>
</tbody>
</table>

On the power view (Figure A-27), water view (Figure A-28) and hospital view (Figure A-29), the dependency links connected to the backup power disappear and the backup power nodes turn grey, which indicates that the backup power is no longer active and the power service is back to normal.
Figure A-27 Power view at t5
Figure A-28 Water view at t5
Figure A-29 Hospital view at t5
REFERENCES


UBC emergency operations centre (EOC) exercise plan, 2005. Department of health, safety and environment, University of British Columbia.


Ware, C. (2004). Information Visualization: Perce$$
