

Prototyping and Cells Modeling of the Infrastructure Interdependencies Simulator I2Sim

by

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Abstract

The functioning of modern societies is strongly dependent upon an array of complex national infrastructure networks such as power utilities, information technology, health care, water supply and transportation; these networks provide material support for the delivery of basic services to all segments of the society. However, these critical infrastructures are becoming increasingly complex and fragile because of their tightly coupled structures which can rapidly propagate failures. Thus, there is a need to investigate the highly complex physical, information, geographic, and logic interdependencies among critical infrastructures. One needs to fully understand the dynamic behaviors of these interdependent networks in order to analyze and evaluate their robustness and resilience to natural disasters. This also helps operators to take actions in order to optimize the coordination among infrastructures during emergencies. Models based on a novel approach have been implemented. In this thesis, a reduced scale test case model of the University of British Columbia's critical infrastructures has been developed and implemented in software. Critical entities are defined as cells. The cell models are built based on input-output relationships discussed with and validated by the personnel involved with the concerned infrastructures; the interconnections between the cells are modeled as a variety of channels that defines quantities exchanged by different infrastructures, like electric power. The aggregated cells and channels are simulated with an interactive graphical user interface for the study of infrastructure interactions. The simulation indicates that the redundant systems increase the robustness of the cells such as the backup generators in the Hospital; the critical connections, such as the steam pipe linking the Steam Station with the Hospital are identified. These give the decision makers a better understanding of the emergent system behavior under different operational scenarios. One scenario is studied by using a distributor, which allows an operator to find the optimum allocation of the limited resource in order to ensure the best possible operation of the other critical infrastructures during the event. The simulation itself was parallelized, and distributed in PC-cluster at the UBC Power Systems Lab.

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To My Family

Chapter 1 Introduction

1.1. Background

The advancement in science and technology has made the critical infrastructures of a society tightly interconnected and mutually dependent. Some aspects of this interdependency include physical factors, human behavior and information sharing; however, all these are vulnerable to disasters. Natural or man-made disasters happen and can cause thousands of severe casualties. The Asian Tsunami on December 26, 2004 caused a total loss of 229,866 human lives [1]. Another unfortunate incident, Hurricane Katrina, which struck on August 23, 2005, was responsible for a total damage of \$81.2 billion and a loss of 1,464 human lives [2]. These disasters have made the protection and restoration of critical infrastructures, such as health care, utilities, transportation and communication, a serious national concern. The joint infrastructure interdependencies research program (JIIRP) is part of an ongoing national effort to secure and protect Canada's critical infrastructures [3]. The objective of the JIIRP research at the University of British Columbia is to study decision making for critical linkages in infrastructure networks. A well developed model is essential for facilitating coordinated decision making.

Rinaldi [4] has defined four primary classes of interdependencies: the physical, cyber, geographical and logical. Two infrastructures are physically interdependent if the state of each is dependent on the material output(s) of the other. An infrastructure has cyber interdependency if its state depends on data transmitted through the information system. Infrastructures are geographically interdependent if a local environmental event can create state changes in all of them. Two infrastructures are logically interdependent if the state of each depends on the state of the other via a mechanism that is not a physical, cyber, or geographical connection. The emphasis in this thesis is on the physical layer. Modeling interdependent infrastructures is a complex, multifaceted, multidisciplinary problem, where it

is necessary to choose a specific approach to encompass the infrastructures and their interdependencies.

1.2. Related Research

The modeling of individual entities in the system as well as the combined whole system is fundamental and essential for the analysis of infrastructure interdependencies, the optimization of the restoration process, and for support make the best decisions. Various modeling approaches are reviewed in this section. Disaster situations such as natural disasters, deliberate attacks or accidental system failures within infrastructures may result in cascading effects; these effects between infrastructures are dynamic and may not be apparent or immediately understood. Therefore, the literature on interdependency modeling and simulation has to be reviewed.

Some research has been done on certain types of disasters. In the case of earthquakes, floods and hurricanes, a tool based on GIS has been developed by the Federal Emergency Management Agency called HAZUS; this agency analyzes potential losses from disasters such as earthquakes according to geographic locations; it also analyzes the severity of an earthquake by estimating the physical damage, economic loss and social impact [5]. A similar research has been developed by MCEER at the State University of New York at Buffalo, which is a national center of excellence dedicated to establishing disaster-resilient communities through the application of multidisciplinary, multi-hazard research. MCEER mainly focuses on restoration modeling of lifeline systems and has conducted relevant research on multiple infrastructures [6].

A survey [7] of U.S and International work on critical infrastructure interdependency modeling has been compiled; this survey identifies and catalogs many of the state-of-the-art research being conducted in the area of infrastructure interdependency modeling and analysis. The thirty types of simulations listed in the survey are based on different modeling approaches such as agent-based models, effect-based operation models (EBO), input-output models, system dynamics models, mathematical models, models based on game theory,

models based on risk, etc. In recent years, modeling approaches such as the system dynamics model, input-output model, Petri-Nets model and agent-based model have been implemented in various works on critical infrastructure interdependency modeling. One of the modeling approaches is the cell-channel model for the Infrastructure Interdependencies Simulator (I2Sim) developed at the University of British Columbia.

✧ *System Dynamics*

System dynamics, founded in the late 1950s by Jay W. Forrester of the MIT Sloan School of Management, is an approach for understanding the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire system. The system components of this approach are the use of feedback loops, stock and flows. A stock is the term for any entity that accumulates or depletes over time. A flow is the rate of change in a stock. Stocks and flows help describe how a system is connected by feedback loops. In the terminology of system dynamics, a system is defined as a collection of elements that continually interact over time to form a unified whole. Dynamics refers to change over time. System dynamics is, therefore, a methodology used to understand how systems change over time [8]. The system dynamics model uses differential equations to describe the behavior of systems, so it is well suited to modeling continuous systems and less well suited to providing a detailed representation of a system where there are discrete changes in state variables.

One of the implementations of the system dynamics modeling approach is in the research of a health care system, for example, modeling the consequences of major incidents in a health care system [9]. Natural disasters or terrorist acts can have severe impact on a health care system by overloading it with casualties. The model represents the interrelation between the population, the health care infrastructure and other infrastructures. The population is set as different types of patients and based on the relationship between them, the population changes at different rates in different disaster scenarios. The interactions between types of patient flows are described in detail; the interactions between health care infrastructure and other infrastructures are not mentioned comprehensively. Another research group using system dynamics as the modeling approach is the Sandia National Laboratories [10]. They

have built a modeling framework based on system dynamics and IDEF Φ (a method designed to model the decisions, actions, and activities of an organization or system). Using the system dynamics, a model of infrastructure interdependencies can be built using the causal-loop diagram to capture the structure of the systems. It can provide a high-level view of relationships, interactions, and feedback processes; however, it is hard to see the physical buildup and flows of information and products through the system. At the same time, the model also needs to use IDEF Φ for functional modeling to define data requirements and describe the exchange of information between the individual models. The system dynamics approach can be used in modeling interdependencies of the infrastructures in a high-level view.

✧ *Generalized Leontief Input-Output Model*

Inoperability Input-Output Model (IIM) in [7] is the model based on Leontief's linear input-output relationship. It characterizes interdependencies among sectors in the economy and analyzes initial disruptions to a set of sectors and the resulting ripple effects. Wassily Leontief received the 1973 Nobel Price in Economics for developing what has come to be known as the Leontief's input-output model of the economy[18]. His model gives an understanding of the interconnectedness among the various sectors of an economy and forecasting the effect on one segment of a change in another. With his research group at the University of Virginia, Professor Yacov Y. Haimes [11] [12] [13] developed the technology to model critical infrastructures using the inoperability input-output model. Based on the technology, a Leontief-based input-output model (IIM) is developed for modeling the impacts of willful attacks on interdependent sectors. The IIM is a model for assessing sector vulnerabilities using the inoperability and economic loss impact metrics. For example, the model has been used to research a high-altitude electromagnetic pulse (HEMP) attack scenario. It is mainly used in the economic and risk management of complex interconnected systems. Leontief's model assumes linear relationships between inputs and outputs, also it does not consider the problem of goods transportation.

✧ *Petri-Net Model*

A Petri Net is one of several mathematical representations of discretely distributed systems. It is a graph-based tool for depicting the structure of a distributed system as a directed graph, which is composed of place nodes, transition nodes, and directed arcs connecting places with transitions. Input arcs connect places with transitions, while output arcs start at a transition and end at a place. Places can contain tokens; the current state of the system component is given by the number of tokens in each place. Transitions are active components; when they are triggered, the triggering removes tokens from its input places and adds them to some of its output places. A test case using Petri Net to model infrastructure interdependencies is represented [14]. The model has been designed in high-level abstractions based upon a general interdependent infrastructure system, which includes electric power, oil, transportation, natural gas, telecommunications and water. The static states of the critical infrastructure are “on : 1” and “off: 0.” Based on this model, the interdependencies of the system are identified. However, it is not well suited for describing the model in quantitative and scalabilities analysis under different damage states.

✧ *Agent-Based Model*

Nowadays, the agent-based paradigm has become one of the most popular approaches in general software development. Nearly half of the simulations in [7] use the agent-based model. One of them is the next-generation agent-based economic laboratory “N-ABLE” developed by researchers at Sandia National Laboratories [15]. These agent-based systems try to tackle a variety of complex problems using a fully distributed, bottom-up approach. The tool has been mainly used for studies involving the economic impact resulting from disruptions on infrastructures and supply chain.

✧ *Cell-Channel Model*

The cell-channel model used in the I2Sim simulator under development at UBC [16] considers the nonlinear relationships among all interdependent entities in the system. The model is based on the idea of service token delivery to different infrastructure entities. The system components include cells, channels, and tokens. Tokens are goods and services that

are provided by one entity to another entity that uses them. A cell is an entity that performs a function. Channels are the means through which tokens flow from one generator node to a load node. The interrelationship between the input(s) and output(s) of the cells determines the cells' functionality. The channel is described using functions with capacity limitations and time delay. The combined cells and channels model makes up the multiple networks system. It has been used on physical layer modeling of interdependent infrastructures and run in the I2Sim simulator. The I2Sim simulator aims at simulating the conditions of each infrastructure component (cells, channels, input and output tokens) for large disaster scenarios to support decision making to mitigate the disaster effects.

In conclusion, many modeling approaches have been implemented in the research on interdependent infrastructures. Each of them has its strengths in specific study fields. Actually, the system of the interdependent infrastructures is a mixed system, consisting of both continuous and discrete subsystems. Considering the emergent scenarios after a disaster, the interdependent infrastructures are very complex and many discrete events are at work on the system, changing the state of the variables in the model. Moreover, the model has to provide the quantity and scalability of the nature for the system. As a result, to study decision making for critical linkage in infrastructure networks, especially for the physical layer of the system, the best-suited approach for modeling the system is the cell-channel model. In this thesis, the cell-channel model has been chosen as the approach to model and simulate critical interdependent infrastructures.

1.3. Research Objective

The work presented in this thesis has been part of a team effort to develop UBC's I2Sim simulator. Specific contributions have been the development of cell models for the UBC test case, including the complex hospital model. Another contribution has been the development of a test bench based on the MATLAB/Simulink software to serve as a prototype of the OVNI-based I2Sim software. In conjunction with the work by Siva Singupuram, this prototype has been implemented in a PC-cluster hardware architecture. The MATLAB I2Sim

prototype has been used as a proof-of-concept for full working demonstrations of the I2Sim capabilities to represent complex interdependencies scenarios.

Detailed nonlinear input-output models in the form of “Human Readable Table” (HRT) are developed in this thesis for five types of cells in the UBC campus: the electrical substation, the power house, the water station, the steam station, and the UBC hospital. The I2Sim concept was then implemented in a MATLAB/SIMULINK prototype using the detailed HRT tables developed. The prototype demonstrated the validity of I2Sim to replicate complex interdependency scenarios. The work also included the development of a user-friendly interface to allow operators to have a better insight into interdependencies. A soft clock was implemented to show the developed “real-time” simulation at human-friendly speeds for interactive simulation. In terms of hardware the prototype was implemented and demonstrated on a PC-cluster simulator developed at UBC’s Power Systems Lab.

The thesis is organized as follows:

Chapter 1 gives a brief introduction of the current JIIRP research and research objectives.

In Chapter 2, the general description of the interdependent infrastructure system is represented. The modeling approach, which is best suited to accomplish the research objective, is described based on the characteristics of the critical system components.

Chapter 3 describes the modeling of each individual component of the reduced-scale test case model, and then the overall system is described.

Simulation of a real world scenario is implemented and simulation results are analyzed in Chapter 4. A simulation related to the University of British Columbia’s critical infrastructures is described. An interactive, graphical user interface was designed to allow the decision makers to get a better understanding of the emergent system behavior in different operational scenarios. One such scenario is studied by using a distributor, which allows an operator to find an optimum allocation of a limited resource in order to ensure the best

possible operation of the other critical sectors during the event. The simulation was parallelized and distributed on the UBC Power Systems Lab PC-cluster.

The conclusion is in Chapter 5, which also includes suggestions for future research.

Chapter 2 I2Sim System Description

A system of interdependent infrastructure sectors is highly nonlinear and complex in nature. While modeling and simulation tools can provide insight into the behavior of individual infrastructure networks, a far less understood area is that of the interrelationships between multiple infrastructures. Specially, how does an event in one infrastructure directly or indirectly affect the operation of the other infrastructures? In this chapter, the I2Sim interdependent infrastructure system, including its critical components, is explained. I2Sim's critical components, cells, channels, and tokens are described. Finally, the I2Sim method of discrete event simulation for an interdependent infrastructure system is explained to represent the multiple infrastructure systems behavior in the time domain.

2.1. I2Sim Overview

The research objective of the JIIRP project in UBC is to study decision making processes in the context of critical linkages in multiple infrastructure networks and develop better strategies to mitigate disaster situations. The present volatile world situation and the rising trends of natural hazards have raised concerns for the smooth operation of these critical infrastructures. However, up to this date, only a few computational frameworks have been developed to assist researchers, decision makers and infrastructure service providers to understand the operational characteristics of these infrastructures during disaster scenarios. Based on this observation, the JIIRP group at UBC has been taken the initiative to develop simulation tools that can be useful for policy makers and infrastructure service providers. I2SIM is an effort which is a part of that initiative.

A number of modules are designed to support the functionality of the I2Sim simulator, for example, the database and the visualization modules, to name a few. Integration of the simulator with the database (I2DB), visualization (I2VIS), damage assessment (I2Dam), and other modules is shown in the figure 2.1.

I2Sim (Infrastructures Interdependencies Simulator) is a tool to achieve time-domain simulation of disaster scenarios affecting large scale systems of infrastructures. In particular, it is concerned with the simulation of both the physical layer and the human layer of infrastructures consisting of a large number of functional units. The I2SIM simulator is based on the methodology developed for the simulation of large power systems and implemented in the OVNI (Object Virtual Network Integrator) simulator developed by UBC's Power System Laboratory. The components in the I2Sim are identified by their function and at the highest level they are divided into two categories: cells and channels. Mathematically each cell and channel has a unique mapping to a large infrastructure matrix. The solution of this infrastructure matrix is based on the Multi-Area Thévenin Equivalent (MATE) network [22] partitioning technique, which gives the ability to solve a very large infrastructure matrix in a very efficient manner. In order to get the infrastructure matrix, first we need to model the functions of these cells and channels using Human Readable Tables (HRT), and then using a linearization method to convert the HRT table to the matrix. The linearization coefficients are incorporated into the MATE solution matrix.

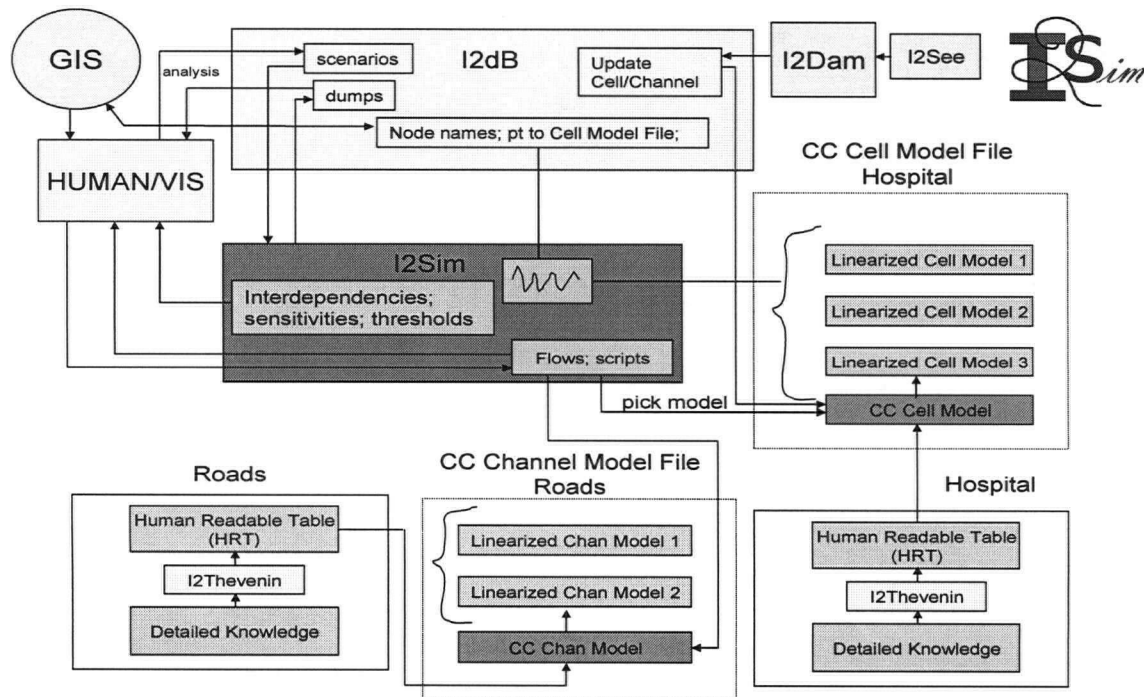


Figure 2.1: Diagram of Infrastructure Interdependencies Simulator [17]

The description of a system of infrastructures includes at least two layers: the physical layer and the human layer [16]. This thesis concentrates on modeling I2Sim aspects related to the physical layer. Many well defined models exist for individual infrastructure's analysis, but they do not tie the infrastructures together in a form representative of the actual interdependencies among individual infrastructures and do not support high-level coordination. The I2Sim cell-channel model approach [16] allows to model the infrastructure interdependencies. Within this context, the critical components in the cell-channel approach such as cells, channels and tokens have specific meaning and are defined as follows:

Definition 1: A cell is an entity that performs a function.

Definition 2: Transportation channels are the means by which tokens flow from a generator node to a load node.

Definition 3: Tokens are goods or services that are provided by one entity to another entity that uses them.

The cell-channel model for interdependent infrastructures mainly represents two parts: one is the performance of cells and channels themselves, and the other is the interconnecting relationship of these individual entities.

Figure 2.2 shows how a collection of infrastructure networks and their tight interconnection mechanisms compose a highly complex nonlinear system. The collection of cells and channels represents a dynamic and complex structure. The links between the different infrastructures can be clearly described as channels; channels can link two cells in two different infrastructures or in the same infrastructure. Figure 2.2 illustrates how a channel links the electrical Substation cell in a power system to the telephone service cell in information and telecom system. All the critical points in each infrastructure can be represented by cells and their interconnections by channels. Models of cells and channels have to be identified and built. The UBC Campus test case will be used in this thesis [19] to build an I2Sim prototype.

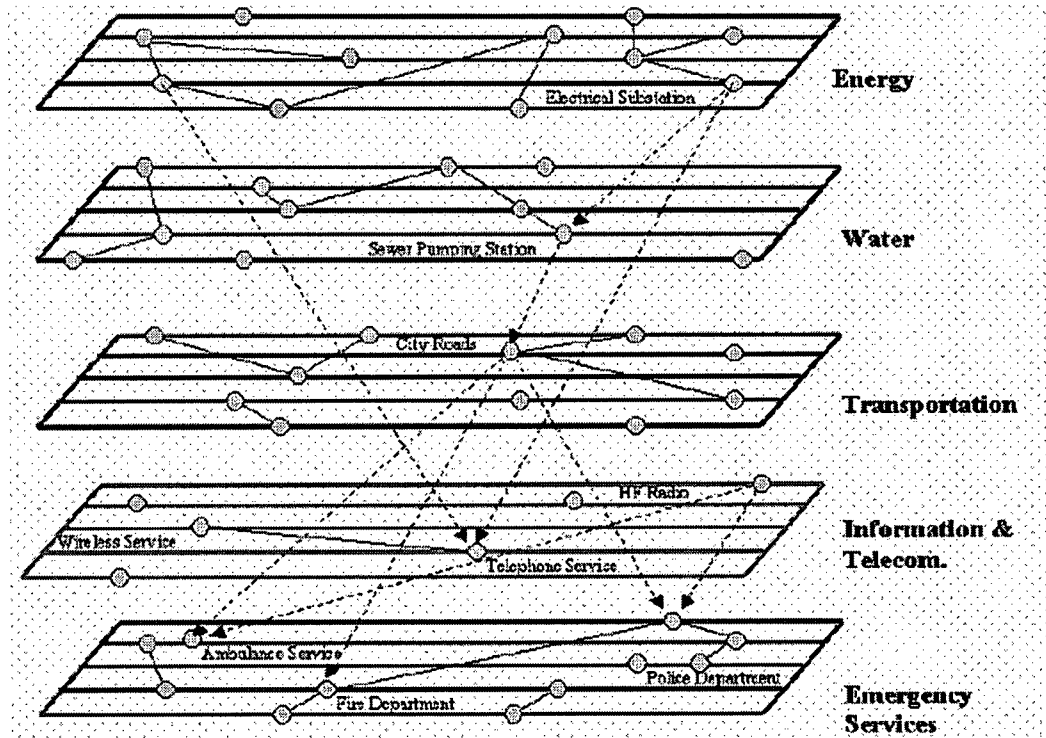


Figure 2.2: Infrastructure Interdependencies [7]

2.2. Characteristics of Cells and Channels

In the UBC test case [19], cells are first classified into several types according to their functions. The following 19 general categories are the cells in the UBC test case:

- ✧ Hospital
- ✧ Fire Hall
- ✧ Ambulance service
- ✧ RCMP
- ✧ Classroom and library
- ✧ Research lab and museum
- ✧ Residential
- ✧ Parking lots
- ✧ Recreation and society
- ✧ Substation
- ✧ Water station

- ◇ Telecom generator
- ◇ Transportation
- ◇ Food
- ◇ Commercial
- ◇ Administrator
- ◇ Services and utility
- ◇ Power House
- ◇ Steam station.

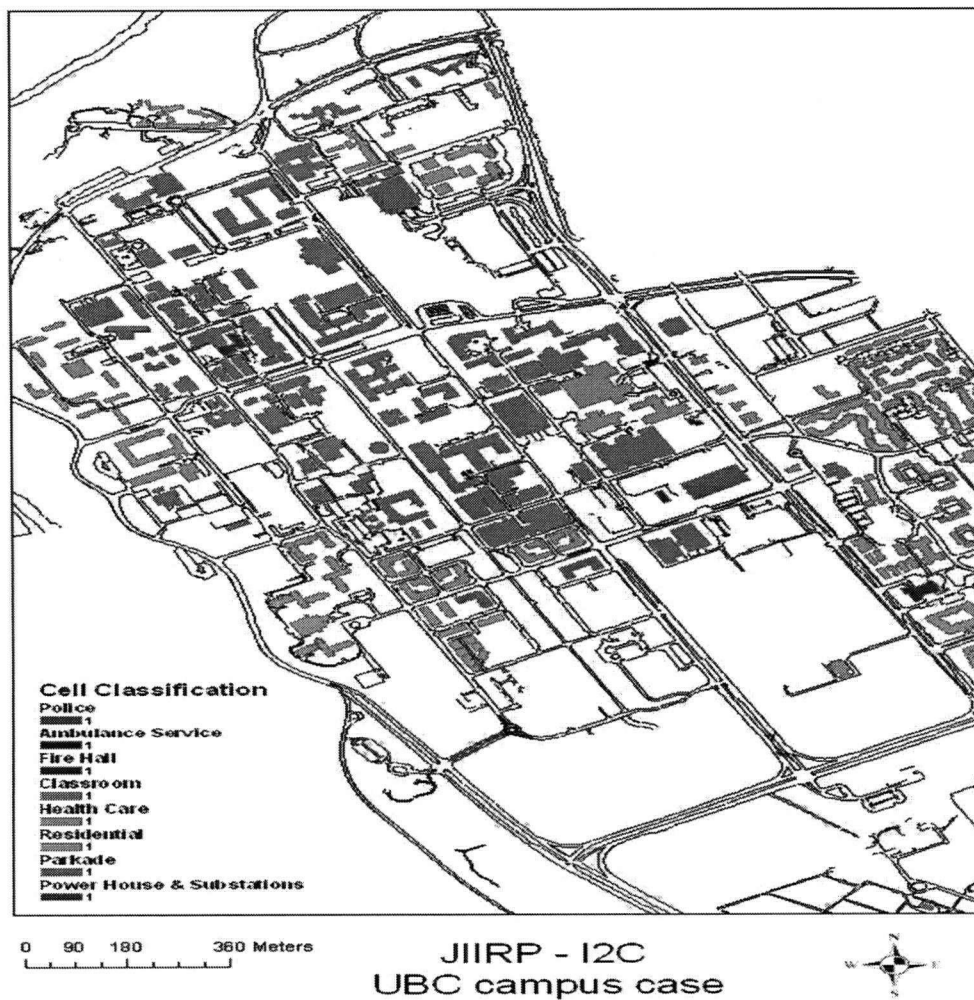
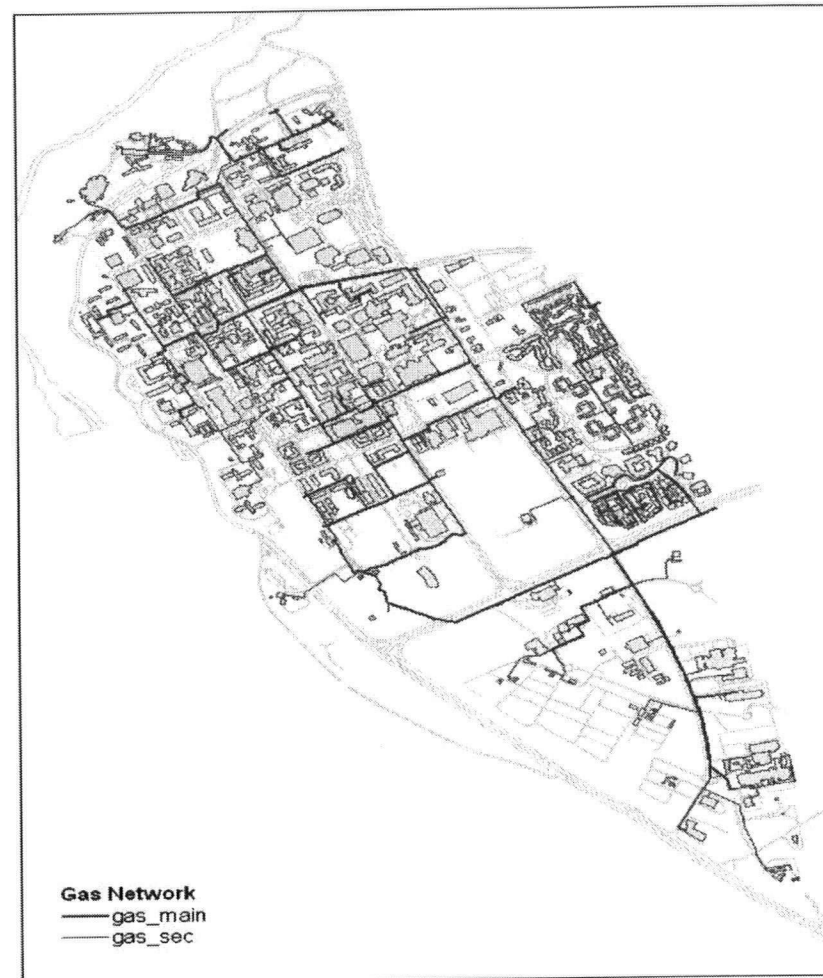


Figure 2.3: Cell Classification [17]



JIRP - I2C
UBC campus case



JIRP - I2C
UBC campus case

Figure 2.4: Electrical and Gas Networks [20]

Eight types of cells and two types of channels in the UBC test case are shown in Figure 2.3 and Figure 2.4. Each of them has its own functionality. It can be seen from Table 2.1 that different types of cells have different tokens and various channels link the cells to critical infrastructures.

Type of Cells	Critical Infrastructures					
Hospital	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input checked="" type="checkbox"/> steam	<input checked="" type="checkbox"/> gas	<input checked="" type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Fire Hall	<input type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Ambulance service	<input type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
RCMP	<input type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Classroom	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input checked="" type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input type="checkbox"/> communication
Research	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input checked="" type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input type="checkbox"/> communication
Residence	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input checked="" type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Parking	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input type="checkbox"/> communication
Recreation and society	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input type="checkbox"/> communication
Substation	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input type="checkbox"/> communication
Water station	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input checked="" type="checkbox"/> oil	<input type="checkbox"/> communication
Telecom generators and Hubs	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Transportation bus stop	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input checked="" type="checkbox"/> oil	<input type="checkbox"/> communication
Food and shops	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input checked="" type="checkbox"/> steam	<input checked="" type="checkbox"/> gas	<input type="checkbox"/> oil	<input type="checkbox"/> communication
Financial service and Commercial	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Administration	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Service and utility	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input type="checkbox"/> oil	<input checked="" type="checkbox"/> communication
Power house	<input checked="" type="checkbox"/> power	<input type="checkbox"/> water	<input type="checkbox"/> steam	<input type="checkbox"/> gas	<input checked="" type="checkbox"/> oil	<input type="checkbox"/> communication
Steamstation	<input checked="" type="checkbox"/> power	<input checked="" type="checkbox"/> water	<input checked="" type="checkbox"/> steam	<input checked="" type="checkbox"/> gas	<input checked="" type="checkbox"/> oil	<input checked="" type="checkbox"/> communication

Table 2.1: Cells and their Links to Critical Infrastructures

Cells have multiple inputs and outputs. Based on the relationship of inputs and outputs, the functions can be represented. It can be seen from Figure 2.5 that the outputs of cell #1 are the inputs of channel 1 and channel 2, through which tokens flow to cells such as cell #2 and cell #3. Depending on the function of a cell, the types of input tokens and output tokens are not always the same. The inputs can be water, gas, or power, and the outputs can be the number of beds in the hospital or steam flowing out of the steam station.

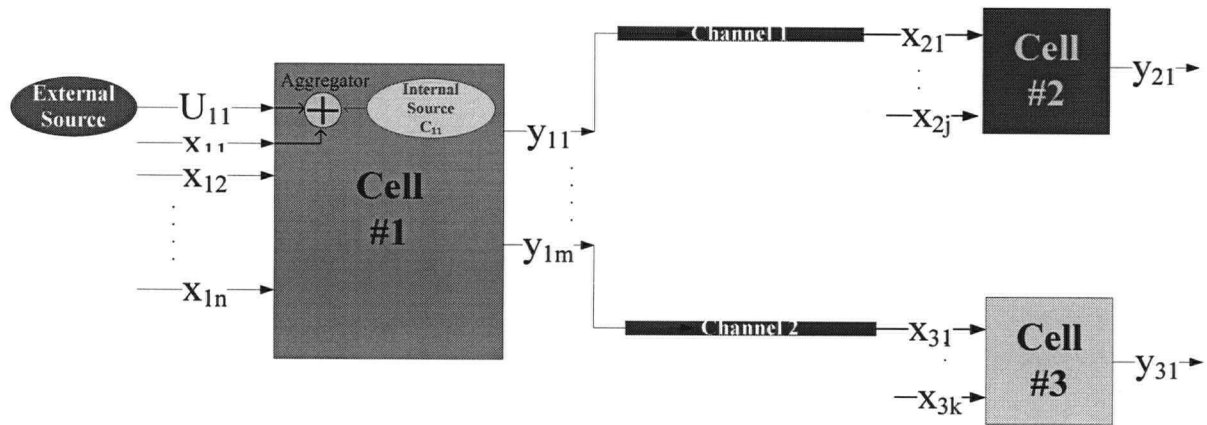


Figure 2.5: Structure of the Generic Cell-channel Model

A cell can have two other types of inputs. One is external sources which come from cells outside the selected system, through a channel sending specific types of tokens into the inside system of the cell; this is shown as U_{11} in the figure; the other is internal sources, which are the backup reservoirs inside the cell. Both of them are the inputs to the cell model. Since they own the same type of token, they are combined together as one input in the cell model by a "aggregator", which is shown in Figure 2.5. The variables in the figure follow the rules below:

- ✧ U : external sources
- ✧ C : internal sources
- ✧ x : input variable of each cell or output variable of each channel
- ✧ y : output variable of each cell or input variable of each channel
- ✧ subside letters ij
 - i means in cell $\#i$
 - j means j^{th} input or output of cell $\#i$, the number of j shows how many types of tokens the cell has

According to the types of tokens sent and received through the channel, the types of channels defined in the UBC test case are:

- ✧ Electricity
- ✧ Water
- ✧ Gas
- ✧ Steam
- ✧ Oil

The generic channel model has one input and one output. Each channel has its characteristic function, capacity and time delay. For example, in the water supply system, the water flowing through the water pipe from the sending end to the receiving end can be represented by using a function within three variables, which are the capacity, functionality and time delay of the channel.

- ✧ The capacity constrains the maximum amount of tokens transmitted through the channel.
- ✧ The functionality of the channel represents the state of the channel, which ranges from values between zero to one according its damage state.
 - 1 : the channel can carry 100% of its normal capacity.
 - 0.5: the channel can carry 50% of its normal capacity.
 - 0 : the channel is fully damaged and can not carry any token.
- ✧ The time delay depends on the type of token and the functionality of the channel.
 - In the normal state, the time for a token to be transmitted from the sending end to the receiving end is the delay factor of the channel. Usually the delay factor for the channel sending power can be zero, but the delay for transportation cannot be omitted. However, in this thesis, the delay time is not taken into consideration because it will not affect the performance of the reduced-scale test case model.
 - After a disaster, the functionality of a channel or cell drops because of damage and the time needed for repairs; the repair time is added to the normal time delay of the channel.

2.3. The Input-Output Model

The relationship between the inputs and the outputs of the cell, which defines its functionality, is described using the equivalent input-output model developed in I2Sim. Each cell has its own characteristic and is a non-linear system. The resolution represented by the input-output model depends on the selection of the critical components inside the cell.

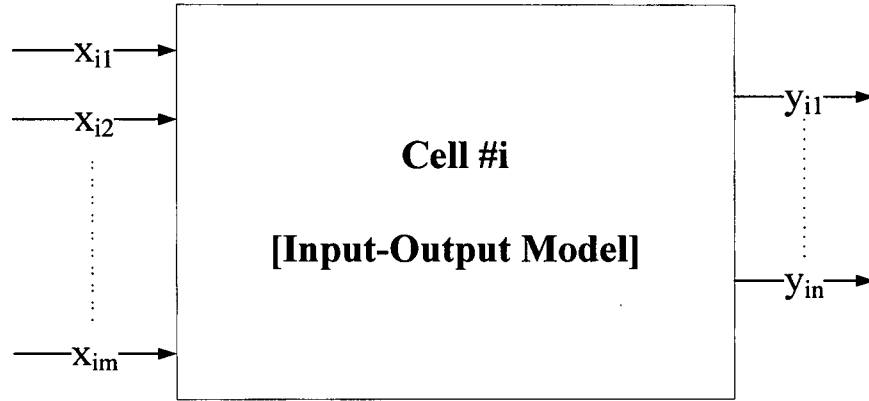


Figure 2.6: The Input-Output Model for Cells

The performance of cell #i in Figure 2.6 is illustrated as a black box. First, based on knowledge and industrial experiments, we can get information that certain amount of outputs depends on certain amount of combined inputs. For example, the hospital has seven input tokens--water, power, steam, heating, gas, medicines, doctors and nurses and three output tokens--numbers of beds for long-term, short-term and urgent patients. The input-output relations indicate the performance of the medical service capacity in the hospital. The different amount of each input token will make a difference in the outputs of the hospital. When in a normal state all of these input tokens sent into the hospital, the generated tokens for outputs are the hospital's maximum capacity; when one of these input tokens drops to zero, the outputs drop to zero. These two combined states can be described using the easily readable Table2.2 (defined as the "Human Readable Table" HRT in I2Sim).

Inputs							Outputs
water	power	steam	heating	doctors	nurses	medicines	Urgent
x_{i1}	x_{i2}	x_{i3}	x_{i4}	x_{i5}	x_{i6}	x_{i7}	y_{i1}
100%	100%	100%	100%	100%	100%	100%	100%
0%	100%	100%	100%	100%	100%	100%	0%

Table 2.2: Sample Data in the Human Readable Table for a Hospital Cell

The HRT rows can be used to define a multivariable piece-wise linear function. Mathematically, the relationship of the inputs and outputs of the hospital represent a set of nonlinear functions: $y_{i1} = f_1(x_{i1}, x_{i2}, \dots, x_{im})$. The rows in the HRT correspond to particular values of these functions. In I2Sim simulator, the behavior of the functions is assumed to be linear between these points. Figure2.6 illustrates the most basic case of a single input single output cell.

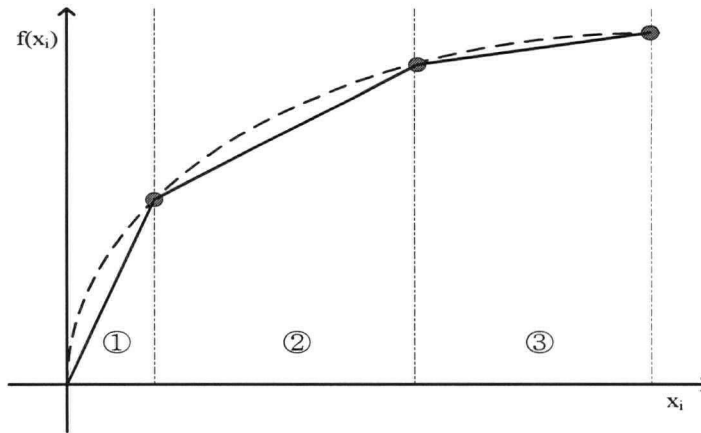


Figure 2.7: Piece-wise Linear Approximation for One Dimensional Function

The critical components inside cells whose functionality can influence the interaction of the input-output relationship are considered in the Human Readable Table as internal variables.

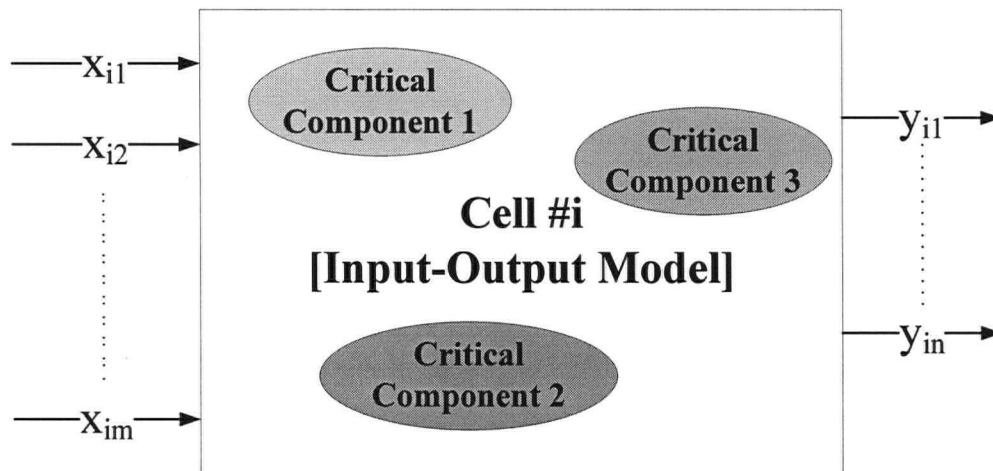


Figure 2.8: The Input-Output Model for Cells with Critical Components

The input output model includes critical components as well as inputs tokens. The critical components inside cells have their own functionality which can influence the outputs, even if the input tokens are maintained at fixed values. For example, in the Water Station, pumps are critical components; their functionality is the pumping of water. When the functionality of the pump drops to zero under some conditions, even if the input tokens of power and water are at the maximum amount, the output will be kept at zero. In the Water Station, many types of equipment support the water supply system; they do not need to be modeled explicitly

because only the external interdependency are studied in the model. In the input-output model of the Water Station cell the functionality of the pumps is one of the internal variables. Small time constants in the internal cell processes that are not relevant for the external scale of events are not explicitly represented.

Since the cells are connected to different infrastructures, which mean they receive different types of input tokens and produce some types of output tokens, the HRT table will describe the performance of the cells by combining quantities of different physical nature. The inputs of cells are multiple tokens such as water and power, and the physical amounts are different. For example, in the hospital cell, the average amount of power flow is about 1500kW and the average water consumption is about 14.5 m³/hr; they are different both in physical nature and in level of magnitude. In power system calculations a normalization of variables called per unit normalization is almost always used [21]. It is especially convenient when transformers and different voltage levels are involved. The idea is to pick base values for quantities such as voltages, currents, impedances, power and so on, and to define quantities in per unit as follows :

$$\text{quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}}$$

Using the per unit method of power systems for the input-output model for interdependent infrastructures, the cell functions can be described on a percentage level; this is achieved by using the maximum amount of each token as the base value of quantity; the actual quantity of tokens under any situation is represented as per unit value ranging from 0 to 1. In table 2.2 the quantity of input and output tokens has been calculated by using the per unit method. In the case of multiple cells with different physical units capacity, a common base needs to be chosen for the global system and the individual cell functions need to be scaled according to their rated capacity as compared to the global system base capacity.

2.4. Discrete Event Simulation

Based on the HRT input-output model for the cells, the interdependent infrastructures can be described as a discrete event-driven system. A discrete event system (DES) is a dynamic

system with discrete time and event-driven characteristics, which are asynchronous and possibly nondeterministic. In physical systems, events correspond to the actions that can change the state of the system, that is, they can trigger a transition between states. This form of description is usually based on the internal observation of the system dynamics. Alternatively, a discrete event system can be described by logical predicates over a set of state variables. In this case, an event corresponds to the change in one or more state variables and, consequently, results in a transition from one state to another. A discrete event system can also be described externally through its observed behavior. This is represented formally by the set of all event sequences that generate state transitions over time.

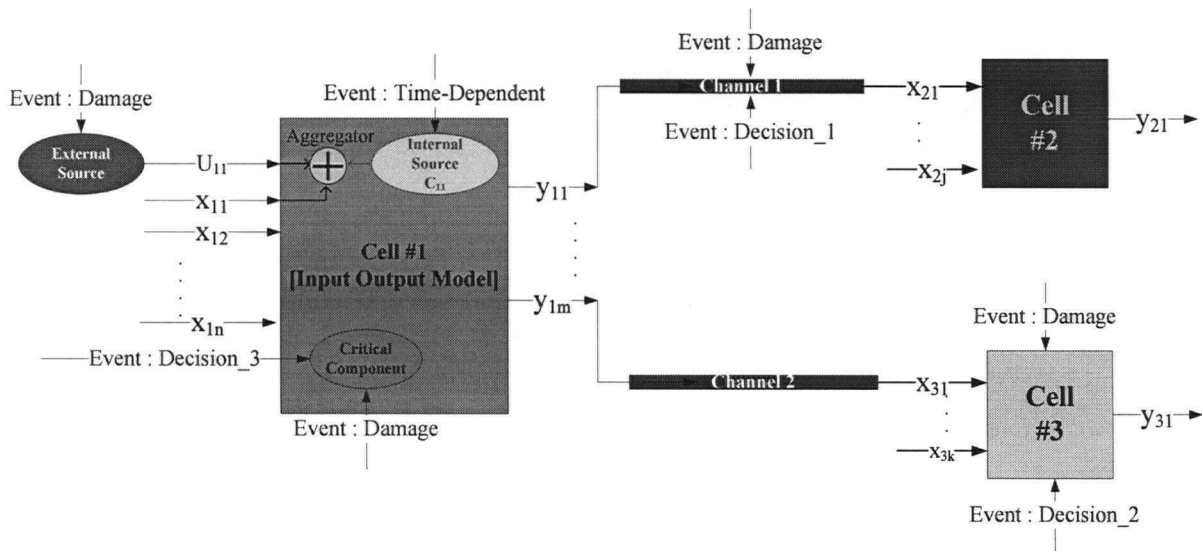


Figure 2.9: Events in the Cell-Channel Model

Figure 2.8 shows three types of events in the interdependent infrastructure system. These events are:

- **Uncontrollable event:** When a natural disaster or an operation failure occurs, the damage of the system can be described as the event to each cell and channel which change the internal state variables such as functionality of the cell or capacity of the channel. When a nondeterministic uncontrollable event strikes the system, the damage to a critical component--to cells or channels will depend on the type of disasters and the time when the disaster takes place.

- Time-dependent event: The event happens at a given cell at a certain time when a given cell is in a specific state. The event will affect both itself and through the interdependencies, the cells connected to it (Figure 2.9 cell #1). As an example, the power house has oil storage; when there is a power outage, the backup generator will begin to work and the stored oil will be consumed by the backup generator. How long the backup generator will work depends on when the storage-oil will be used up, and the oil run-out time is one of the critical factors of this event. After a certain time phrase, the event, "out of backup oil," is triggered. It will change the functionality of the power house cell and the outcome will affect cells linked to the power house.
- Decision-making event: This event is caused by a human being and is a stochastic event; it happens when people make decisions. After a natural disaster, many restoration procedures are in operation. Because of limitation in resources and repair crews, the restoration procedures follow a sequence of priorities. According to the decisions and the sequence of the procedures, events happening stochastically lead to different outcomes. For example, in Figure 2.9, it can be seen that parts of the cells and channels in the model need to be repaired and the decision makers make the decisions in a certain order. The action 'repair #1 channel first' is taken and the functionality of #1 channel is restored to its fully operational state 1 after it has been fixed; this affects cell #2 which is connected with this channel and then other entities linked to cell #2. Next, the decision to "repair cell #3" is made and the repair crew is sent to fix it; then the decision is to fix the critical component in cell #1. Each of the decisions affects the performance of the whole system.

The interdependent infrastructure system is composed of a set of interaction cells and channels. The interaction can be described by the change in the quantity of tokens sent or received by the cells or by the change in the linkage state of channels. The interaction schema of the system components is usually specified in one form or another and given as a part of the system description. In general, the existence of certain interactions between the cells means that the behavior of each cell in the system depends not only on its internal structure but also on the behavior of the other cells or channels. For example, when the channel of power, which is the transmission line sending power from the Substation cell to

the hospital cell, is damaged, the hospital cell will change its functionality because of this event (channel broken).

Furthermore, the interaction between the cells and channels also means that the set of events at any time in a given cell depends not only on the current state of these cells and channels, but also on the current states of the other components. For instance, if the power house is out of power; then the backup generator begins to work so that the power sent to the steam station will have no change; consequently, the hospital cell will receive steam from the steam station cell as usual. When the oil for the backup generator runs out, the power will drop to zero; at that moment, the event of being out of power will be sent to the hospital cell and influence its functionality. The current state of the hospital cell depends on the current state of the power house cell. This is a time-dependent event for it depends on how much oil the backup generator will use before it runs out and in turn influences the hospital cell.

In general, the research of infrastructure interdependencies is circumscribed to some degree because it cannot check the state of the whole system and analyze the damage assessment and restoration process because the data records of most real disasters are not complete. Although there are some damage analysis reports for natural disasters such as the disaster caused by Hurricane Katrina in 2005 and the Asian Tsunami caused by an earthquake in the Indian Ocean in 2004, the information is not sufficient for the research. As a tool, simulation has the capability to describe the different types of disaster scenario and use the information in the damage reports for comparison. Simulation can also test different sets of decisions for the same disaster scenario to find the optimal solution for restoration without wasting time and money; finally it can help to develop a strategy that can increase the resiliency of the critical infrastructures.

Chapter 3 The Generic Cell-Channel Model

In this chapter, a reduced scale test case model is built, using the cell-channel model; the test case model represents an interdependent infrastructure system. The model includes the most critical infrastructures in the UBC campus case and their interrelationship; it consists of five cells—the Hospital, Power House, Water Station, Steam Station and Substation. These cells are built based on the input-output relationships discussed with and validated by the personnel of the concerned infrastructures; the interconnections between these cells are modeled as channels. These cells are also modeled with the interaction to accommodate various sizes and capacities. Finally, the whole reduced scale test case model which includes cells and channels is summarized.

3.1. General Description

Although there have been many research studies on interdependent infrastructure systems over the last few decades, no benchmark model has been developed for multiple infrastructure interdependencies. It is important to test, verify and evaluate these models before implementing them in a disaster scenario. The UBC test case shown in Figure 3.1 is the first test case to evaluate the proposed modeling approach discussed in Chapter 2. The University of British Columbia has been chosen as the test case because it has the attributes of a small city and has infrastructures that represent an actual interdependent system containing enough interconnections for research on multiple infrastructure interdependencies. It can be the first step for investigating the interconnections between multiple networks.

The critical entities in the campus test case include five cells—the hospital, power house, water station, steam station and Substation; three external sources, which are defined as ideal external cells which send tokens from outside the campus. In this test case, only selected infrastructures are considered; they are electricity, water, gas, oil and steam. Five types of

channels are defined in the model. Each critical cell is located in the UBC campus in one or several buildings as shown in Figure 3.1.

The UBC electrical Substation is the connection link between the BC Hydro transmission network and the UBC campus power network. The electricity is transmitted from BC Hydro to UBC via two 60kV AC high voltage overhead lines.

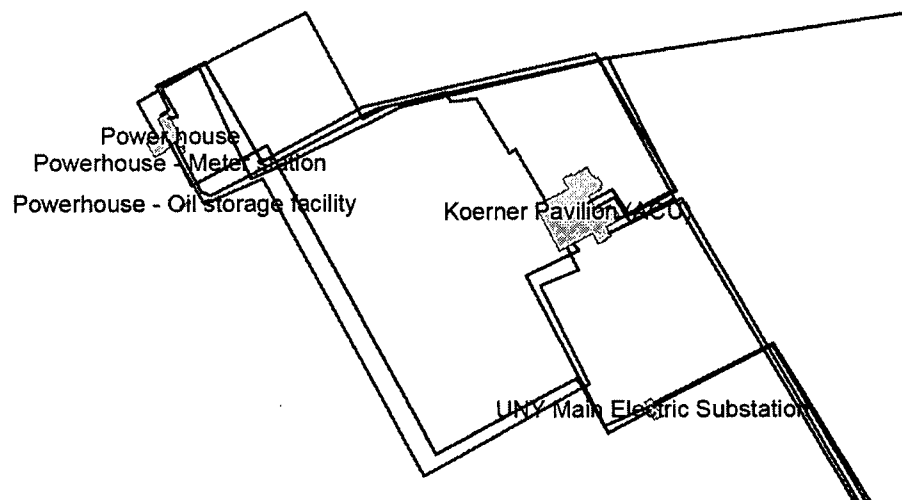


Figure 3.1: GIS-Mapping of the UBC's Test Case [20]

The UBC Hospital is one of two acute care facilities that are part of the Vancouver General Hospital and the Health Sciences Centre. It is located in the UBC campus [23]. The UBC Hospital is composed of three buildings--Detwiller Pavilion (Short-Term, Psychiatry), Koerner Pavilion (Acute Care, shown in Figure 3.1) and Purdy Pavilion (Long-Term Care). In the Koerner Pavilion there is an urgent-care centre which offers specialized treatment for non-life threatening emergencies by emergency-trained physicians and nurses [24].

In the case of the UBC campus, water and heating are two critical infrastructures for supporting the normal functioning of the campus' life. For the UBC water supply system, the water resource comes from the reservoir located outside the campus in the Pacific Spirit Park. There is a water pumping station in the water supply system which is located in the UBC Power House. On the model, its functionality is defined as a " Water Station" cell.

The steam supply system provides heating to parts of the campus where there are critical facilities such as the UBC hospital. The steam system contains one steam generator located in the UBC Power House. Although it is located in the same building as the water station, based on its functionality, it is defined as the "Steam Station" cell. The steam flows into buildings and then back to the Steam Station through a steam network in a closed loop.

The external cells send electric power from BC hydro, water from Pacific Spirit Water Reservoir and gas from Terasen Gas to the UBC campus. The Pacific Spirit Water Reservoir supplies water to the Water Station, then the Water Station supplies water to the UBC Hospital. There are two transmission lines between BC Hydro and the Substation. The Substation supplies electricity to the Power House and the Hospital, and the Power House supplies electricity to the Water Station and Steam Station. The external resource Terasen Gas provides gas to the Hospital and Steam Station.

The interconnections between these cells are illustrated as follows:

- ✧ Electric power
 - Power sent from BC Hydro to the Substation
 - Power sent from the Substation to the Hospital and Power House
 - Power sent from the Power House to the Water Station and the Steam Station
- ✧ Water
 - External water sent from outside to the Water Station
 - External water sent from the outside to the Steam Station
 - Water sent from the Water Station to the Hospital
- ✧ Steam
 - Steam sent from the Steam Station to the Hospital
- ✧ Gas
 - External gas sent to the Steam Station
 - External gas sent to the Hospital
- ✧ Oil
 - Oil sent from the Power House to the Water Station
 - Oil sent from the Power House to the Steam Station

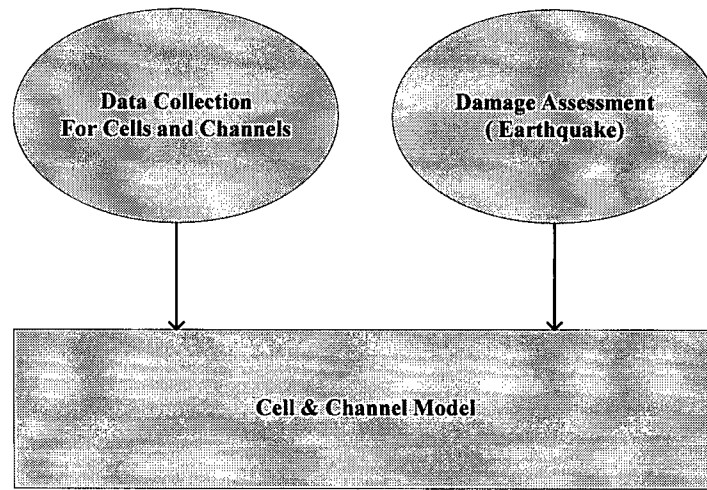


Figure 3.2: Data Flow for the Cell-Channel Model

A key to modeling is the availability of credible and traceable data. Gathering information on a particular cell is a significant challenge when developing the model's structure. All the data used in this thesis comes from UBC Utilities and the UBC Hospital.

Actually only the owner of the cell has the detailed knowledge of the internal detailed structure and relationship for the entity. The model tries to capture the input-output relationship among the critical interdependencies with other sectors. The Human Readable table is exactly filled in by the cell owner. In the case of the reduced scale test case shown in the thesis, we did it because it is the new approach for modeling the system and also we built it with the owners of UBC facilities.

Another data source for the model is the functionality of the system components. The functionality of a building after an earthquake will affect the performance of the cells located in these buildings. The structural damage can be divided into four levels; each of them has functionality data which are used for developing the model. If there is no damage to the building, the functionality of the cell is at 100% functionality; when the building gets slightly damage, the functionality is at about 80%, moderately damage at 50%, and severely damage at 0% [32]. These data can change depending on the type of disaster.

In this thesis, the external sources are considered ideal sources; the external source is always in normal state without any damage. In this chapter, both the data collection and the models of the critical cells will be described.

3.2. The Substation Model

3.2.1. Inputs and Outputs of the Substation Cell

As mentioned in section 3.1, the UBC Substation gets power through two transmission lines from BC Hydro and it in turn supplies power to the UBC campus. It primarily includes two matching transformers which have 47.6MVA maximum capacity, two tiebreakers, buses and feeders. The basic functions of the Substation are illustrated in Figure 3.3.

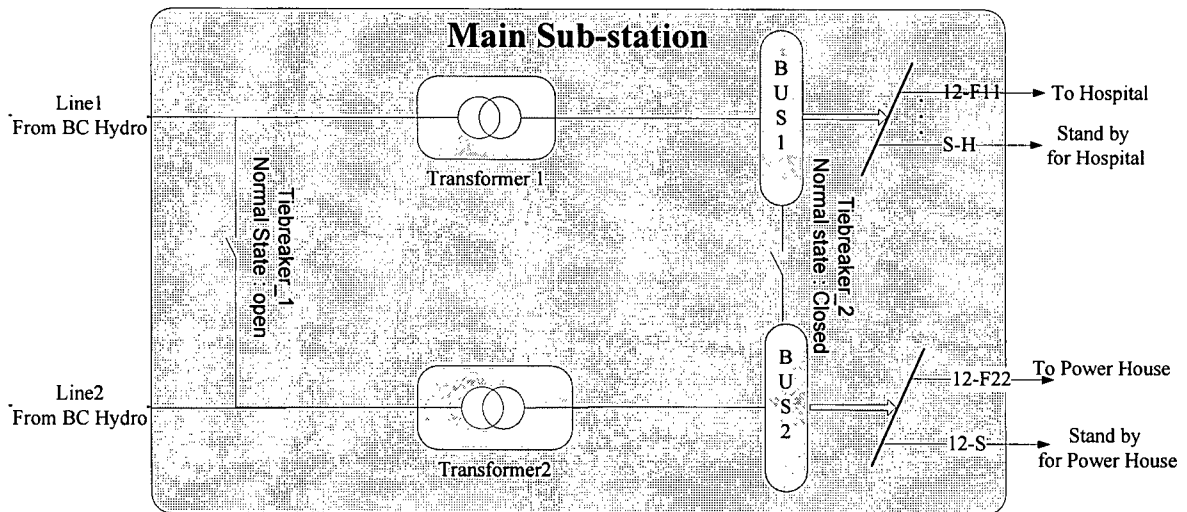


Figure 3.3: Diagram of the Basic Functions of the UBC Substation

The consumption of electricity at the campus sub-station is about 200 GW-hr over a period of one year; this means an average power flow of 0.0228Gw for the whole campus. There are 16 high voltage “distribution” feeders in two buses, which leave the main substation to other buildings. These bus feeders, known as the main substation common buses, are normally connected in parallel with a normally closed tiebreaker, which is tiebreaker2 in Figure 3.3. There is some redundancy built into the Substation. For example, tiebreaker2 is linked to bus1 and bus2; if one of the external transmission lines is broken or if one of the transformers does not work, the campus will keep running. Each building on campus has two transmission

lines linking the building with the Substation. One of the lines sends power to the building; the other is the standby line. When the working line is damaged, the standby line will switch to “on” state, and keeps sending power to the building. Figure 3.3 shows how power is sent through feeder 12-F11 to the hospital, and the other transmission line is linked with feeder S-H, which is the standby line for the hospital.

If damage occurs in the Substation, it has to be repaired or switched off manually. The length of the operation time for repairs is the time delay represented in the model.

Based on the data and information collected from experts working at UBC Utilities, a diagram of the cell model for the Substation has been developed and shown in Figure 3.4.

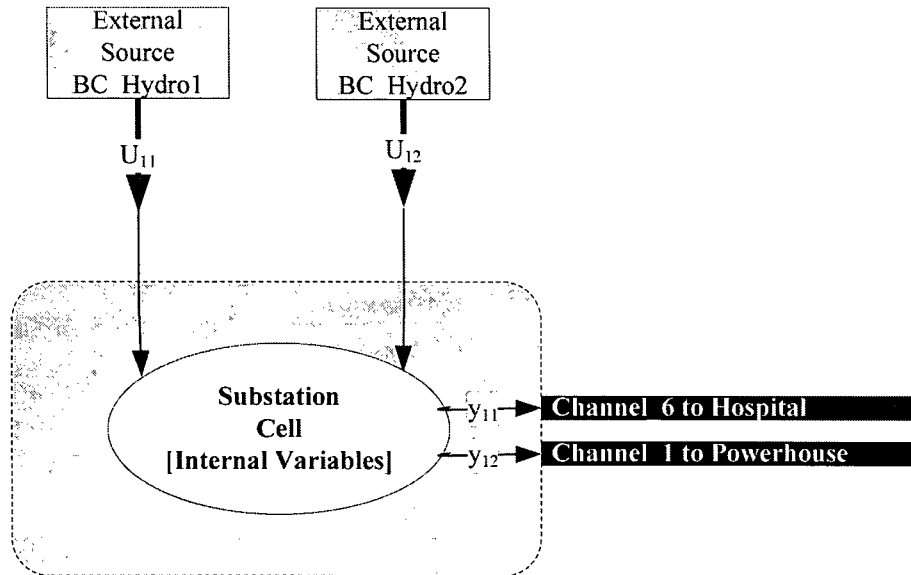


Figure 3.4: Diagram of the Substation Cell Model

It can be seen that there are two inputs and two outputs in the model. The inputs come from the external power sources, which are set as external cells, and the outputs send power to the cells such as the hospital and the power house through channel 1 and channel 6. In reality, the Substation sends power to all the buildings on the UBC campus; in this model, only two cells, the Hospital and the Power House, are considered.

3.2.2. The Generic Model of the Substation Cell

The Substation cell uses one type of input token, “electricity,” to produce the output token, which is the same as the input token “electricity.” The Human Readable Table (HRT) of the Substation includes two inputs, two outputs, and internal variables such as the state of the transformers T_1 and T_2 , the state of tiebreakers BK_1 and BK_2 , and the state of the feeders to the Hospital and the Power House. Figure 3.4 shows how the state of the critical components will affect the outcome of the cell. The function between the inputs and outputs can be described as a nonlinear function,

$$[y_{11}, y_{12}] = f(U_{11}, U_{12}, T_1, T_2, BK_1, BK_2, K_1, K_2) \quad (3-1)$$

Where:

- ✧ U_{11} is the external source 1 from BC hydro
- ✧ U_{12} is the external source 2 from BC hydro
- ✧ T_1 is the state of transformer 1, $T_1=1$ normal state; $T_1=0$ damage state
- ✧ T_2 is the state of transformer 2, $T_2=1$ normal state; $T_2=0$ damage state
- ✧ BK_1 is the state of tiebreaker 1:
 - $BK_1=0$ normal state: Open
 - $BK_1=1$ other state
- ✧ BK_2 is the state of tiebreaker 2:
 - $BK_2=1$ normal state: Closed
 - $BK_2=0$ other state
- ✧ K_1 is the state of the feeder to the Hospital:
 - $K_1=1$ normal state
 - $K_1=0$ damage state
- ✧ K_2 is the state of the feeder to the Power House:
 - $K_2=1$ normal state
 - $K_2=0$ damage state

In equation (3-1), the Substation model is shown as a nonlinear function with eight variables; each of them with its own characteristics. The external sources U_{11} and U_{12} are ideal sources

3.3. The Power House Model

3.3.1. Inputs and Outputs for the Power House Cell

As described in section 3.1, the Power House gets power from the Substation and it in turn supplies power to the Water Station and the Steam Station. It primarily includes one transformer, one diesel backup generator, and storage for oil. The basic functions of the Power House are illustrated in Figure 3.5.

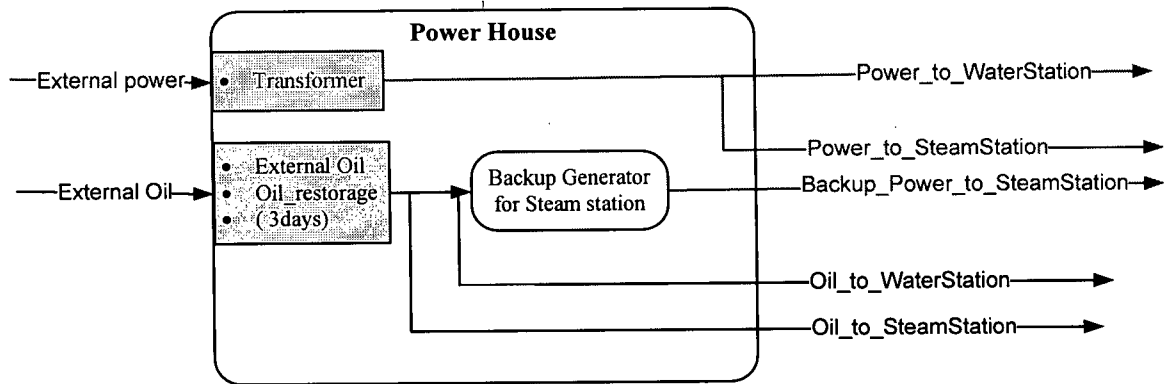


Figure 3.5: Diagram of the Basic Functions of UBC's Power House

As indicated Figure 3.5 shows that the Power House gets power from the Substation and through its transformer sends power to the Water Station and the Steam Station. The daily electricity consumption is 3360 kW-hr. The average power flow into the Power House is 140kW. There is a backup generator, which works automatically when the external power drops to zero. The power generated by the backup generator only sends power to the Steam Station. Similarly, there is storage for oil inside the Power House; it provides oil not only to the Power House but also to the Water Station and to the Steam Station. The total amount of oil can last three days, depending on the disaster scenario.

In reality, the cells of the Power House, Water Station and Steam Station are in the same building and any damage to a building will affect all of these three cells. For example, in the Steam Station, the boilers use gas to generate steam; if the gas pipe leaks or is damaged because of some disaster, the whole building will shut down immediately to prevent an

explosion. If an earthquake occurs and the building gets damaged, the effect of the overall structural damage will be the same for the three cells. This is because the performance of the Power House cell is defined by its inputs and its critical components, and these are tightly connected with the states of the other cells in the same location.

Based on the data and information collected from experienced engineers working in the UBC Power House [26] [27], a diagram of the cell model for the Power House has been developed and shown in Figure 3.6.

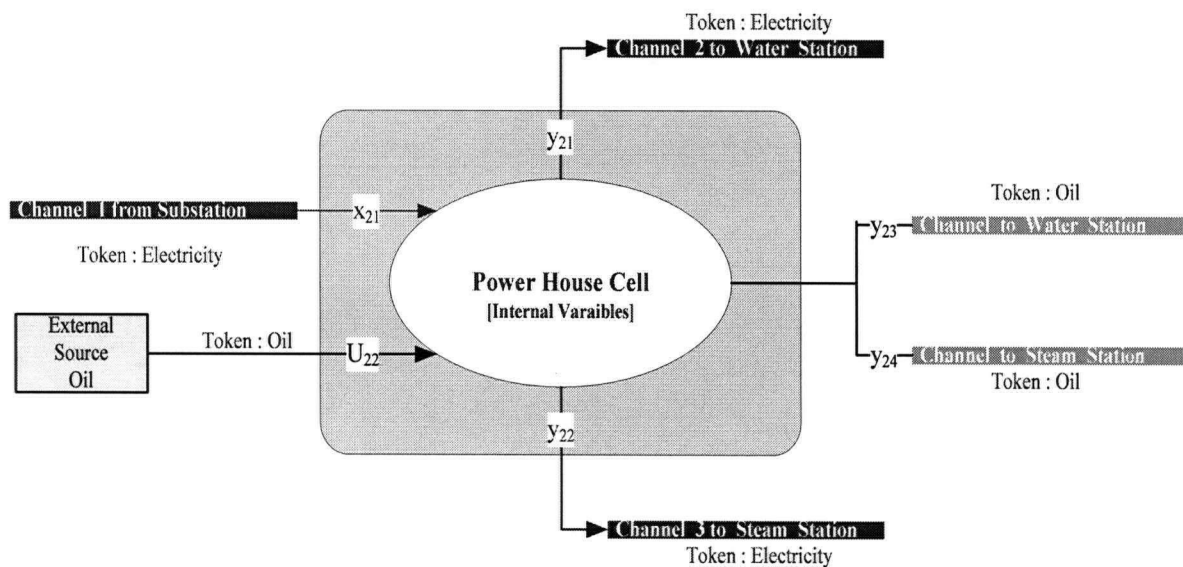


Figure 3.6: Diagram of the Power House Cell Model

Figure 3.6 shows the Power House cell model and its relation with the linking channels. It has two inputs or two types of tokens coming into the cell. One input comes from the Substation cell, and the other comes from an external oil source. The external oil source is oil sent to the UBC Power House through a transportation channel when the oil in the oil tank in the Power House runs out. This model is set as an ideal source from an outside system. Two of the outputs send power to the Water Station and Steam Station cells through channel 2 and channel 3; the other two outputs send oil to these same cells.

3.3.2. Generic Model of the Power House Cell

The Power House cell includes two types of tokens. Based on the number of inputs and outputs and the relation between them, the input-output model for the Power House cell can be represented by two parts: one represents the electricity token, the other represents the oil token.

✧ Oil

The oil token comes from the external source U_{22} and the backup oil C_{22} . In this thesis, both U_{22} and C_{22} are time-dependent variables [27]; the outputs are the states of the oil consumption and y_{23} and y_{24} described as functions of U_{22} and C_{22} .

The function of the oil states is a time-dependent nonlinear function.

$$[y_{23}, y_{24}] = f(U_{22}, C_{22}, x_{21}) \quad (3-2)$$

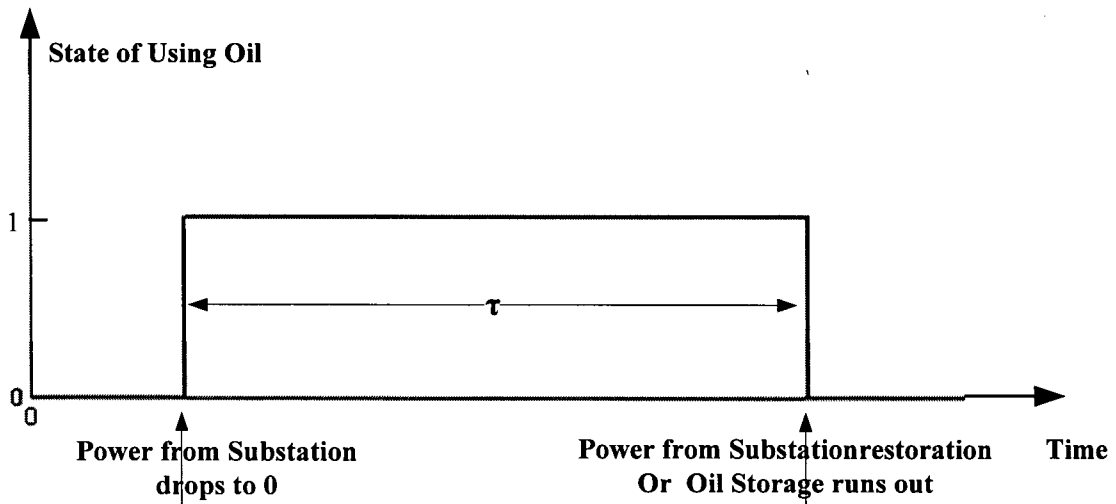


Figure 3.7: Function of Oil in the Power House Cell

Oil is supplied to the backup generator when power in the Substation drops to zero. Figure 3.7 illustrates how the state of oil consumption depends on the event “power in Substation drops to zero”; the time of the oil consumption τ depends on the event “power in Substation restored” and the amount of oil in the oil storage.

◇ Power

Figure 3.6 shows that the cell function includes five factors: the input power, and internal variables such as the states of the transformer, backup generator, oil, and gas. The internal variables and the input power can change their states and performance because of damage during or after a disaster, and these changes in turn cause a change in the output. Thus, the relationship of the inputs and the outputs can be described by the nonlinear function,

$$[y_{21}, y_{22}] = f(x_{21}, T_1, BK_1, K_{oil}, K_{gas}) \quad (3-3)$$

Where:

x_{21} : the input of power from the Substation to the Power House cell

y_{21} : the output of power sent to the Water Station

y_{22} : the output of power sent to the Steam Station

T_1 : the state of the transformer

BK_1 : the state of the backup generator

K_{oil} : the state of oil

K_{gas} : the state of gas

HRT Table for PowerHouse							Status
x_{21}	T_1	BK_1	k_{oil}	k_{gas}	y_{21}	y_{22}	
100%	1	0	*	1	100%	100%	→ Normal State
.....							
50%	1	0	*	1	50%	50%	→ Input Power drops to 50%
.....							
0%/*	*/0	1	1	1	0%	100%	→ Input power drops to 0, Backup generator works
.....							
0% (*)	*(0)	0	1	1	0%	0%	→ Input power drops to 0, Backup generator gets damaged
.....							
0% (*)	*(0)	1	0	1	0%	0%	→ Input power drops to 0, Oil storage runs out
.....							
*	*	*	*	0	0%	0%	→ Gas leaking, PowerHouse shut down

Table 3.2: Status Mapping for the Human Readable Table for the Power House Cell

Table 3.2 shows the changes of the Power House cell under a normal state and after a disaster. The first row of figures shows the outputs of the cell in a normal state. When the state of the internal variables or the functionality of channels change, the outputs change simultaneously. In the case of the situation indicated in the third row, the input power drops

to 0; this result can come about when the connected channel is damaged or the power sent from the Substation drops to zero. At this point, the backup generator starts to work and sends power to the Steam Station. For a given state of the disaster scenario, the outputs can be calculated using the Human Readable Table at Table 3.2.

3.4. The Water Station Model

3.4.1. Inputs and Outputs for the Water Station Cell

The Water Station is a critical cell in the UBC campus model; it provides water to the whole campus. It is set to provide water to the hospital cell in the simplified model. The cell primarily includes three booster pumps, two of them are working and one is the hot standby. The operating pumps are rotated once a month. The Water Station also has two backup diesel pumps, one of them is working and the other is the standby, to be used if there is no electricity from the Power House. All these pumps mainly add pressure from 60psi to 90psi into the water; the pressure allows the water reach to the top of the high-rises on campus. The water comes through water pipes into the Water Station from the Sassamat water reservoir.

The basic functions of the Water Station are illustrated in Figure 3.8.

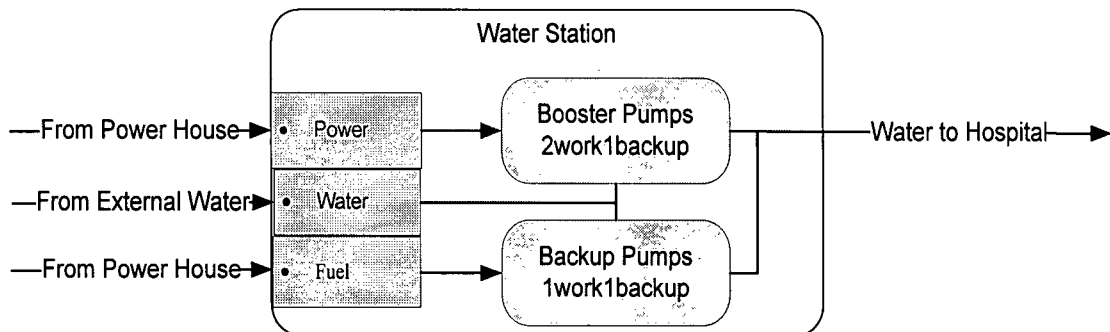


Figure 3.8: Diagram of the Basic Functions of UBC's Water Station

The daily electricity consumption is 960 kW-hr. The average power flow to the Water Station is about 40kW. The average daily water pumped by the booster pumps is about 9000

cubic meter per day, which is 375 cubic meters per hour. The backup pump can pump the same amount of water [26] [27].

Based on the data and information collected from experienced engineers working in the UBC Power House, a diagram of the cell model for the Water Station has been generated and shown in Figure 3.9.

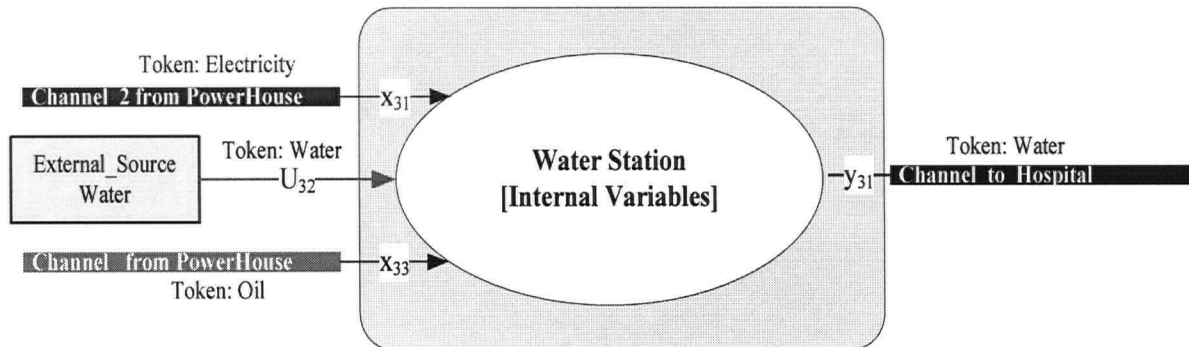


Figure 3.9: Diagram of the Water Station Cell Model

Figure 3.9 shows the input-output relationship of the Water Station cell and its links with other cells through channels. Three types of input tokens are sent into the Water Station--electricity, water and oil. Of the three inputs, two are from the Power House cell, and the third one is from an external source. Of these three inputs, the most critical input is water. In the Water Station, electricity and oil are used to keep the pumps running; if there is no power for the pumps, the backup oil and diesel pumps will be used to keep the Water Station working. However, if there is no water, the whole water station will shut down. The output token is water. In this model, the output is sent through one channel to the UBC hospital.

3.4.2. Generic Model of the Water Station Cell

The input-output model of the Water Station cell can be represented by three inputs, one output and internal variables. Figure 3.8 and Figure 3.9 illustrate how the internal variables of the Water Station are the state of the three booster pumps and two diesel pumps. The function relating the inputs and output can be described as follows:

$$y_{31} = f(x_{31}, U_{32}, x_{33}, k_{pump}, k_{bk}, k_{gas}) \quad (3-4)$$

where:

- x_{31} : the input of power from the Power House cell
- U_{32} : the input of water from the external source
- x_{33} : the input of oil from the Power House cell
- k_{pump} : the state of the booster pumps
 - ◆ 1 : two booster pumps working
 - ◆ 0.5 : one booster pump working
 - ◆ 0 : idle or damage state
- k_{bk} : the state of the backup diesel pumps
 - ◆ 1: working state
 - ◆ 0 : idle or damage state
- k_{gas} : the state of gas
 - ◆ 1 : normal state
 - ◆ 0 : leaking

HRT Table for Water Station							Status
Input			Internal Variables			Output	
x_{31}	U_{32}	x_{33}	k_{pump}	k_{bk}	k_{gas}	y_{31}	
100%	100%	*	1	*	1	100%	→ Normal state
.....							
50%	100%	*	1	*	1	50%	→ Input Power drops to 50%
.....							
100%	50%	*	0.5	*	1	25%	→ Input Water drops to One booster pump working
.....							
0%	100%	1	*	1	1	100%	→ Input Power drops to 0, Diesel pump works
.....							
0%	50%	1	*	1	1	50%	→ Input Power drops to 0, Input water drops to 50% Diesel pump works
.....							
0%	*	*	*	*	0	0%	→ Gas leaking, Water station shut down

Table 3.3: Status Mapping for the Human Readable Table for the Water Station

It can be seen in Table 3.3 that when the inputs of the cell are in a normal state (100%), and the internal variables are in a working state, the output of the cell is 100%. During or after a disaster, the damage causes the state to change. In the second row of Table 3.3, the input

power drops to 50% because the connecting channel or cell providing power to the Water Station has lost its function. Although the two booster pumps are operational, the decrease in power supply makes it impossible for them to work at the previous state; as a result, less water flows to the hospital. The last row in Table 3.3 indicates that a leakage of gas will shut down the Water Station regardless of the states of the internal variables or the amount of the inputs.

3.5. Steam Station Model

3.5.1. Inputs and Outputs for the Steam Station Cell

The Steam Station is another critical cell in the UBC campus model. It provides steam heating to the buildings in the campus. In this model, the station only provides steam to the Hospital cell. This cell primarily includes boilers, water pumps, air fan, water conditioning equipment and deaerator.

The basic function of the Steam Station is illustrated in Figure 3.10.

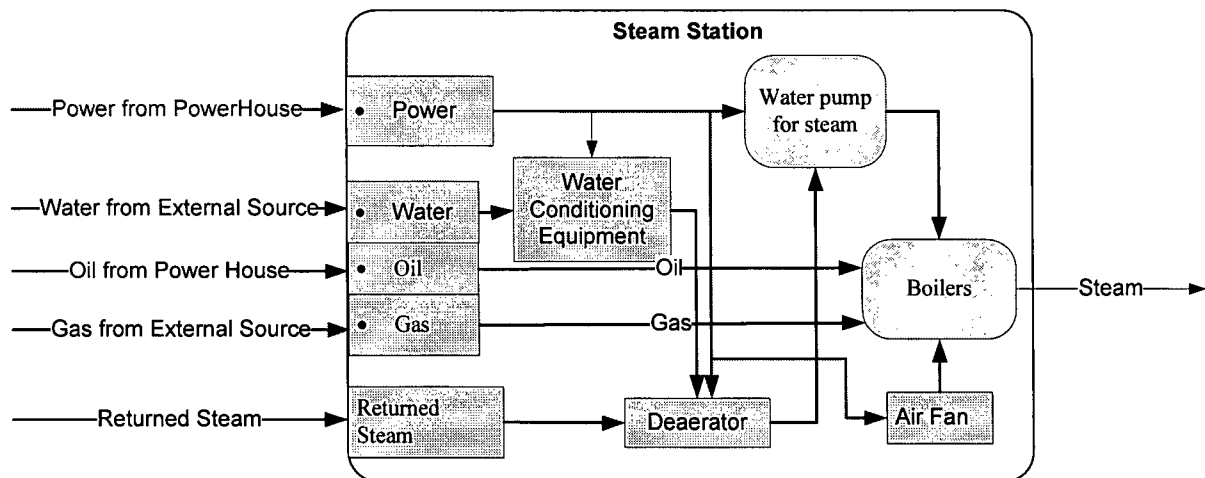


Figure 3.10: Diagram of the Basic Function of UBC's Steam Station

The steam system is a closed loop circuit and the steam loss in the loop is about 30% of the total steam water when it flows back to the Steam Station. Both the returned steam water and the raw water combined are sent into the deaerator equipment to reduce its oxygen content and then sent into the boilers. The boilers generate steam by burning gas or oil.

The daily electricity consumption is 2400 kW-hr. The average power flow of the Steam Station is about 100kW. The average daily water pumped into to boilers is about 880 klbs, which is equal to 400,000 Kg, or approximately 400 cubic meter per day and 16.7 cubic meters per hour. The returned steam, that is the condensed water, is about 70% of the total water in the boiler. In this thesis, because only the hospital is considered as the building consuming the steam, the returned steam for the whole campus is set as the ideal source in the system. The external water sent into the Steam Station makes up for the 30% water loss through the steam supply system. The average daily total steam is about 2755.38 klbs per day, which is about 115 Klbs per hour. The average daily gas consumption is about 3834.36 GJ, which is about 160 GJ per hour.

Based on the data and information collected from UBC Utilities, a diagram of the cell model for the Steam Station has been generated and is shown in Figure 3.11.

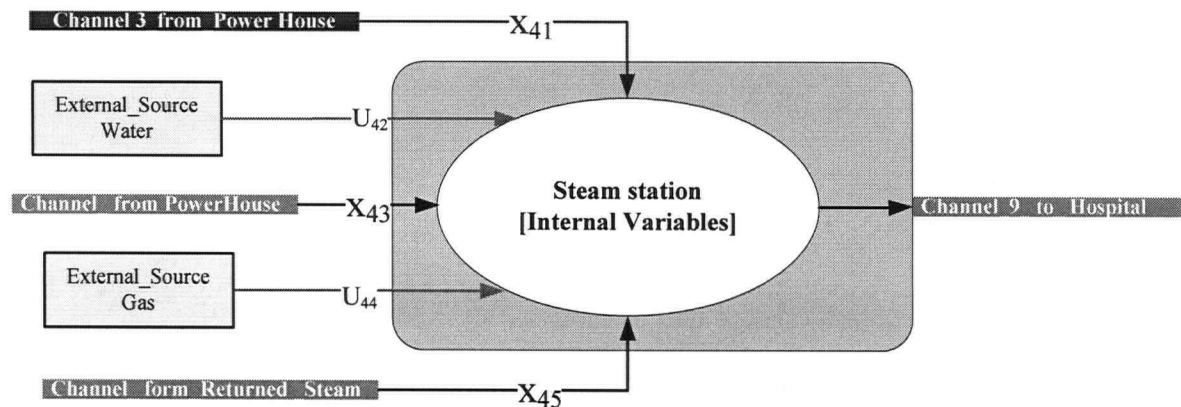


Figure 3.11: Diagram of the Steam Station Cell Model

Figure 3.11 shows the input-output relationship of the Steam Station cell and its links to channels connected to other cells. There are five types of input tokens sent into the Steam Station--electricity, water, gas, returned steam and oil. Of the five inputs, electricity and oil are from the Power House cell, water and gas are from external source cells, and the returned steam is from buildings in the UBC campus. Of these five inputs, the most critical input is water. Without water, no steam can be generated in the Steam Station. The second critical input is gas, which is used to heat the boilers that generate the steam. If there is no gas, the

boilers can use oil. The output token is steam only. In this model, the output is linked to one channel which sends it to the UBC hospital.

The diagram illustrates that the internal variables are also critical because they affect the output of the Steam Station. For example, if the deaerator is damaged, it can be very dangerous because it is on top of the power house building and the water inside the deaerator has a high temperature and high pressure. If the deaerator is damaged, the whole power house building will stop working. The same situation will happen when the water conditioning equipment and air fan are damaged.

3.5.2. Generic Model of the Steam Station Cell

The input-output model of the Steam Station can be represented by five inputs, one output and internal variables. Figure 3.10 and Figure 3.11 show that the internal variables of the Steam Station are the states of the pumps, air fan, deaerator, water conditioning equipment and boilers. The function relating the inputs and output can be described as follows:

$$y_{41} = f(x_{41}, U_{42}, x_{43}, U_{44}, k_{\text{pump}}, k_{\text{boiler}}, k_{\text{gas}}, k_{\text{fan}}, k_{\text{cond}}, k_d) \quad (3-5)$$

Where:

- ✧ X_{41} : the input of power from the Power House cell
- ✧ U_{42} : the input of water from the external source
- ✧ x_{43} : the input of oil from the Power House cell
- ✧ U_{44} : the input of gas from the external source
- ✧ k_{pump} : the state of pumps
 - 1: working state
 - 0: idle or damaged state
- ✧ k_{boiler} : the state of the boilers
 - 1: working state
 - 0: idle or damaged state
- ✧ k_{gas} : the state of gas
 - 1: working state

- 0: leaking
- ◇ k_{fan} : the state of the air fan
 - 1: working state
 - 0: damaged state
- ◇ k_{cond} : the state of the water conditioning equipment
 - 1: working state
 - 0: damaged state
- ◇ k_d : the state of the deaerator
 - 1: working state
 - 0: damaged state

HRT Table for Steam Station										Status
Inputs				Internal Variables					Output	
x_{d1}	U_{d2}	U_{d4}	x_{d5}	k_b	k_p	k_{cond}	k_d	k_{fan}	Steam	
100%	100%	100%	100%	1	1	1	1	1	100%	→ Normal State
100%	100%	100%	100%	0	1	1	1	1	0%	→ Boilers damaged
100%	100%	100%	100%	1	0	1	1	1	0%	→ pumps damaged
100%	100%	100%	100%	1	1	0	1	1	0%	→ Water_conditioning equipment damaged
100%	100%	100%	100%	1	1	1	0	1	0%	→ Deaerator damaged
100%	100%	100%	100%	1	1	1	1	0	0%	→ Air Fan Damaged
80%	80%	100%	80%	1	1	1	1	1	60%	→ Different state of water, power and returned steam
*	*	0%	*	1	1	1	1	1	0%	→ Gas Leaking

Table 3.4: Status Mapping for the Human Readable Table for the Steam Station

It can be seen from Table 3.4 that when the inputs of the cell and the internal variables are in a normal state, the output of the cell is at 100%. During or after a disaster, the damage can be broken pipes, power outage or breakdown of critical components inside the building; these types of damage states are also shown in the figure. When the water pump is damaged (3rd row in the table) or the power sent to the Steam Station drops to 80 % (7th row in the table), the steam sent out will decrease to a certain level, depending on the internal states. If the air fan does not work (6th row in the table), it will affect the whole steam system because the boilers will shut down and no steam can be generated. The amount of generated steam from

the Steam Station depends on the variables and inputs and their relationship, as shown in the table.

3.6. Hospital Model

3.6.1. Inputs and Outputs for the Hospital Cell

Hospitals are one of the critical cells in the health care system, which is one of the critical infrastructures described in Chapter 1. It provides medical service to people living in nearby communities and plays an important role in people's health. The purpose of building the hospital model is to estimate the hospital's capacity under different states and these are shown as follows:

- ✧ While in a normal state, critical support infrastructures can get disturbed, for example, by a power outage for a short period.
- ✧ Both the critical support infrastructures and backup systems are struck during a disaster.

The UBC Hospital is a site of the Vancouver Coastal Health and provides a variety of medical and surgical services including short-stay surgery, sub-acute medical and diagnostic services, surgical and medical clinics, etc [30]. An analysis of the information and data from the UBC Hospital shows three main factors that allow the hospital to perform medical services to meet the needs of patients. In the more realistic simulation, hospital need to consider the patients flow, in this work this factor is neglected and only the capacity of the hospital is considered. These factors are the critical support infrastructures, medical service staff and the capacity of the medical service.

✧ Critical support infrastructures:

- 1) Electricity Power
- 2) Water
- 3) Steam
- 4) Oil
- 5) Gas

✧ **Medical service staff:**

- 1) Doctors
- 2) Medicine
- 3) Nurses

✧ **Capacity of the medical service**

- 1) Number of beds for long-term patients
- 2) Number of beds for short-term patients
- 3) Number of beds for urgent patients

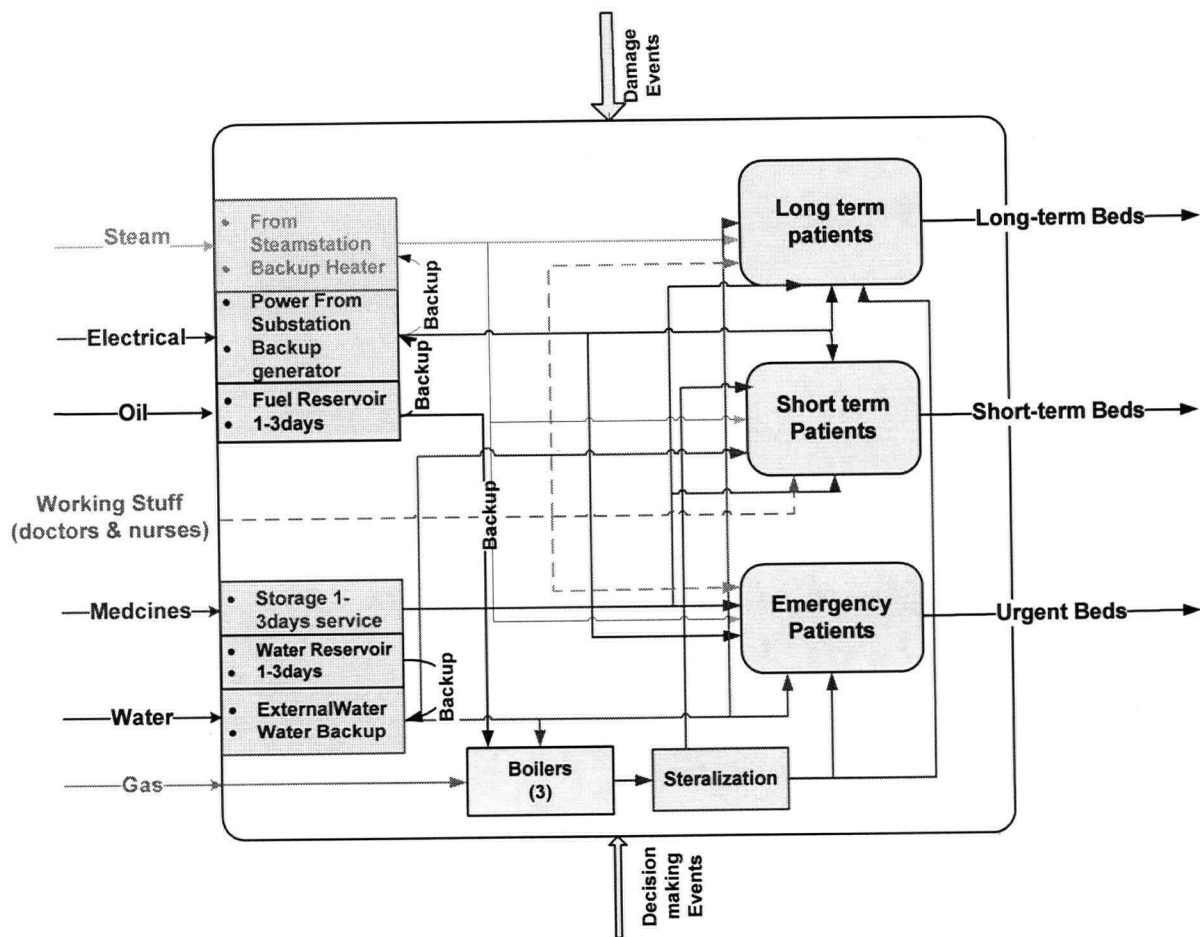


Figure 3.12: Diagram of the Basic Functions of the UBC Hospital

It can be seen in Figure 3.12 that the critical support infrastructures and medical service staff are the inputs of the hospital model; any change in the quality and quantity of these factors

will change the capacity of the medical service in the hospital, that is, the output of the hospital model.

The hospital data from the UBC hospital is as follows [25][28]:

✧ **The consumption of critical support infrastructures:**

- Water: 4.5 M cubic feet of water per year, that is 14.5 cubic meter per hour
- Gas : 29,000 GJ per year, which is about 3.3 GJ per hour
- Electricity : 12.4 GW-hr per year, that is 1416.7 kW
- Steam : 1375 pounds per hour

✧ **Medical service staff and medicines**

- Doctors:
 - ◆ daytime: 25
 - ◆ after-hours: 10
 - ◆ after 10pm :1
- Nurses
 - ◆ daytime: 70
 - ◆ after-hours :25
- Nearly 60% of doctors and nurses live off campus
- The medicines supply in the hospital storage can last for 1-3 days

✧ **Numbers of beds**

- Number of beds for urgent patients = 20;
- Number of beds for short-term patients = 311;
- Number of beds for long-term patients = 300;

Compared with the data in [29], which cites that the total monthly energy intensity is about 3301 Kw·hr/beds in large hospitals in Brazil, the total monthly energy intensity in the UBC hospital is about 3238 Kw·hr/beds.

It can be seen from Figure 3.12 that the critical support infrastructures of the hospital have backup systems. The backup for each of the critical resources is listed in Table 3.5. The backup resources are very critical and perform the functions of the support infrastructures during an emergency or when the supply system is not working.

Type	Supply system	Backup
Electricity	Through electric channel from the Substation	Backup generators: 1-3days
Water	Through water channel from the Water Station	Water reservoir : 1-3days
Gas	Boilers using gas from gas channel	Boilers using oil : 1-3days
Steam	Through steam channel from steam station	Electric heaters

Table 3.5: Redundancy of the Critical Infrastructures for the UBC Hospital

3.6.2. Interdependent Performance of the Hospital Cell

Although each critical support infrastructure in the hospital has its own backup system, the state of the hospital's operation, which can range from normal operation to various levels of disruption or restoration, must be considered in interdependencies analysis. Furthermore, it is necessary to understand those changes in the supply systems and in the states of the backup systems that cause changes in the hospital interdependencies. For example, the power supply has no interconnection with other infrastructures in the hospital. When the power supply is disturbed, the backup generator starts to work with no delay by using oil. However, if there is no oil in the hospital at that point in time, the backup power supply system will not perform any function for the hospital.

Table 3.6 shows that the supply systems inside the hospital are not directly interdependent; for example, the power supply cannot affect the water supply system. The steam system is the only system used for the sterilization of surgical equipment, which is tightly dependent on water and gas.

Normal	Affected Infrastructures			
Type	power	water	steam	heating
power	√			
Water		√	√	
Steam			√	
heating				√
Gas			√	
Oil				

Table 3.6: Interdependency of the Critical Infrastructures inside the UBC Hospital

Where √ is the tight interdependent relationship between two infrastructures.

Damage	Affected Infrastructures							
Type	power	BK power	water	BK water	steam	BK steam	heating	BK heating
Power	√			√		√		√
BK power		√		√		√		√
Water			√		√	√		
BK water				√	√	√		
Steam					√			
BK steam						√		
Heating							√	
BK heating								√
Gas					√			
Oil		√				√		

Table 3.7: Interdependency between the Critical Infrastructures and the Backups inside the UBC Hospital

The table illustrates that the most critical infrastructure is electric power. Without power, the backup system of any other infrastructures cannot work. The steam system, which provides steam for the sterilization of surgical equipment and other medical devices, is involved with almost all of the infrastructures inside with the Hospital.

The interdependencies among the infrastructures are more complex during emergencies than under normal conditions. In Table 3.7, only direct effects to the infrastructures are listed. For example, when the backup water supply system is working, it needs power to run the pump; should there be a power outage at the same time, the backup generators that need oil to run will still work. However, if there is no oil, the pump will stop pumping and the water system will not provide water anymore.

3.6.3. Generic Model of the Hospital Cell

It can be seen that the output of the UBC Hospital is divided into three types: the capacity for serving long-term patients, short-term patients and urgent patients. Each of these capacities depends on the connected infrastructures in the hospital, but the relationship between these resources and the patients is different for each type of output. For example, the steam for heating is very important for long-term patients, but not that important for short-term and urgent patients; the steam for sanitation is important for urgent patients, especially those who need surgery, but it is not nearly as important for long-term patients.

Separated tables are generated to represent the aggregators of the inputs into the Hospital cell model.

input		Variables			output	
power1	power2	oil	bk1	bk2	ye1	ye2
100%	100%	*	0%	0%	100%	100%
50%	50%	*	0%	0%	50%	50%
0%	0%	100%	100%	100%	100%	100%
100%	100%	100%	100%	100%	100%	100%
0%	0%	*	0%	0%	0%	0%
0%	0%	0%	100%	100%	0%	0%

Table 3.8: Power Aggregator of Hospital Cell

input		Variables		Output
water	ye2	wbk	pump	yw1
100%	*	100%	0%	100%
50%	*	100%	0%	50%
0%	100%	100%	100%	100%
0%	100%	50%	100%	100%
0%	100%	0%	100%	0%
0%	50%	100%	100%	0%
0%	0%	100%	100%	0%
1	0	0	0	1

Table 3.9: Water Aggregator of Hospital Cell

The tables describe one type of input token aggregates in the hospital cell model. Since each of the inputs has its backup, the aggregator is used to combine the external input and backup as one single input to the generic hospital input-output model. It can be seen from Figure 3.12 that there is a backup generator for power located inside the hospital. Under normal conditions, the functionality of the power supply in the hospital is 100%; however, if disaster occurs and the power from outside the hospital drops to zero because of failure in the supply or damage to cells or channels connected to the hospital, the hospital's backup system will work immediately to supply power to the whole hospital, and the number of beds does not change under this situation. Table 3.8 and 3.9 shows the interdependencies between the critical resources delivered to the Hospital and their corresponding backup system inside the Hospital.

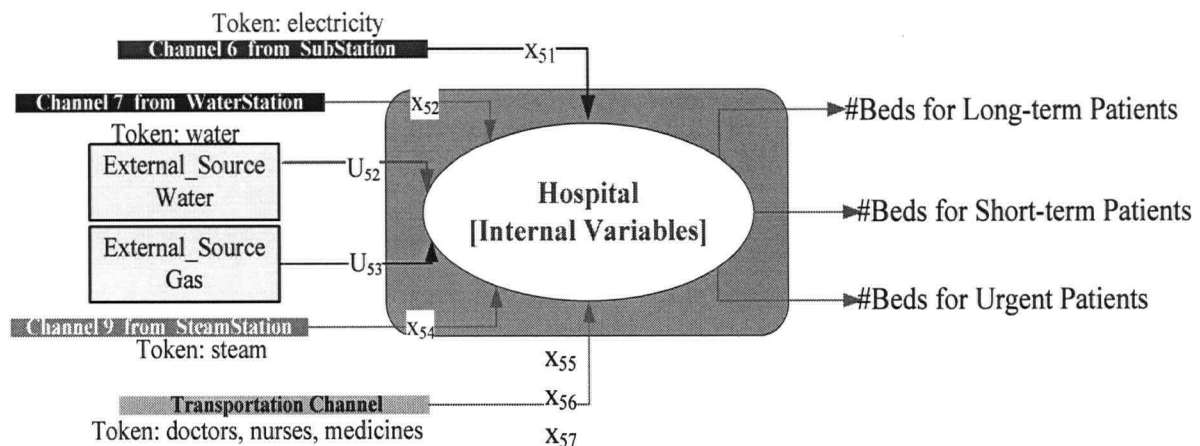


Figure 3.13: Diagram of the Hospital Cell Model

In order to describe the hospital performance and the complex interdependency between the infrastructures, a hospital model has been developed using HRT table to represent the interrelationship between the inputs and outputs. In this thesis, the transportation channel is set as an ideal channel and there are no detailed data and information for these channels.

The Human Readable Table that defines the simplified input-output model for the hospital to be used by the Infrastructure Interdependencies Simulator I2Sim is shown in the Table 3.10:

HRT Table for Hospital										Status		
Inputs									Outputs			
xw1	xe1	xs1	xh1	xe2	xs2	doctors	nurses	medicines	Urgent	shortterm	Longterm	
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	→ Normal State
.....												
90%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	→ Water drops to 90%
.....												
100%	90%	100%	100%	100%	100%	100%	100%	100%	80%	80%	100%	Power sent to Urgent and short term patients drops to 90%
.....												
100%	100%	100%	100%	90%	100%	100%	100%	100%	100%	100%	80%	→ Power sent to longterm patients drops to 90%
.....												
100%	100%	80%	100%	100%	100%	100%	100%	100%	95%	95%	100%	Steam sent to Urgent and short term patients drops to 90%
.....												
100%	100%	100%	100%	100%	80%	100%	100%	100%	100%	100%	80%	Steam sent to long term patients drops to 90%
.....												
100%	100%	100%	90%	100%	100%	100%	100%	100%	90%	95%	95%	→ Steam sent to long term patients drops to 90%
.....												
80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	50%	50%	→ Inputs in different states For example all in 80%
.....												
0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	→ Total Damage state
.....												
Data describing different states which are not listed on this table												

..... Data describing different states which are not listed on this table

Table 3.10: Status Mapping for the Human Readable Table of the UBC Hospital

The data in Table 3.10 illustrates how the multiple inputs sent to the hospital affect the number of beds in the hospital. In the normal state, 100% inputs are sent into the hospital to allow it to give 100% outputs in terms of beds served. Each input or combined inputs can change the state of the hospital's outputs; these interconnections and changes are calculated using the input-output HRT table.

For example, when the water sent to the hospital is reduced because of a broken water pipe or a pump failure in the Water Station, the operation in the hospital will be affected. From the HRT table, it can be seen that when water drops to 90%, the hospital can still maintain its normal state because of the hospital's emergency plan. One of the plan's strategies is to cut

down the use of water during the emergency by using one washroom in each floor. By implementing this plan, the water needed for medical care operation will only go down to about 85%.

The variables x_{s1} and x_{s2} indicate the steam heating for the patients in the hospital. When both of these variables are reduced to 80%, the results of the output will be remarkably different. At this point, the hospital's output or its ability to provide medical service to long-term patients becomes about 80% of its full capacity; and the output of the short-term and urgent patients' care is 95%. This is because long-term patients totally depend on steam for heating, but short-term and urgent patients do not depend on steam as much as long-term patients do.

3.7. Channel Model

In sections 3.2 to 3.6, each cell is linked to other cells by different types of channels. As mentioned in Chapter 2, in this thesis, a delay associated with the delivery of tokens in normal state was not taken into account because of the short distances of facilities within the UBC campus. Delays associated with physical channels' damage are taken into account. The modeling for the channels can be represented as below:

$$x_{ij} = f(y_{jk}, \tau, k_f, C_{\max}) \quad (3-6)$$

Where:

- ✧ $i j$: the channel connecting cell i and cell j , and the token flowing from cell j to cell i .
- ✧ x_{ij} : amount of token received by cell i .
- ✧ Y_{jk} : token sent from cell j , the k^{th} input connected with the cell.
- ✧ τ : time delay depending on repair procedure only.
- ✧ k_f : functionality coefficient, ranging from 0 to 1 determined by the type of damage.
- ✧ C_{\max} : the total capacity of the channel, the limit of the total quantity of token flowing through it.

3.8. Reduced Scale Test Case Model

An overall cell-channel diagram for a simplified UBC test case model is shown in Figure 3.19. It includes five cells, whose model has been developed in the pervious sections. In addition, there are several external sources designated as external cells in the model; these cells provide tokens such as electric power, water and gas from outside systems to the simplified UBC test case. The external sources are assumed to be in an ideal state, which means there is no damage in these cells.

The cell model is a generic model so that it can represent the same type of cells with various sizes and capacities. The input-output model can be customized based on the limited information from the specific cell or the types of input(s), which means the state of its connection with the critical infrastructures needs to be considered. For example, the model of the Hospital cell includes inputs such as power, water, gas and steam, and its internal sources are oil and water from backup systems. If the model is applied to another hospital without water backup, the information related to the specific critical components for backup can simply be deleted. The table is flexible and data or information can easily be added or updated when more information is acquired from the industry or when there is an actual disaster scenario. The system model is designed to cover different situations ranging from normal state to various emergency states, depending on the types of disasters.

The essential task of the reduced scale test case model is to indicate the capacity of the medical services in the Hospital under different scenarios. The outputs of the Hospital are the number of beds for different types of patients. These outputs depend on the quantities of input tokens coming through the channels connected to the other cells. The Figure 3.14 shows that the Power House has no direct connection with the Hospital, but when the performance of the Power House changes, the capacity of the Hospital will change because the Power House is connected with the Water and Steam Stations. In the next chapter, the interactions between these five cells and the performance of the Hospital are shown in time domain using simulation.

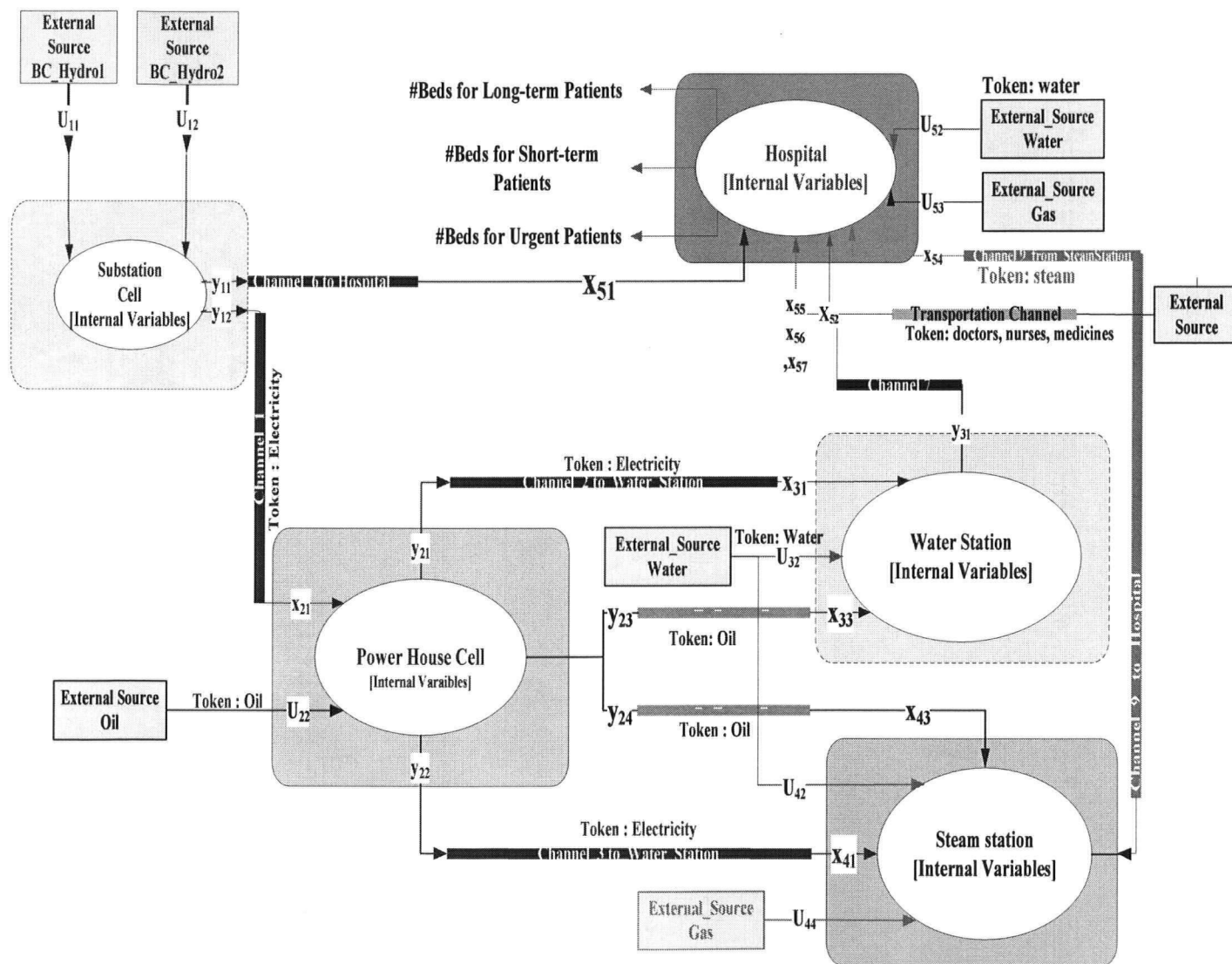


Figure 3.14: Reduced Scale UBC Test Case Model

Chapter 4 Simulation and Results Analysis

In order to validate the infrastructures interdependencies model and the theoretical framework for the modeling of I2Sim, it is important to test the model built in Chapter 3 with a real-life known scenario with predictable results. In this chapter, the reduced-scale model of the critical infrastructures of the University of British Columbia is set up using the MATLAB/Simulink/Stateflow™ software [33]. A soft simulation clock and a graphic user interface with controllers and indicators have been developed to realize an interactive simulation that allows the decision makers to get a better understanding of the emergent system behavior in different operational situations. The simulation indicates that the redundant systems such as the backup generators in the Hospital increase the robustness of the cells. Critical connections, such as the steam pipe linking the Steam Station with the Hospital are also identified. One such scenario is studied by using a distributor, which allows an operator to find the optimum allocation of a limited resource so that the operator can ensure the best possible operation of the other critical infrastructures during an event. The simulation itself has been parallelized, and distributed on the University of British Columbia Power Systems Lab PC-cluster [41].

4.1. Simulation Model for the UBC Test Case

In the previous chapter, a reduced-scale model of the critical infrastructures of the University of British Columbia has been developed. Based on this model, a prototype simulation has been built by using MATLAB/Simulink/StateFlow™ [33] [34] to validate the model and demonstrate the methodology of the cell-channel modeling approach. An analysis of the outcome demonstrates the interdependent relationship among the cell and channel components of the system.

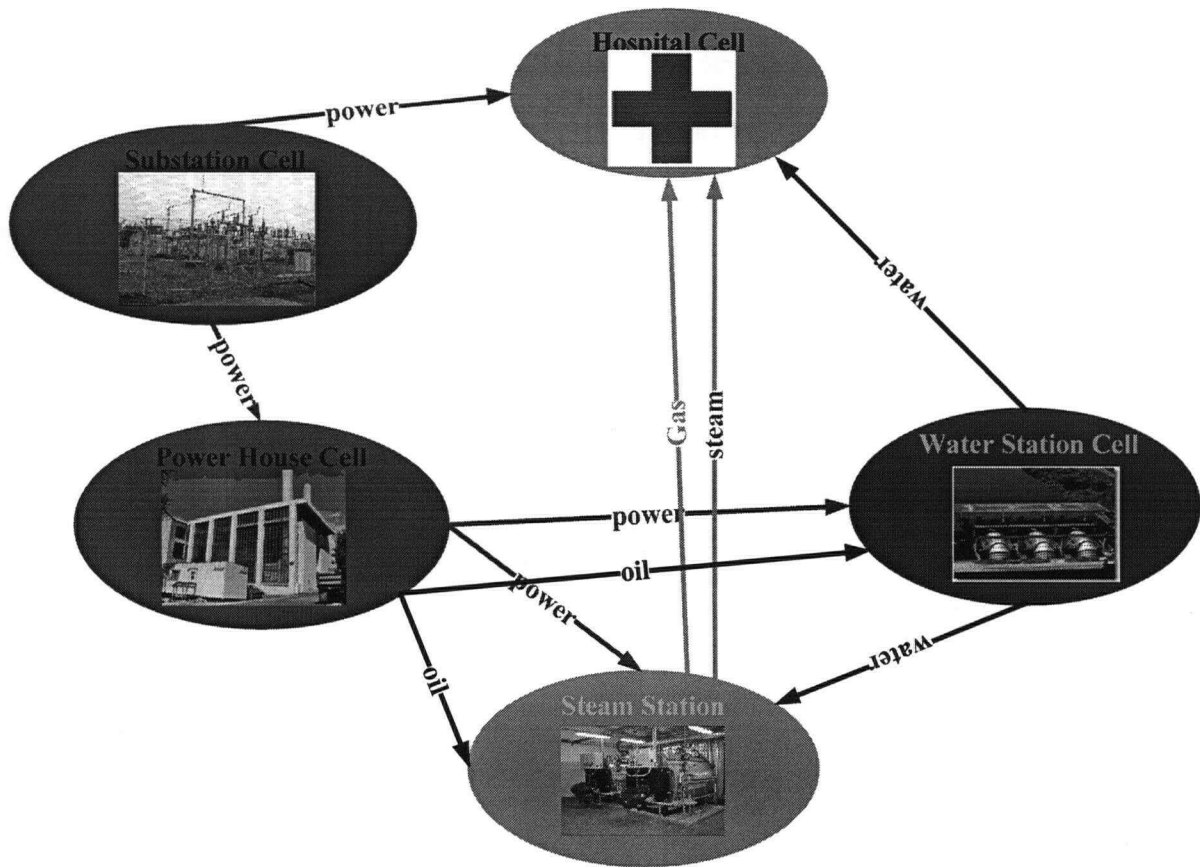


Figure 4.1: Interconnection Structure in the Reduced Scale UBC Test Case

The interconnection between the components of the reduced-scale model is shown in Figure 4.1. These interconnections are represented by channels which send different types of tokens from the sending-end cells to the receiving-end cells. The performance of one cell affects the other cells to which it is connected by channels. The simulation model demonstrates the performance of the interactive cells.

The simulation environment for this prototype is made for several types of researches:

✧ **Off-line simulation**

- Predefined input file of the system, which includes variables such as the loss of functionality of a channel caused by a broken pipe, or the loss of functionality of a cell as a result of damage due to an intensity VIII earthquake;
- During simulation, the system variables change according to the input file;

- Fast simulation speed.
- ✧ **On-line simulation**
 - A soft-clock for simulation has been adjusted to make the simulation run at a human friendly speed for an operator to observe;
 - A graphic user interface has been developed to illustrate the change of system performance during simulation;
 - Discrete events corresponding to different states of the system variables are updated during the simulation.
- ✧ **Support tool for decision making**
 - Combined with optimization techniques, the simulation can provide an analyst with estimations of performance measures for various system alternatives;
 - Uses to test and verify the optimal solution of limited sources re-allocation problems.

There are mainly three types of blocks used in the model. One of them is the Stateflow Block, which represents the discrete events occurring in the model. For example, the backup generator in the Power House requires two conditions to start working: one is power from the Substation dropping to zero and the other is the quantity of oil storage.

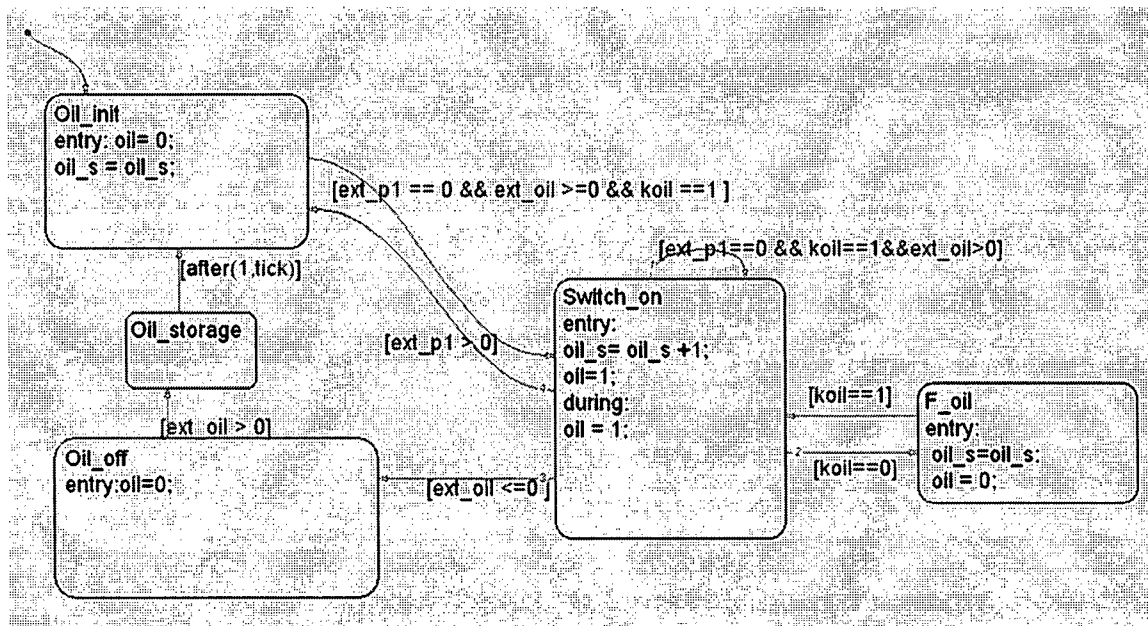


Figure 4.2: State of Oil Usage in the Power House

The total oil storage, the current state of oil and oil usage are shown in Figure 4.2. For example, the figure shows the state of oil changes when the event “power from Substation drops to 0” or “oil storage used up” occurs. The event is a time-based event; no matter what time the event happens, the function of the oil state runs to show the curve presented in Figure 3.8.

The logic behavior of the input-output model has been realized using truth table functions, which contain conditions, decisions and actions. For example, the state of the transformers in the Substation is at only 0 or 1, no other states in between, and different combination of transformers' state generates different outcomes. The logic behaviors are illustrated in Table 4.1.

Condition Table															
	Description	Condition	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13
1	State of Transformer 1	t1==1	T	T	F	T	T	T	F	T	T	T	F	T	T
2	State of Transformer 2	t2==1	T	T	T	F	T	T	T	F	T	T	T	F	F
3	State of TieBreaker 1	sw1==0	T	T	T	T	T	T	T	T	T	T	T	T	T
4	State of TieBreaker 2	sw2==1	T	F	T	T	T	F	T	T	T	F	T	T	F
5	State of feeder 1	k1 == 1	T	T	T	T	T	T	T	T	F	F	F	F	T
6	State of feeder 2	k2 == 1	T	T	T	T	F	F	F	F	T	T	T	T	T
	Actions: Specify a row from the		A1	A1	A1	A1	A2	A2	A2	A2	A3	A3	A3	A3	A2

Table 4.1: Input-Output Table for the States of Transformers, Tiebreakers and Feeders

The Lookup Table (n-D) block evaluates a sample representation of a function in N variables by interpolating between samples to give an approximate value for $y = F(x_1, x_2, x_3 \dots x_n)$, even

when the function F is known only empirically. The input-output model can be illustrated using the look-up table functions in Figure 4.3.

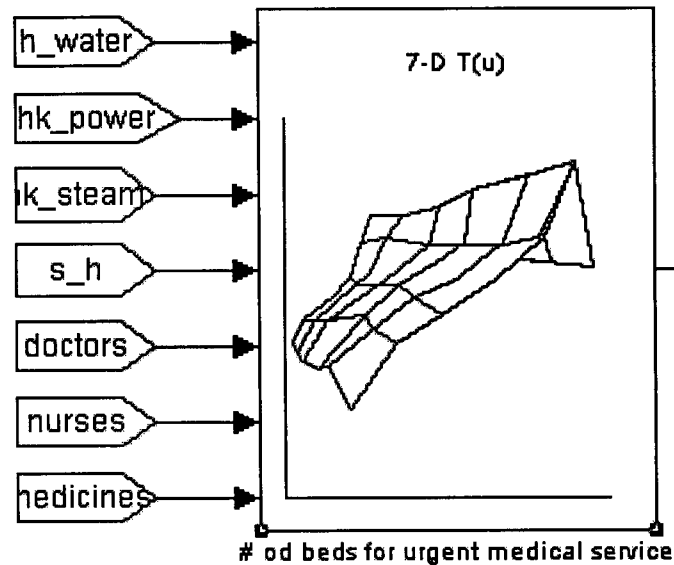


Figure 4.3: Input-Output Table for Beds for Urgent Medical Service

The reduced scale UBC test case model is illustrated in Figure 4.4.

Before running the off-line simulation, an m-file for the predefined scenario has to be compiled. During the simulation, the predefined parameters may be changed according to the scenario. Currently, based on the computation time of the computer, the model runs about 900 time-steps (which indicates 900 minutes in the actual physical clock) in less than five seconds.

Figure 4.4 Simulation Model of the Reduced Scale UBC Test Case

In the simulations presented it is assumed that it is derived to use the full capacity of each cell but that this full capacity may not be available due to structure damage or lack of resources. A more realistic scenario would include the “people’s flow” loop which would include the possibility that not all of the resources are needed because nobody is using them.

The off-line simulation runs so fast that no action can be taken during simulation. In order to make the simulation run with interactive action by decision makers, a soft clock has been devised in the model (the time block in Figure 4.4) to slow the computation at speed. The soft clock makes the simulation time nearly the same as the actual physical clock, so that it can update events and make interaction possible between the operators and the simulation model. The operators have time to observe the outputs of the simulation and change the system variables to adjust the outcome based on different objectives.

By using Matlab/Gauges™ and NI Labview™[35], an interactive interface was built and linked with the model. The output of the model and the critical variables are listed in the interface so that it is easy for operators to update the parameters corresponding of the events.

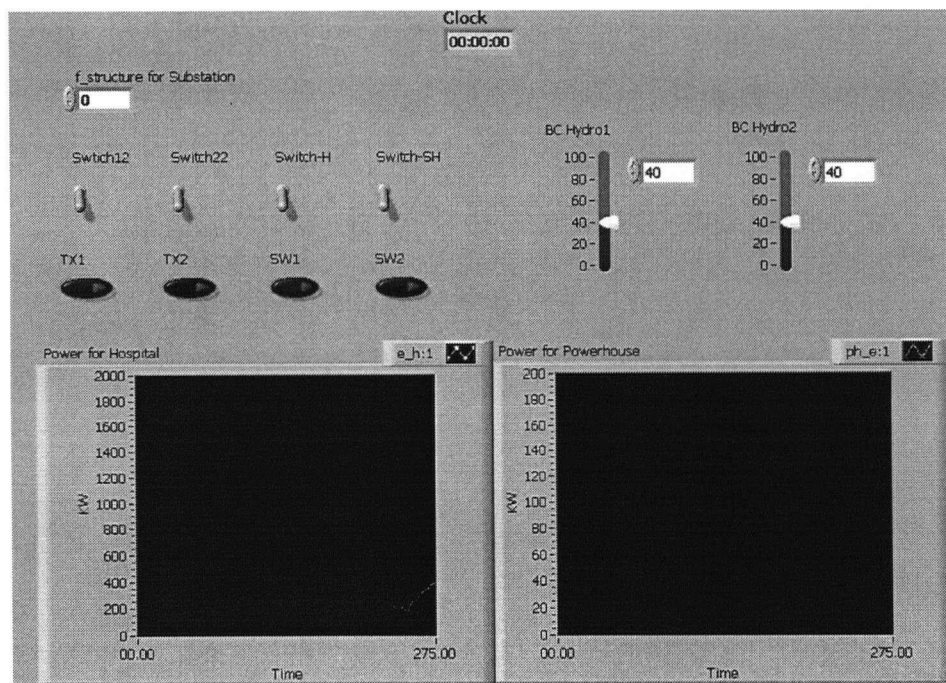


Figure 4.5: Interface of the Substation Cell Model

4.2. Simulation Results

In order to check whether or not the model can reveal critical linkage among the infrastructures, it is vital to choose an actual disaster event with known outcomes as a scenario for the reduced scale test case model [36].

On November 19, 2006, a Pacific storm brought 90 mm of rain and strong winds to coastal B.C. Then a weather warning was issued on an Arctic ridge over the BC interior combined with a Pacific low-pressure system over southwest 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 [37] [38] [39]. During this period, the impact of the snowstorm and power outage caused by falling branches and trees affected the UBC campus. Because of the snow and the resulting power outage at the UBC-Point Grey campus, the whole campus was closed on November 27 following the No. 68 university policy [40] [42]. The campus power outage lasted for about 12 hours.

This power outage at the UBC campus has been chosen as the disaster scenario. The time-based event happening during this scenario has been compiled [36] and set as the updated events during simulation and the known results of the scenario is the criterion for measuring the simulation model. Three different scenarios as a result of this power outage event are discussed in the following sub-sections.

4.2.1. Scenario 1 and Result Analysis

In this scenario, the snowstorm and resulting power outage make the related variables changes; for example, the transmission lines transporting external power from BC Hydro to

the UBC Substation were down and the water pipe sending water to the UBC hospital were broken because of freezing temperatures.

Scenario Description

✧ A snowstorm with a power outage, the following events happened:

- Initial state : $t = t_0$, the whole system runs in normal state until $t = t_0 + 20(\text{min})$;
- $t = t_0 + 21(\text{min})$
 - ◆ Event : A power outage occurs because of fallen trees bring down the transmission lines sending power to the UBC Substation ;
 - ◆ Action : The functionality of the channel linking the external source (BC Hydro) and the Substation drops from 1 to 0;
- $t = t_0 + 40(\text{min})$
 - ◆ Event: The water pipe linking the water station to the hospital burst;
 - ◆ Action : The functionality of the channel linking the Water Station to the Hospital drops from 1 to 0;
- $t = t_0 + 781(\text{min})$
 - ◆ Event : the water pipe is fixed after 12 hrs;
 - ◆ Action : The functionality of the water channel is restored to 1;
- $t = t_0 + 861(\text{min})$
 - ◆ Event: After 14 hrs, the power is restored;
 - ◆ Action : The functionality of the electric power channel is restored to 1;

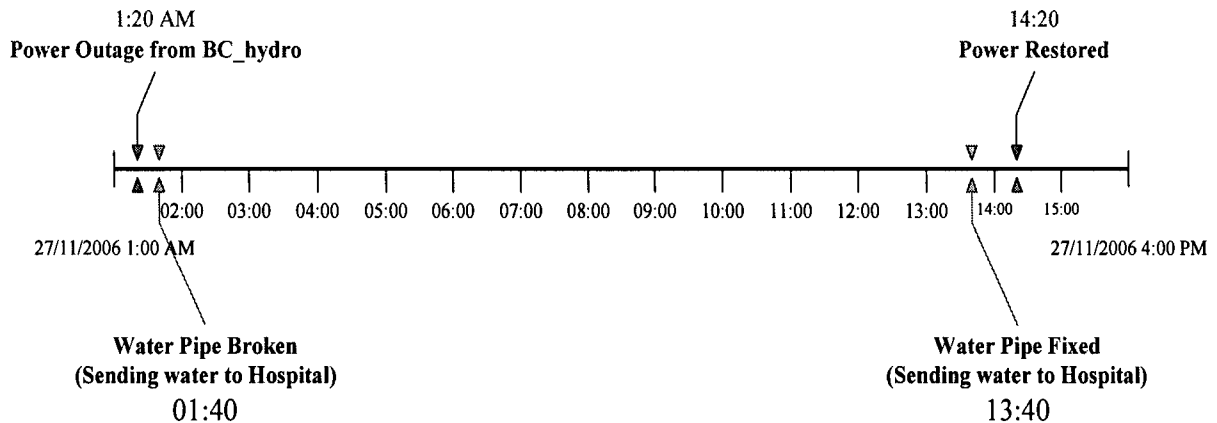


Figure 4.6: Timeline of Scenario 1

Results Analysis

During the simulation of scenario 1, two events occur: a power outage and a broken water pipe. The consequences of these events are shown in Figures 4.7 to 4.13.

In Figure 4.7, the outputs of the Substation change following the event settings of scenario 1. The power outage happens at $t = t_0 + 20(\text{min})$ and power is restored at $t = t_0 + 860(\text{min})$; this influences the output of the Substation and this in turn influences the inputs of the Hospital and the Power House.

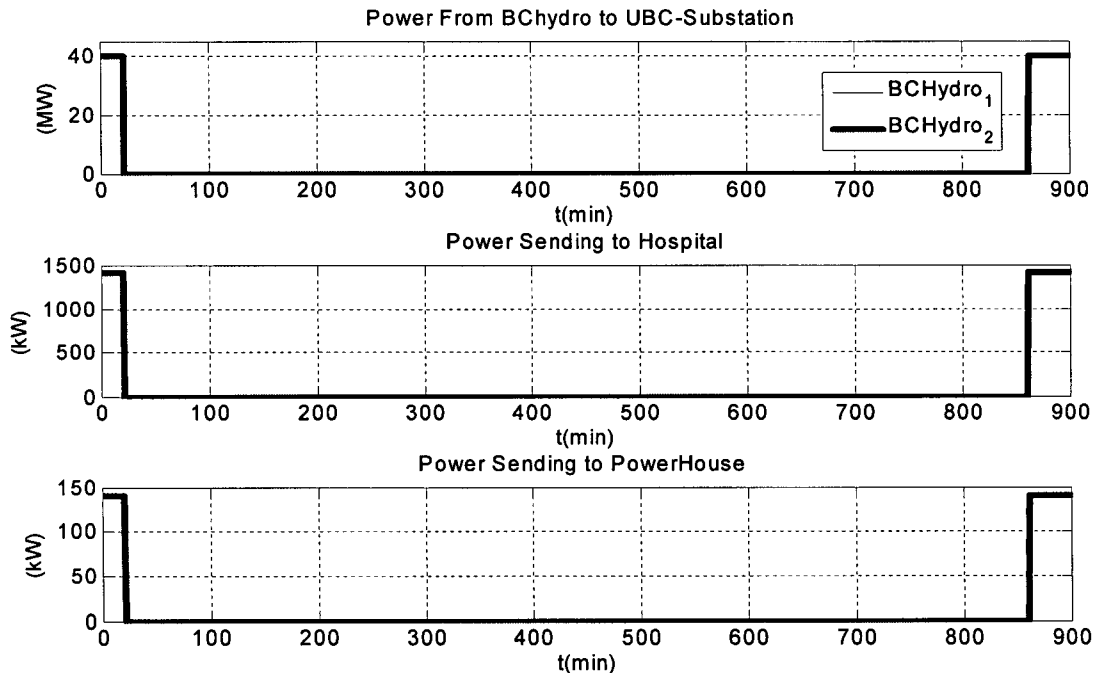


Figure 4.7: Scenario1 - Simulation Results for the Substation Cell

Figure 4.8 shows the state of the power in the Steam Station and Water Station. The power sent to the Water Station drops to zero when the input to the Power House drops to zero. The power sent to the Steam Station drops to zero and then is restored to the normal state because it receives power from the backup generator in the Power House. From the figure, it can be seen that the power sent to the Steam Station has a spike (pointed by the arrow); this is caused by the switch time from using power from the external source to using power from the backup generator. At the point $t = t_0 + 860(\text{min})$, the power sent to the Substation is

restored, then the power sent from the Power House is restored and the power sent to the Steam Station and the Water Station is restored. The normal state returns.

When the backup generator starts working, the amount of oil storage begins to drop. When the Substation restores power to the Power House, the backup generator stops working and then the oil storage is kept at the state shown in figure 4.8.

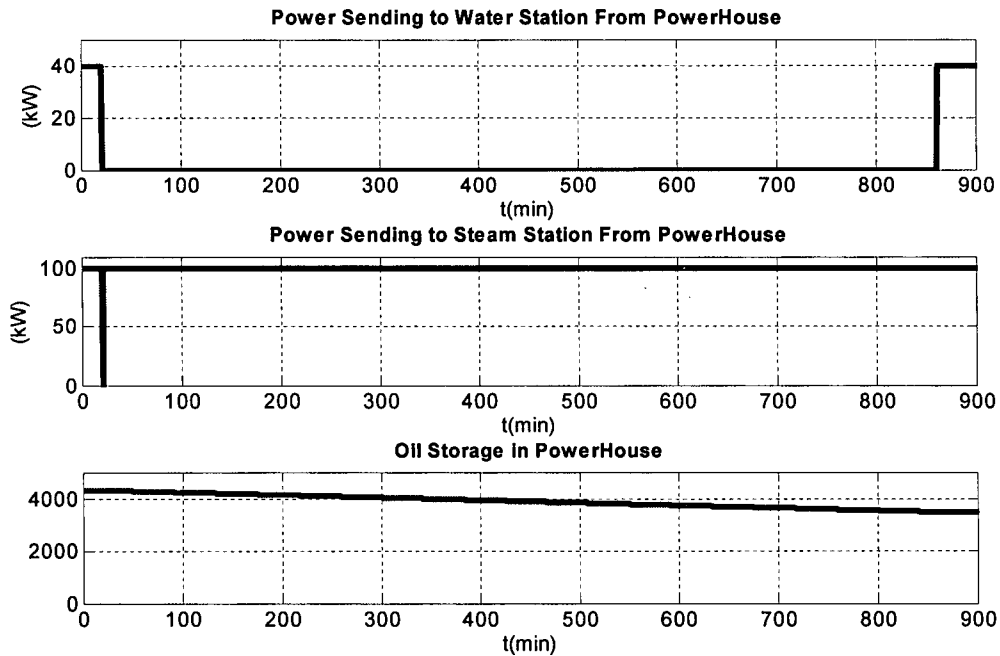


Figure 4.8: Scenario1: Simulation Results for the Power House Cell

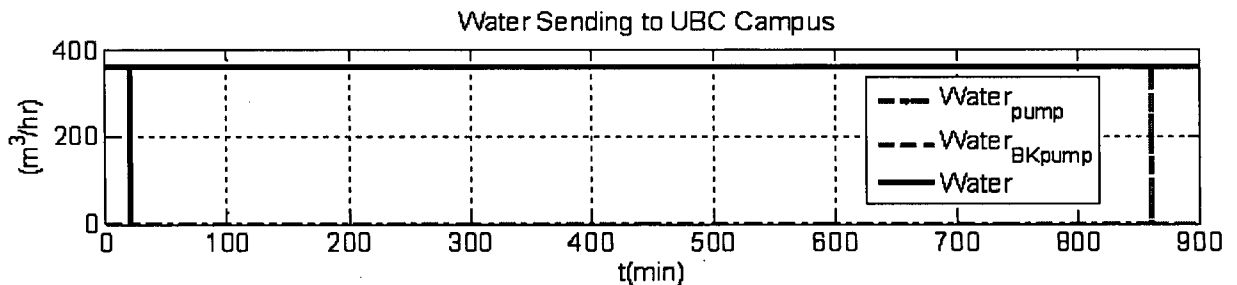


Figure 4.9: Scenario1 - Simulation Results for the Water Station Cell

Before the power outage, three booster pumps work in the Water Station. The power sent to the Water Station drops to zero at $t = t_0 + 20(\text{min})$, and the backup pumps start to work by

using oil. When the Water Station switches from using external power to using oil, the backup pumps begin to pump water to the Hospital. At $t = t_0 + 781(\text{min})$, the power is restored and the booster pumps begin to work again. Although the state of the internal critical variables of the Water Station changes during the simulation, the amount of water sent out to the Hospital is maintained at the level of the normal state.

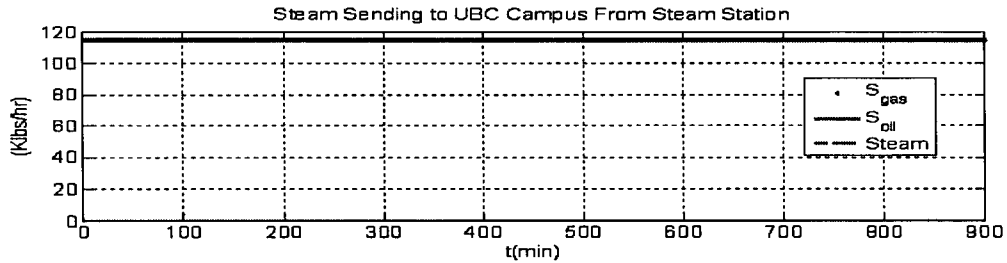


Figure 4.10: Scenario1 - Simulation Results for the Steam Station Cell

The boilers in the Steam Station burn gas to generate steam in the normal working state. Figure 4.10 shows how the Steam Station generates steam without disturbance during the power outage.

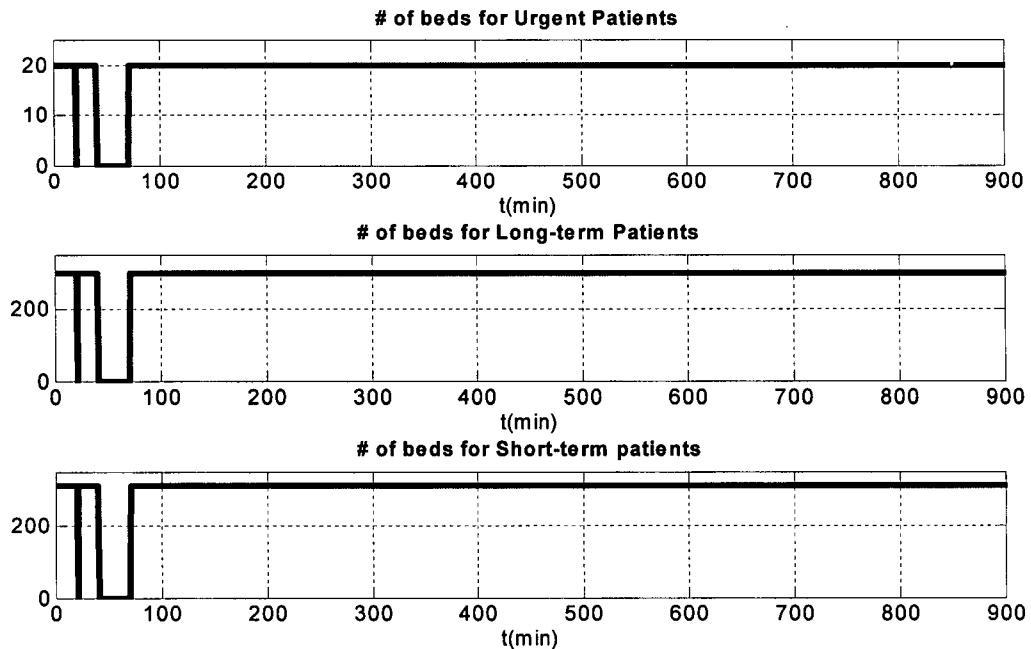


Figure 4.11: Scenario1 - Simulation Results for the Hospital Cell (A)

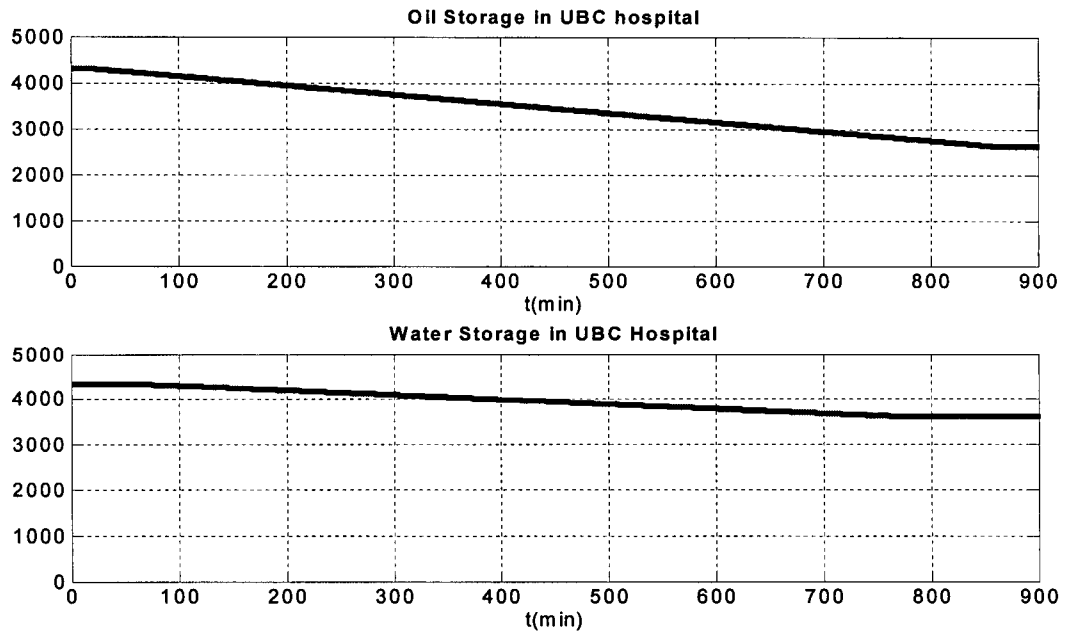


Figure 4.12: Scenario1 - Simulation Results for the Hospital Cell (B)

Figure 4.11 and Figure 4.12 show how the performance of the medical services in the hospital is influenced by the power outage in the Substation and water loss from the Water Station. When there is no power coming from the Substation, the backup generators start to work to provide power to the whole Hospital. The first spike in Figure 4.11 shows the state of the power in the hospital as a result of switching from external power to power from the backup generator. At $t = t_0 + 40(\text{min})$, the water pipe sending water to the hospital is broken and it affects the hospital immediately; the performance of the hospital, which is indicated by the number of beds for long-term, short-term and urgent patients, drops to zero (the second arrow in the figure). The hospital has its own water reservoir and it needs some time (30 minutes) to manually switch from the state of using external water to using backup water; the switch is indicated by the third arrow in Figure 4.11. After this switch, the performance of the hospital is restored to its normal state. In Figure 4.12, it can be seen that the backup water is used until the pipe is fixed at $t = t_0 + 780(\text{min})$, and oil from the oil storage is used until power is restored at $t = t_0 + 860(\text{min})$.

Figures 4.7 to 4.13 illustrate the performance of each of the cells and the interconnection between cells under scenario 1. The hospital was a full self-supporting system during the power outage.

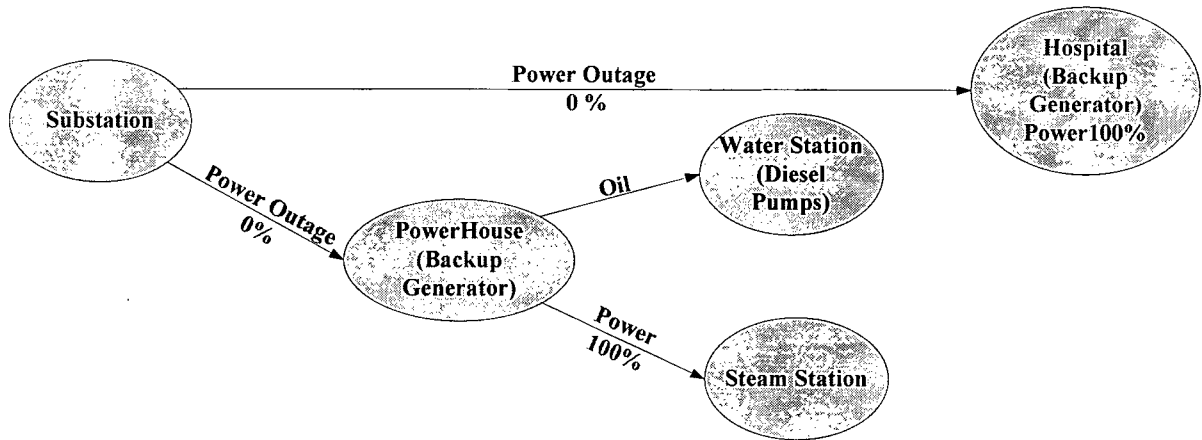


Figure 4.13: Interrelationship of Electrical Power between Cells

Figure 4.14 shows that the Power House and the Water Station also have backups for the critical components in their systems; these backups enable the two stations to maintain their full capacity performance during the power outage. In general, the whole system, especially the Hospital, maintains its performance for a short period after a power outage and loss of water by using its self-supporting backups. The length of the short period depends on the backup sources. The results of the simulation reflect the results of the actual event that happened at the UBC campus during the late November storm. In other words, the results validate the correctness and usefulness of the model and the cell-channel modeling approach of I2Sim.

4.2.2. Scenario 2 and Results Analysis

Based on the first scenario, the second scenario includes an extra event happening in the Power House: the backup generator does not start working when the power outage occurs, affecting the performance of the whole system. Another change in the second scenario is the time-shift for the same event as in the first scenario.

Scenario Description

✧ A snowstorm with a power outage at the UBC campus; the following events occur:

- Initial state : $t = t_0$, the whole system runs in the normal state until $t = t_0 + 20(\text{min})$
- $t = t_0 + 21(\text{min})$
 - ◆ Event1: A power outage occurs because of fallen trees bring down the transmission lines that send power to the UBC Substation.
 - ◆ Action 1: The functionality of the channel linking the external source, BC Hydro, and the Substation drops from 1 to 0.
 - ◆ Event 2: The backup generator in the Power House does not work immediately.
 - ◆ Action 2: The functionality of the backup generator stays at "0".
- $t = t_0 + 40(\text{min})$
 - ◆ Event: The water pipe linking the water station to the hospital breaks down because of the freezing weather.
 - ◆ Action: The functionality of the channel linking the Water Station to the Hospital drops from 1 to 0.
- $t = t_0 + 50(\text{min})$
 - ◆ Event: The backup generator in the Power House starts working.
 - ◆ Action: The functionality of the backup generator stays at "1".
- $t = t_0 + 860(\text{min})$
 - ◆ Event: After 14 hrs, BC Hydro's power is restored.
 - ◆ Action: The functionality of the electric power channel is restored to 1.
- $t = t_0 + 1480(\text{min})$
 - ◆ Event: The water pipe is fixed after 24 hrs.
 - ◆ Action: The functionality of the water channel is restored to 1.

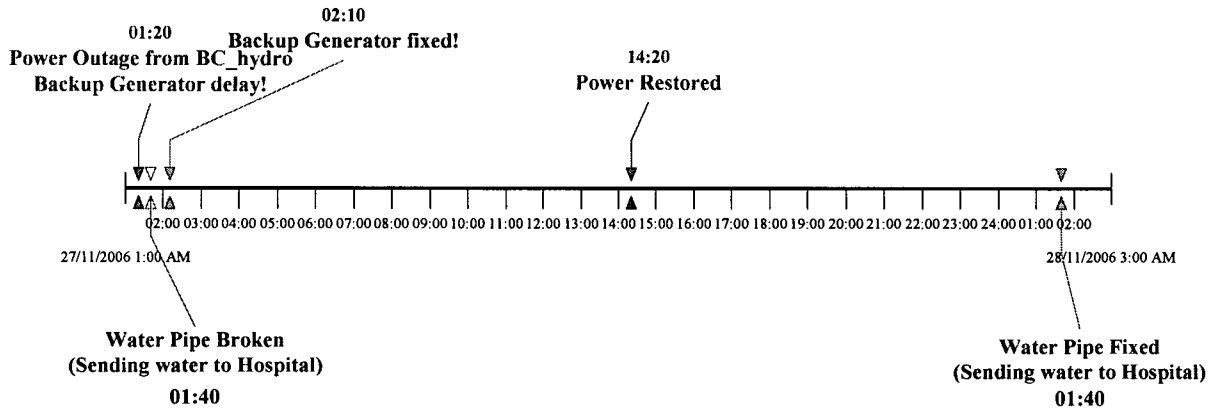


Figure 4.14: Timeline of Scenario 2

Results Analysis

Using the data in Figure 4.14, simulation results are generated and shown in Figures 4.15 to 4.20. The simulation results for the Substation for Scenario 2 are the same as for Scenario 1.

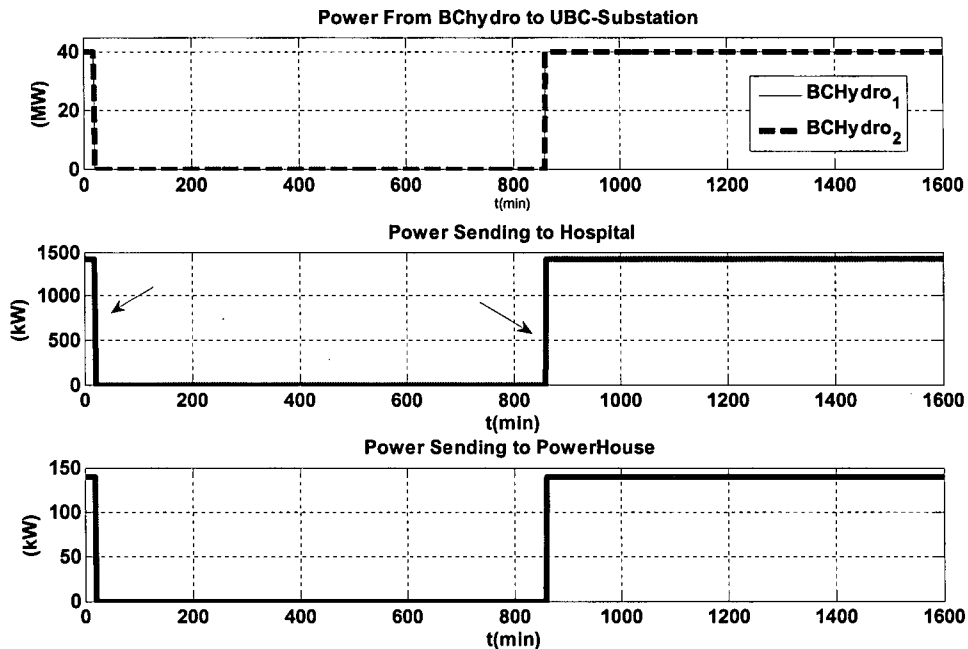


Figure 4.15: Scenario2 - Simulation Results for the Substation Cell

In Figure 4.16, Figure 4.17 and Figure 4.18, it can be seen that the backup generator has not kicked in immediately after the power outage. It takes about half an hour to fix the backup generator; this delays the switch time from using external power to using backup power.

The time delay influences the performance of the Water Station and of the Steam Station simultaneously. In Figure 4.17, it can be seen that the Water Station starts to pump water to the whole campus by using the backup pump after the switch time (the time between the first and second arrow in the figure). After $t = t_0 + 860(\text{min})$, when power is restored, the booster pumps work again and the backup pump returns to its standby state and this is indicated by the third arrow in the figure. The water sent to the whole campus is now at full capacity.

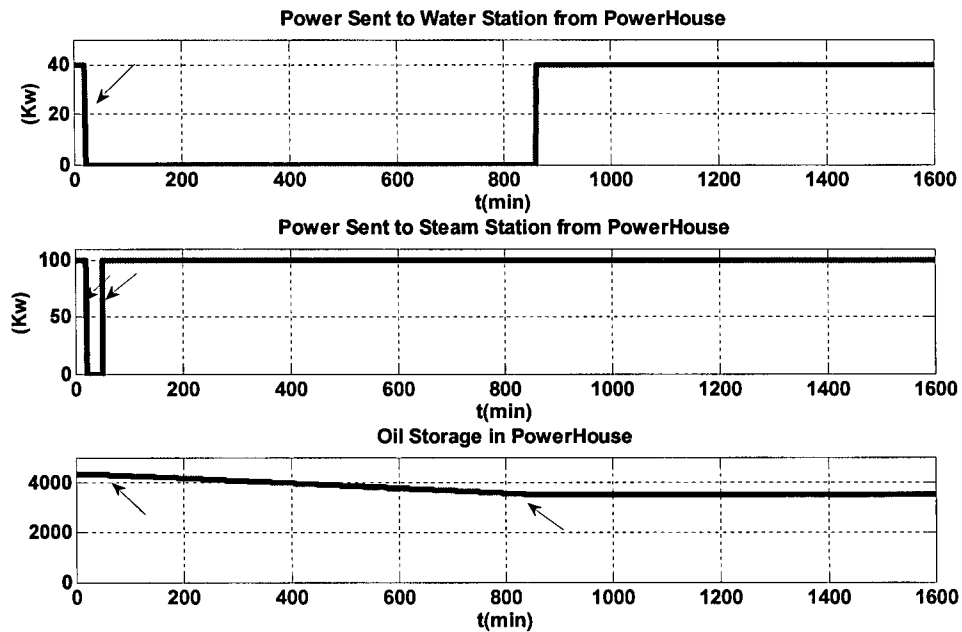


Figure 4.16: Scenario2 - Simulation Results for the Power House Cell

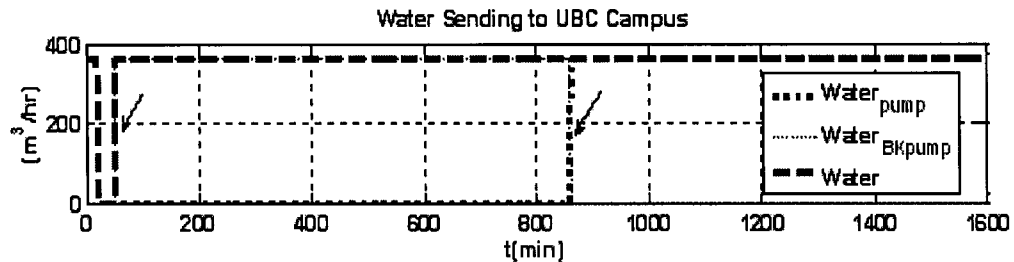


Figure 4.17: Scenario2 - Simulation Results for the Water Station Cell

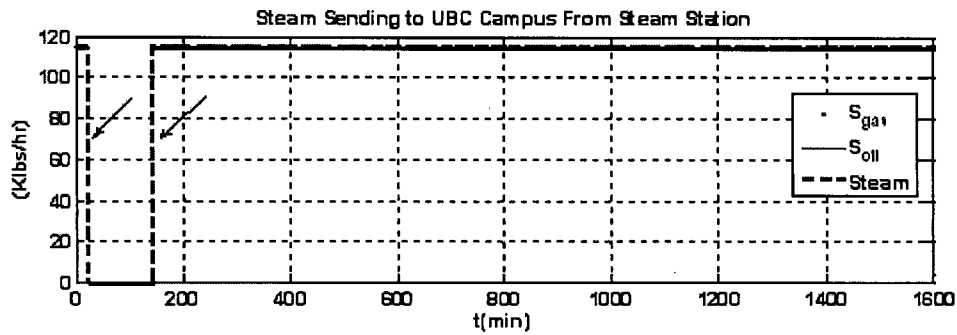


Figure 4.18: Scenario2 - Simulation Results for the Steam Station Cell

After the switching time, the backup generator still does not work; thus, this power outage affects the status of critical components such as the air fan in the Steam Station. The air fan in turn affects the operation of the boilers. The boilers have to stop working until the air fan is restarted and the time for restarting boilers takes one to two hours, depending on the situation. Figure 4.18 shows that the boilers have stopped working for about one hour; this means that steam is not sent out to the campus during this period.

Figures 4.19 and 4.20 illustrate the performance of the hospital when affected by the different states of the other cells. The medical service for long-term patients is affected differently from the medical service for short-term and urgent patients. At $t = t_0 + 20(\text{min})$, when the power outage occurs, the backup generators in the Hospital begin to work. At the same time, the steam from the Power House is delayed because the backup generator has dropped to 0. The performance of the Hospital changes due to the loss of steam. The number of long-term patients taken care of drops to zero because these patients depend on steam for heating; the number of short-term and urgent patients experience little disturbance because of the loss of steam, which is shown in Figure 4.19. At $t = t_0 + 40(\text{min})$, the water pipe breaks; the performance of the hospital stays at zero. After the switching time of 30 minutes and the restoration of steam, the hospital reverts to its normal state gradually.

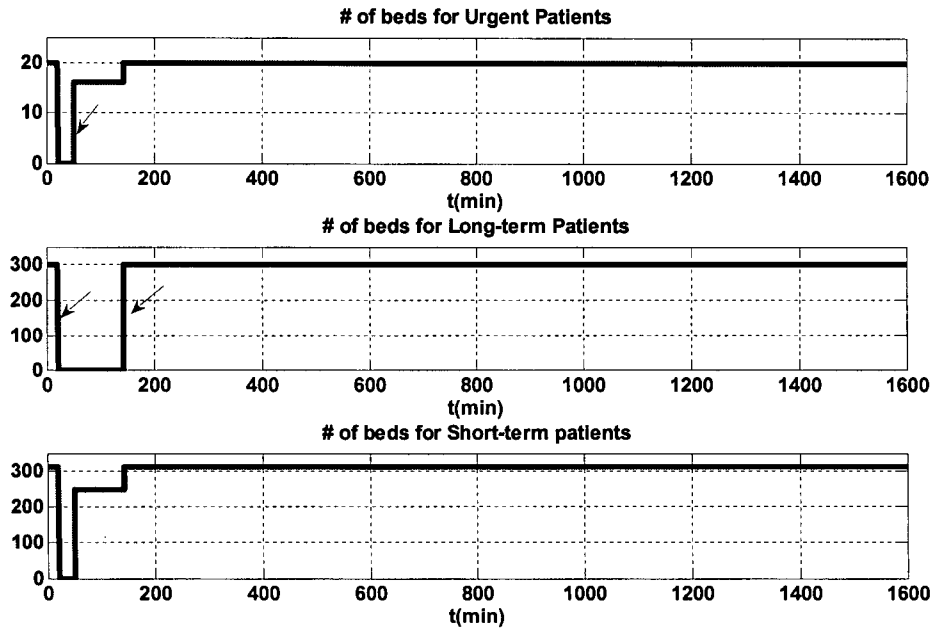


Figure 4.19: Scenario2 - Simulation Results for the Hospital Cell (A)

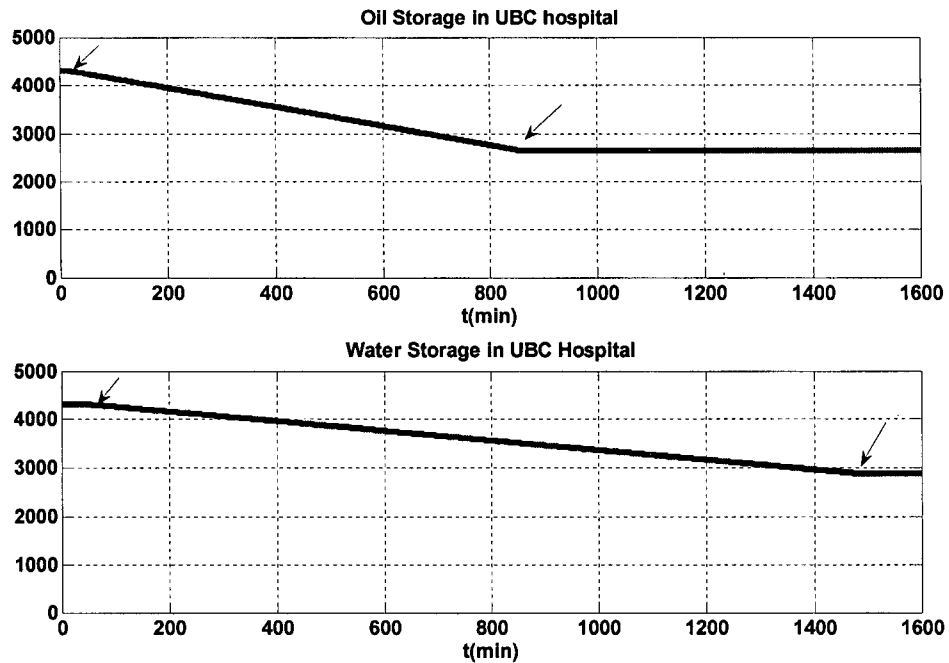


Figure 4.20: Scenario2 - Simulation Results for the Hospital Cell (B)

The difference between scenario 1 and scenario 2 is the state of the critical component inside the Power House cell. The performance of the system, especially the Hospital, has changed. Because of the power outage, the loss of water, and the delay time for the backup generator to take over, the performance of the Power House drops immediately; this drop in performance influences the Water and Steam Stations; finally the performance of the hospital drops because of the drop of performance in these cells, even though the backup system inside the Hospital works well. The results indicate that the backup inside the Power House is the critical component not only to its own cell but also to other cells linked to it. The performance of the hospital, which is the end outcome in the system, is the combination of multiple events. By using the I2Sim model, it is seen that the critical components should be set to a high-level priority of repair after the disaster.

4.2.3. Scenario 3 and Results Analysis

Scenario Description

In this section, a new block, which represents a distributor controller in the Substation cell, is added to the model. This block is used to re-direct power to the Hospital and Power House under different situations. The objective is to use a trial and error procedure to test optimal re-assignment solutions of a limited resource to the system. In this model, the simple distributor controller is a ratio of the amount of power going to the Hospital and to the Power House. In the scenario, the ratio of power sent to the Hospital changes from 0-1, so the performance of the hospital changes accordingly. In order to have a better view of the system without backup support, the time for the backup systems is reduced to a limited time (30 minutes).

- ✧ Power re-assignment with limited internal sources in the Power House and Hospital. The following actions happen:
 - Initial state : $t = t_0$, the whole system runs in normal state until $t = t_0 + 20(\text{min})$.
 - $t = t_0 + 21(\text{min})$
 - ◆ Event: The water pipe linking the water station to the hospital is broken due to freezing cold weather.

- ◆ Action: The functionality of the channel linking the Water Station to the Hospital drops from 1 to 0.
- $t = t_0 + 51(\text{min})$
 - ◆ Event: The backup water in the Hospital begins to work.
- $t = t_0 + 81(\text{min})$
 - ◆ Event: The backup water in the Hospital runs out.
- $t = t_0 + 100(\text{min}) \sim t_0 + 700(\text{min})$
 - ◆ Event: The amount of Power sent to the Hospital by the UBC Substation changes, using distributor control.
- $t = t_0 + 701(\text{min}) \sim t_0 + 800(\text{min})$
 - ◆ Event: The amount of Power sent to the Power House from the UBC Substation changed, using distributor control.
 - ◆ Event: The backup generator in the Power House is delayed to come to operate.
- $t = t_0 + 801(\text{min}) \sim t_0 + 900(\text{min})$
 - ◆ Event: The steam pipe linking the Steam Station to the Hospital gets damaged.
 - ◆ Action: The functionality of the steam channel changed from 1 to 0, and then back to 1.

Results Analysis

The power is in normal state. The water pipe breaks and then after 30 minutes' delay, the hospital manually switches to using its internal water source; the limited amount of backup water is available for use for only 30 minutes. The performance of the hospital drops to 0, goes back to full capacity and then drops to 0 again in the first 100 minutes because of changes in the input water state. This is illustrated in Figure 4.28.

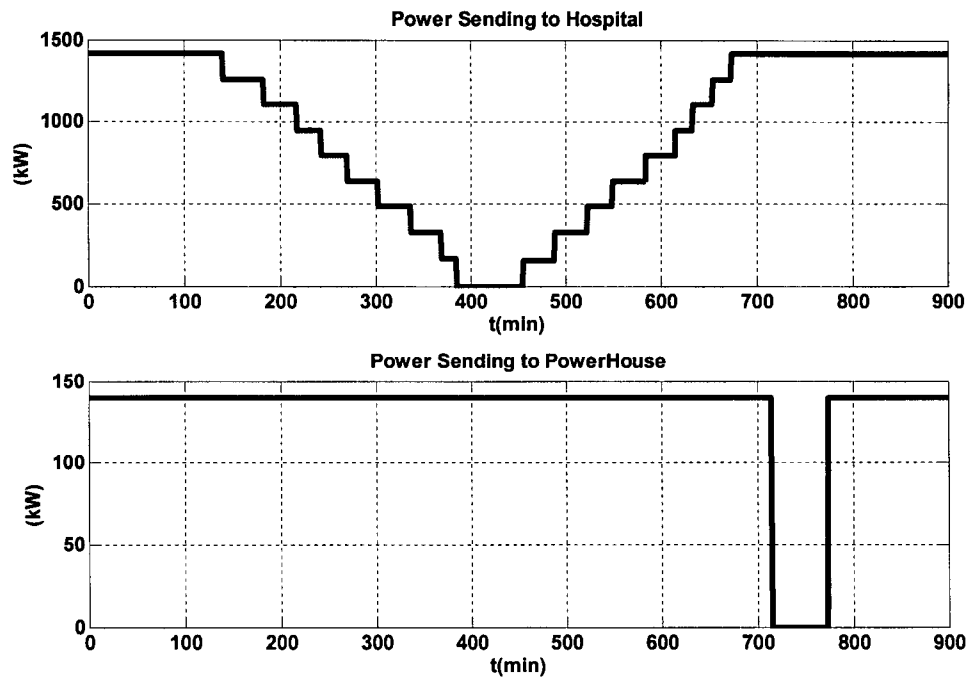


Figure 4.21: Scenario 3 - Distributor Sent Power to the Hospital and Power House

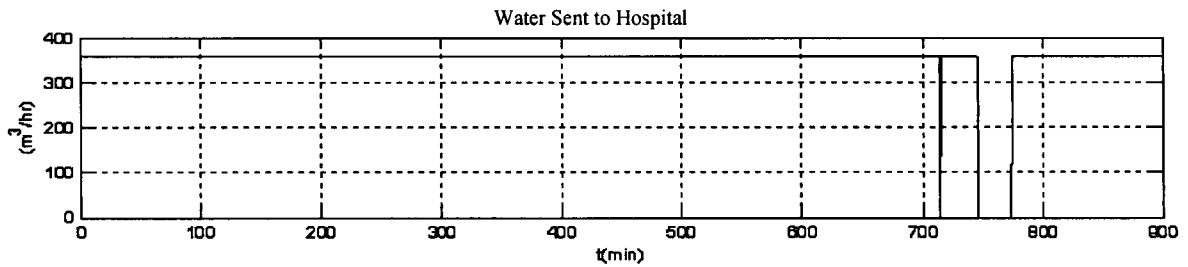


Figure 4.22: Scenario3 - Simulation Results for the Water Station Cell

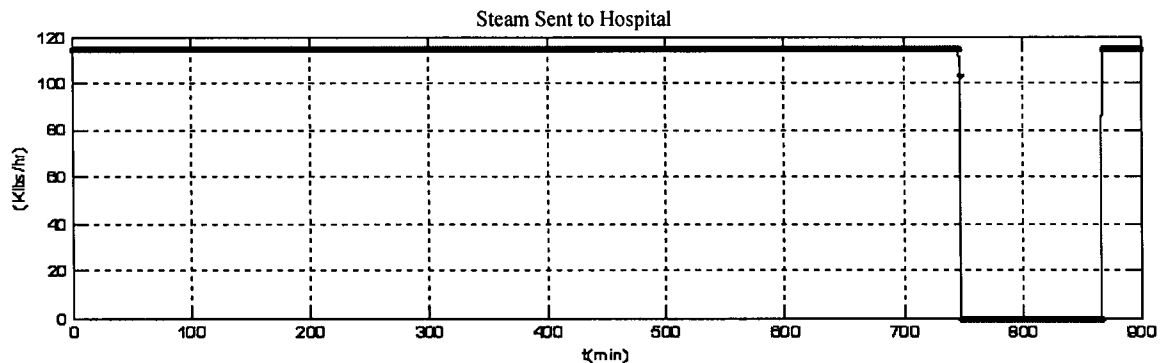


Figure 4.23: Scenario3- Simulation Results for the Steam Station Cell

It can be seen from Figures 4.24 and 4.28 that from 200 to 800 minutes, the power sent to the Hospital and the Power House is changed by adjusting the distributor's ratio in order to affect the performance of the Hospital. After using the backup generators for a limited time period, the Power House and Hospital's performance drops to 0 and is then restored when the external power returns.

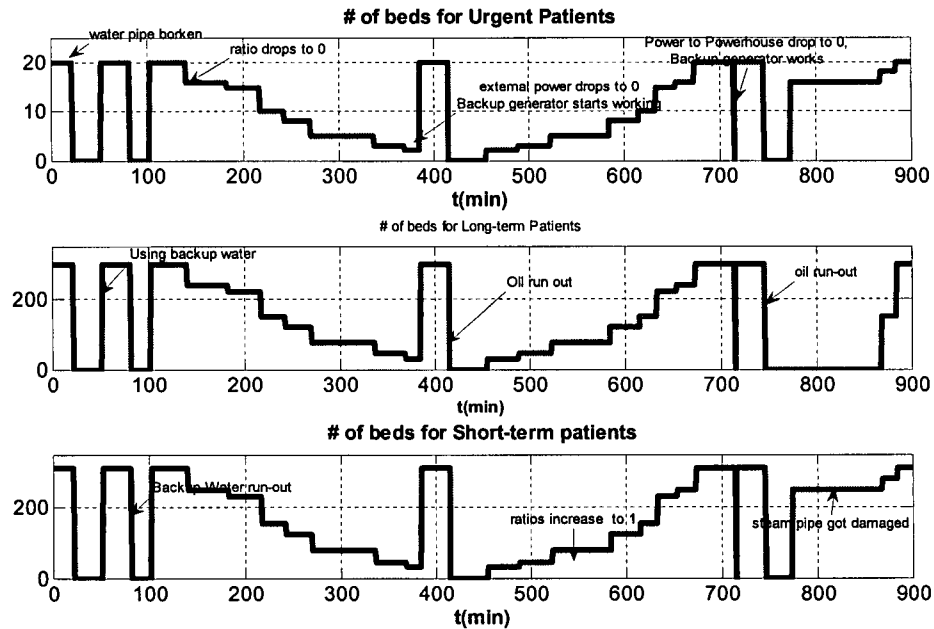


Figure 4.24: Scenario 3 - Simulation Results for the Hospital (A)

Finally, the performance of the Hospital changes following the functionality change of the steam pipe in the last 100 minutes. The figure illustrates that the hospital medical services for long-term patients changes rapidly when the amount of input steam is decreased.

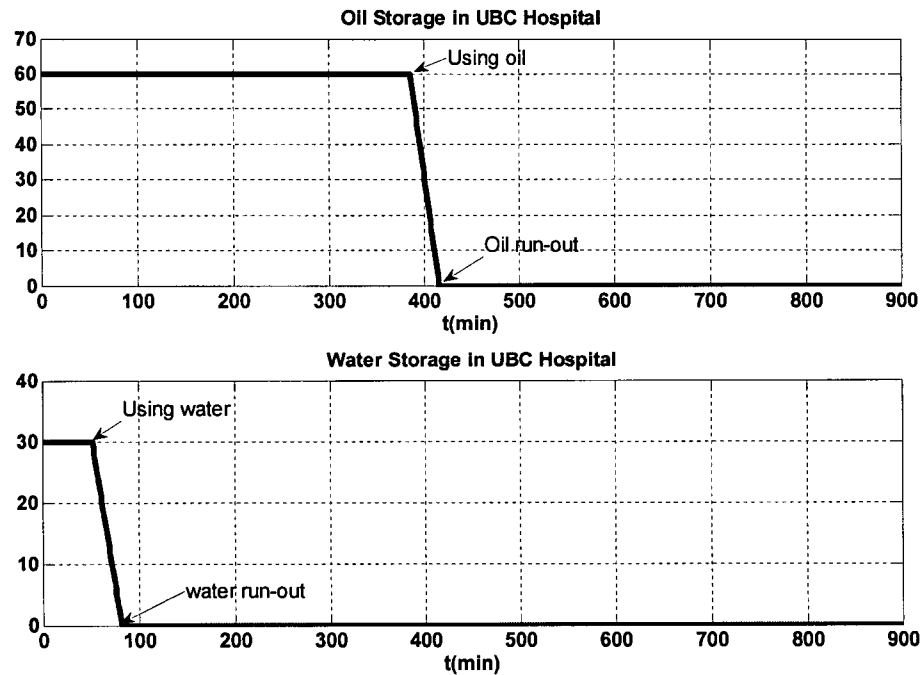


Figure 4.25: Scenario 3 - Simulation Results for the Hospital (B)

In scenario 3, the simulation results illustrate that the backups for cells increase the reliability of the cells' performance, depending on the amount of storage. The results indicate how different distribution of limited resources influences the system performance; the input token of steam is critical to long-term patients in the Hospital. Based on the emergency plan of the Hospital, when the loss of steam lasts for more than 2 hours, the long-term patients have to be transferred to other hospitals such as the Vancouver General Hospital.

4.3. Distributed Simulation

The simulation itself was parallelized, and distributed on the UBC Power Systems Lab PC-cluster, so that the computational load, as well as the scalability of the approach, can be studied. In this section, a distributed simulation for the simplified UBC test case is tested by using the SCI based PC cluster [41].

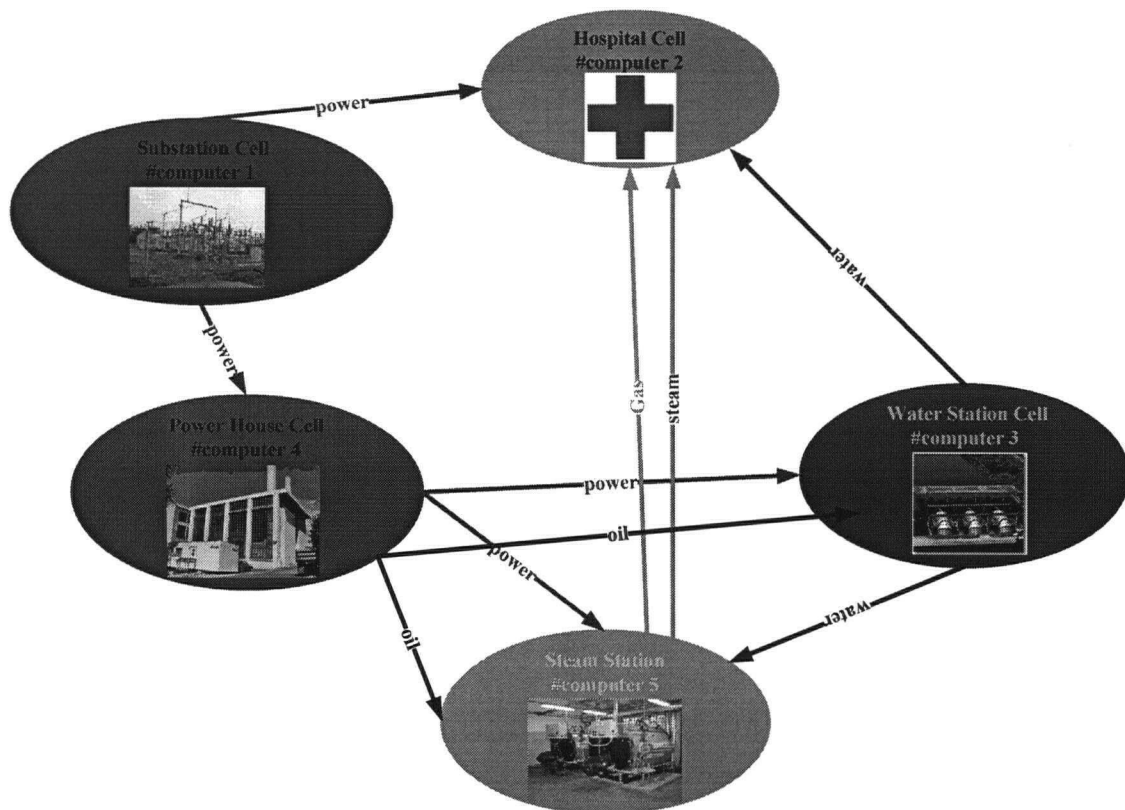


Figure 4.26: Structure of the PC Cluster Simulation

Figure 4.26 illustrates how the simplified UBC test case model is separated into five PCs; each of them represents one of the cells. For example, the cell Substation is installed in computer #1 and it is connected with the Hospital and the Power House cells by an SCI interface [36]; similarly, the other four cells are connected to the other PC's. The connection of the different types of channels to the PC cluster is also shown in this figure. The computation speed is about five times faster when using the PC-Cluster [41] than using a single computer.

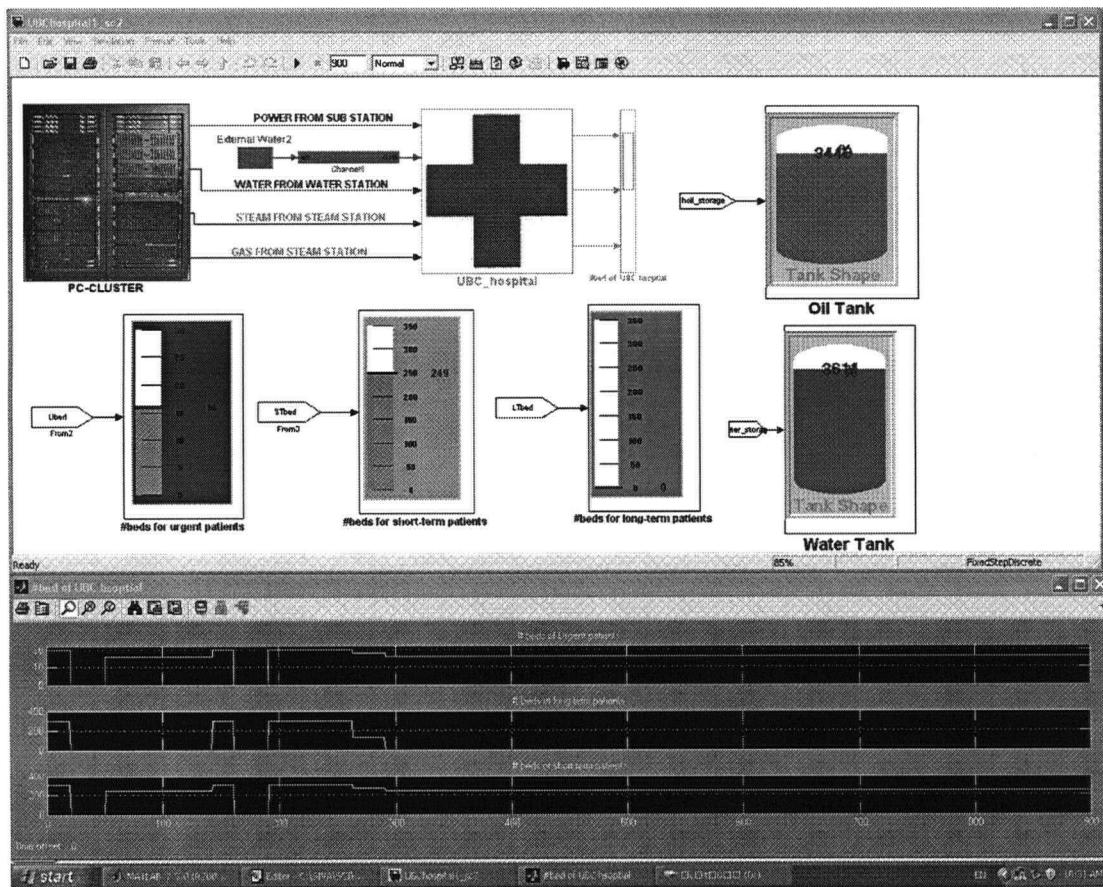


Figure 4.27: PC Cluster Simulation A

The distributed display of each cell gives the decision makers a more practical view of the actual situation than a single display. In reality any interdependent infrastructure system is composed of a number of cells and channels. The cells in real-world are usually located in different geographical position and are linked with other cells by physical channels. Because of the geographic separation, the models for cells are in different PCs. At the same time, the PC cluster makes the system more understandable by using more indicators, controllers and time-dependent scopes for showing the simulation results in multiple ways.



Figure 4.28: PC Cluster Simulation B

Figure 4.27 and 4.28 show how the simulation of the simplified test case runs in the PC cluster.

4.4. Simulation Conclusion

In this chapter, the system model was validated and tested by using known scenarios and the model demonstrated its usefulness and correctness for the research on infrastructure interdependencies. System's redundancy increases the robustness of the cells, such as in the case of the backup generators in the Hospital; the critical connections, such as the steam pipes linking the Steam Station with the Hospital, influence the system performance in a very remarkable way. These critical connections have been analyzed and identified based on the simulation results. A distributor allows an operator to find the optimum allocation of limited resources in order to ensure the best possible operation of the other critical infrastructures during an event. The simulation itself can be parallelized and distributed on the UBC Power Systems Lab PC-cluster.

Chapter 5 Conclusions and Future Work

5.1. Conclusion

This thesis presented contributions made to the development of UBC's Infrastructure Interdependencies Simulator I2Sim. In particular, this work has contributed a methodology to build the Human Readable Tables (HRT) which is an essential aspect of the I2Sim modeling approach. A prototype of I2Sim has been built and tested using MATLAB/SIMULINK/CVI. The prototype has been used to demonstrate the validity of I2Sim to replicate complex interdependency scenarios. A user friendly interface was developed in order to simulate various disturbances on-line to allow decision makers to have a better insight into interdependencies. A better understanding facilitates the formulation of better strategies for each scenario. A reduced scale test model based on the UBC test case data of the I2Sim project which includes the Hospital, Substation, Water Station, Power House and Steam Station was implemented.

To analyze the real case scenario of the November 19th 2006 snowstorm that affected the UBC campus, the simulation's results were consistent with the outcome of the actual event. The redundancy provided by the backup systems was vital in increasing the robustness of the critical UBC cells such as Hospital. Critical interconnections such as the channel between the hospital and the steam station were represented and identified through the simulation results. The capacity of the Hospital's medical service was estimated under these conditions and the patients' sensitivity to the different input tokens was evaluated. The research shows that that a discrete event simulation with a distributor controller could provide a better distribution of limited resources for the overall system's performance in the same scenario. These capacities give the decision makers a better understanding of the emergent system behavior under different operational scenarios.

Other lessons were learned during the process of setting up the system models for the UBC test case that point to important policy and operational issues in the system. For example, in the steam station, boilers can use gas or oil to burn the steam, the oil is the backup of the gas, but the boilers need gas to start-up. When there is no gas, or the gas pipe is broken, there is no start-up for boilers and it does not matter how much gas or oil the powerhouse gets, the plant cannot generate steam any more. Another example is the following. When there is a power outage on Campus, the powerhouse can generate and send the steam out by using backup generator, but the problem is that if other buildings have no power, fans and the equipment in those buildings for sending the steam inside those building will be shut down, therefore no steam will be delivered.

5.2. Future Work

In this thesis, no delay was assumed for the transportation of tokens through channels in their normal state. Future research is to include this delay which can have an important influence on the system's performance when it covers a large geographic area. The model takes into consideration the number of available beds in the hospital with urgent, short-term and long-term patients. Another extension to the research would be the estimation of the capacity of the hospital taking into account the physical presence of types of patients; the results would then depend on some factors such as the inflow and outflow of patients after a disaster, priority in treatment and so on. The results of this thesis will be used as a benchmark system for validating the full version of the I2Sim Simulator, which is built around the full capabilities for large systems simulation of the OVNI (Object Virtual Network Integrator) core [43] of UBC's power systems simulation group.

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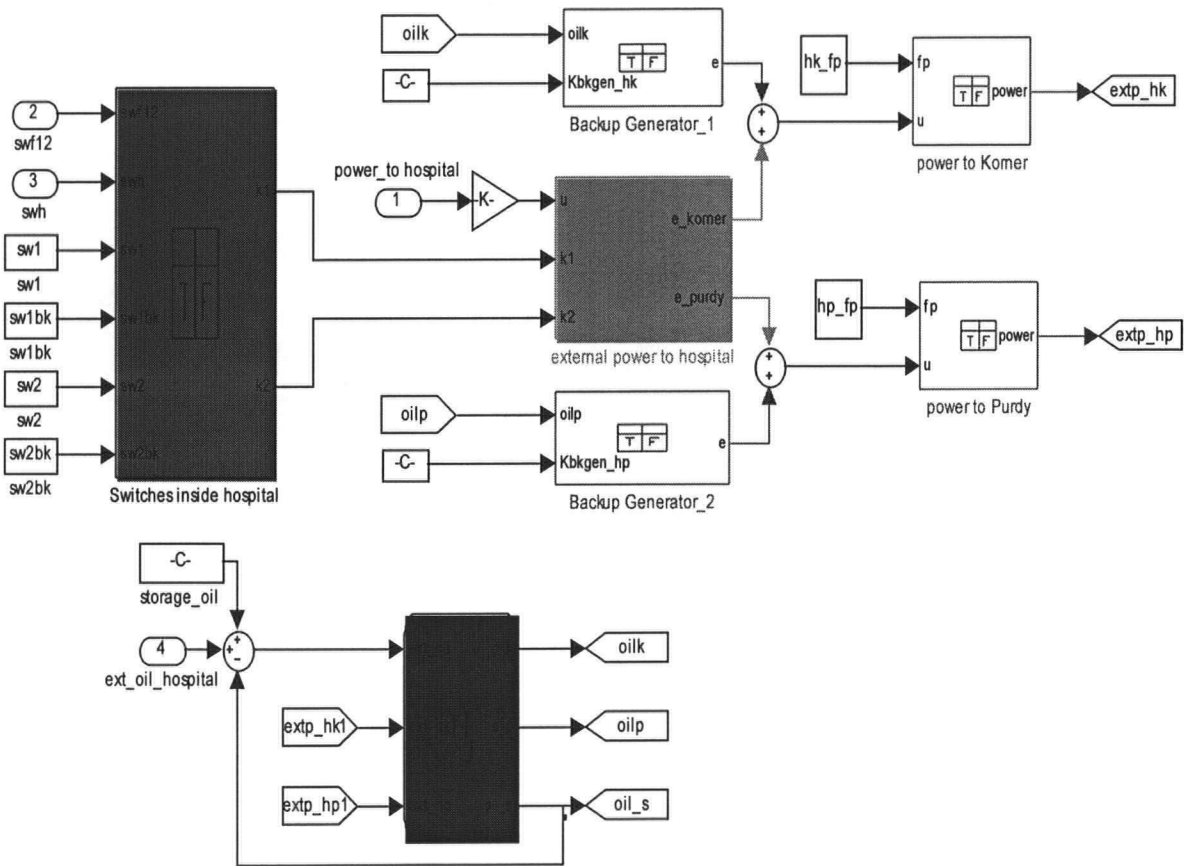
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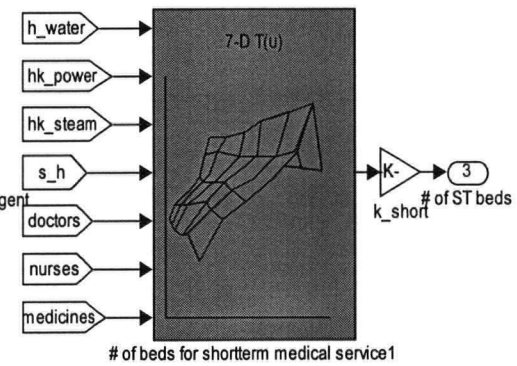
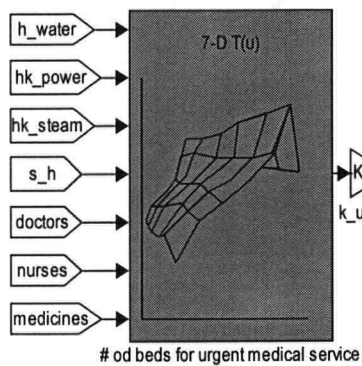
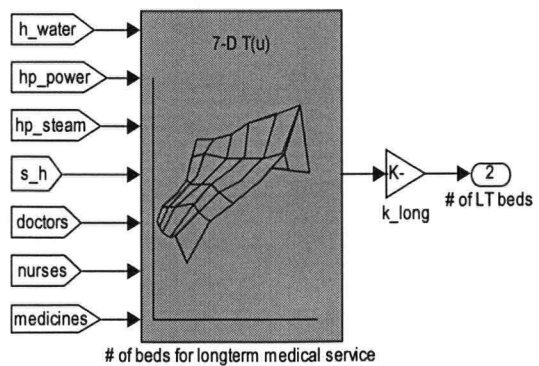
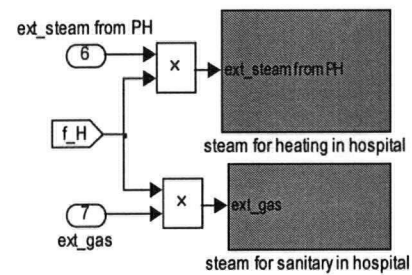
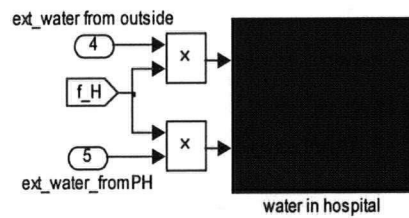
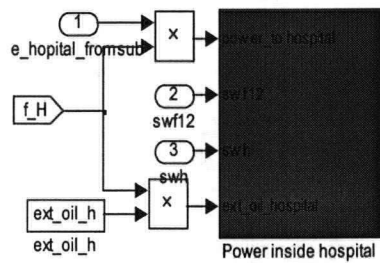
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Appendix

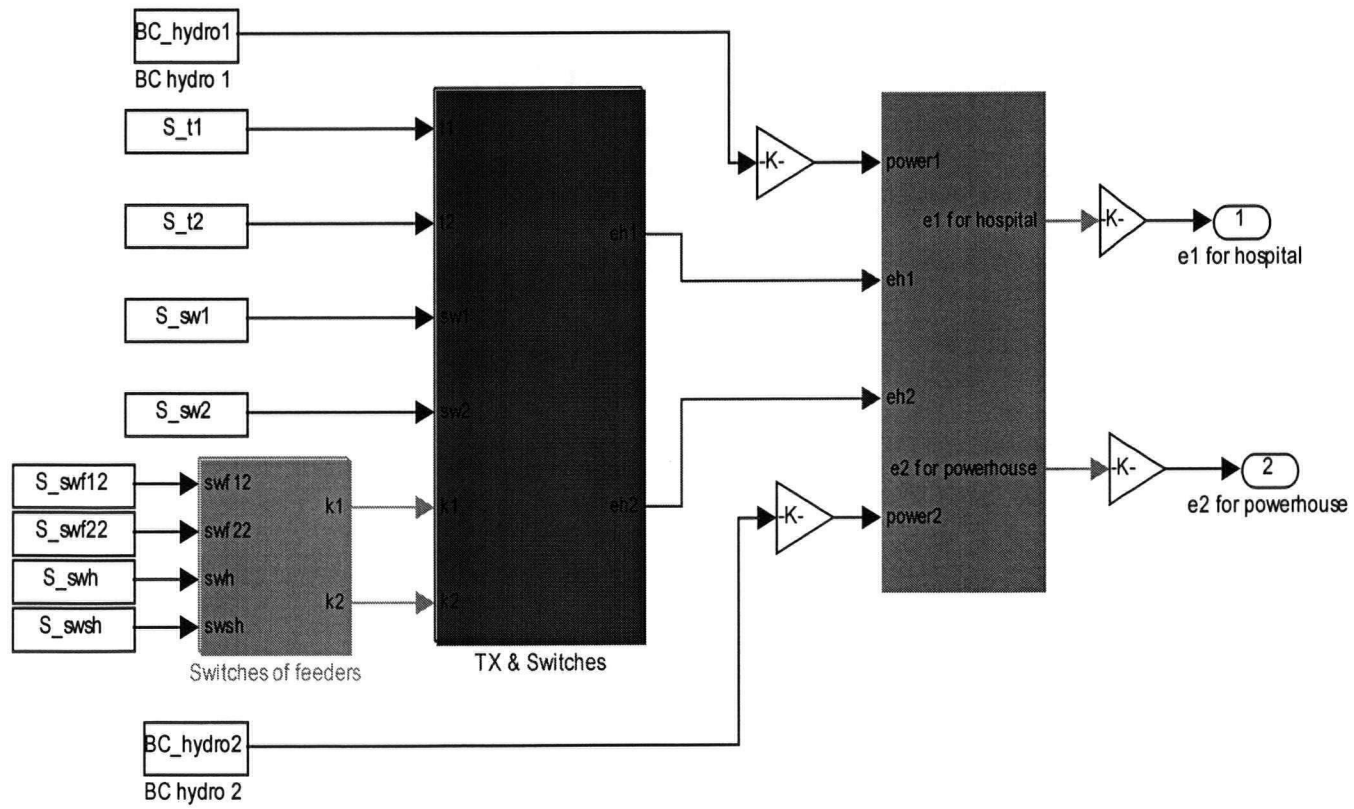
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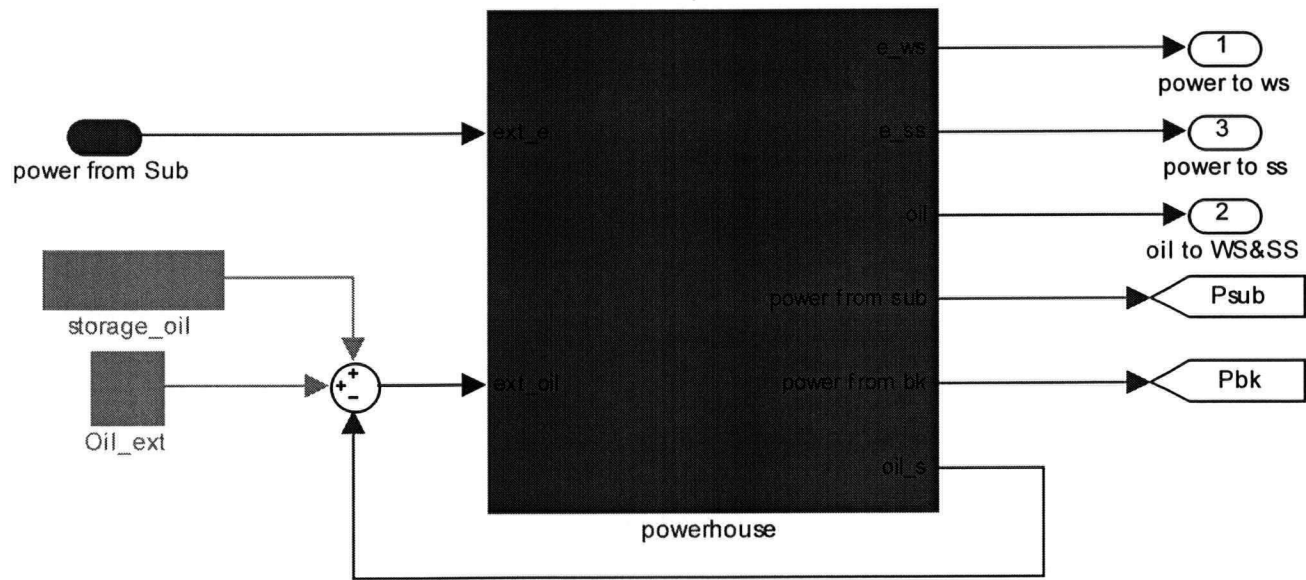
- UBC's Hospital Cell Model



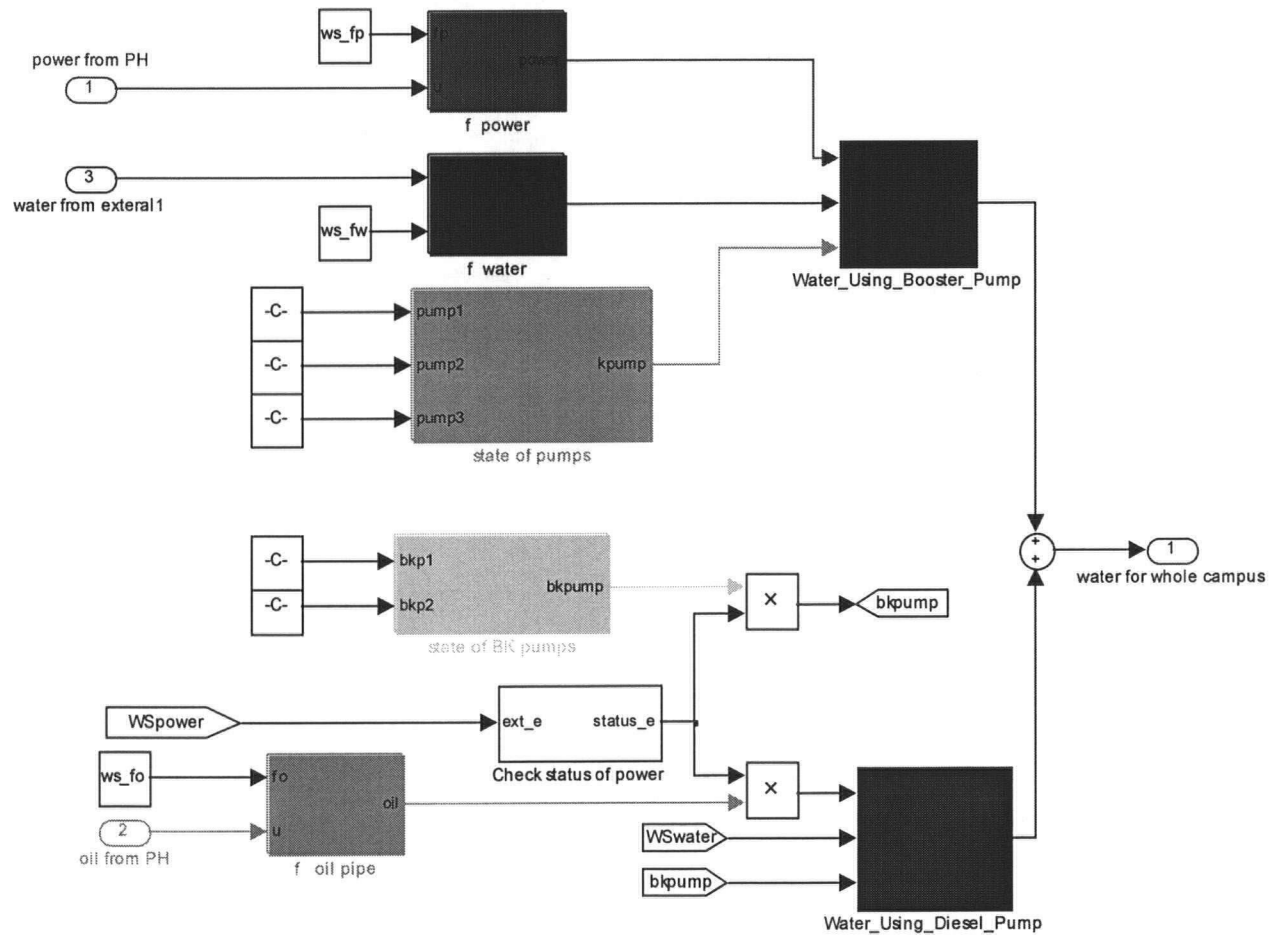
- UBC's Substation



- UBC's PowerHouse



- UBC's Water Station



- UBC's Steam Station

