Power Systems Modeling for Multiple Infrastructure Damage and Repair Simulations

by

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Abstract

The interdependencies that exist within and between infrastructures can cause unexpected system properties to emerge when their components fail due to large disruptions. As witnessed following emergencies such as Hurricane Katrina, the complexities of these interdependencies make it very difficult to effectively recover infrastructure because of the challenges they create in prioritizing the most critical components for repair. The Joint Infrastructure Interdependencies Research Program was initiated by Public Safety Canada (PSC) and the Natural Sciences and Engineering Research Council of Canada (NSERC) in 2005 to research methods for remedying this problem. As a part of this research, the University of British Columbia (UBC) is developing an infrastructure interdependency simulator, named I2Sim, to simulate disasters and develop strategies for dealing with emergencies.

Part of this development is to construct a model of the UBC electrical distribution system and interface it with I2Sim. In this research, a general methodology for such a model is presented, which employs an off-the-shelf powerflow modeling tool. In addition, a model of the UBC information technology infrastructure is developed to provide a second infrastructure model to demonstrate the electrical model's usefulness in multi-infrastructure disaster recovery simulations. Simulations with these models have shown that the recovery of this two-infrastructure system can be carried out more effectively following an earthquake if both infrastructures are considered *together* in the repair approach, rather than *individually*. This difference was on the order of thirty percent.

To extend this research from electrical *distribution* systems to electrical *bulk* systems, an interdependency model of the British Columbia Transmission Corporation bulk power network and its communications system was also developed, along with a post-blackout restoration procedure. Using these, simulations of a post-blackout recovery were carried out to study the level of risk that communications outages may pose to the electrical network's recovery. These simulations revealed a correlation between restoration time and the number of communication points lost. This research also demonstrates there is value in combining the results of such simulations with risk evaluation tools. Together these results provided a clearer indication of where vulnerabilities exist.

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Acknowledgements

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To my loving mother.

Chapter 1

Introduction

The topic of this thesis is electrical power system modeling for the purpose of studying the interdependencies between multiple infrastructures. This is part of the Infrastructure Interdependencies Simulation (I2Sim) research being carried out at the University of British Columbia (UBC) for the Joint Infrastructure Interdependencies Research Program (JIIRP) [1].

1.1 Background

It is clear that the delivery of goods and services to people through infrastructures is essential to modern society and that the systems of components constituting these infrastructures are large and complex. What is less obvious, however, is the fact that many of the components and services that are necessary for infrastructures to operate are employed from *other* infrastructures or are fed back from within themselves, meaning dependencies between and within them exist. These inter and intra-infrastructure dependencies are referred to as 'interdependencies'.

Interdependencies are facilitated by advances in technology and driven by economics, causing them to become more and more commonplace [2]. The emergence of Voice Over IP (VOIP), a technology where telephony is performed using existing IP networks, is a good example of this as it is a technology that has created an interdependency that previously did not exist because it is less expensive than using two independent physical systems [3], [4]. Interdependencies, however, are often much simpler than this. A type of interdependency known as a 'Geographical' (as classified by Rinaldi et al [3]) exists anytime more than one infrastructure relies on the same civil structure as another, such as when power lines and communications cables share towers, or when network servers are housed in the same building as their power source. In the event of large disturbances, common interdependencies like these, while economically advantageous, jeopardize reliability and can make seemingly robust systems fragile because they allow disruptions in one infrastructure to echo through to others unpredictably. The implication is that a group of many individual infrastructure systems must be treated as a single interdependent 'super-system', which makes analyzing disturbances in them extremely complex [2], [5], [6] as is illustrated in Figure1.1.

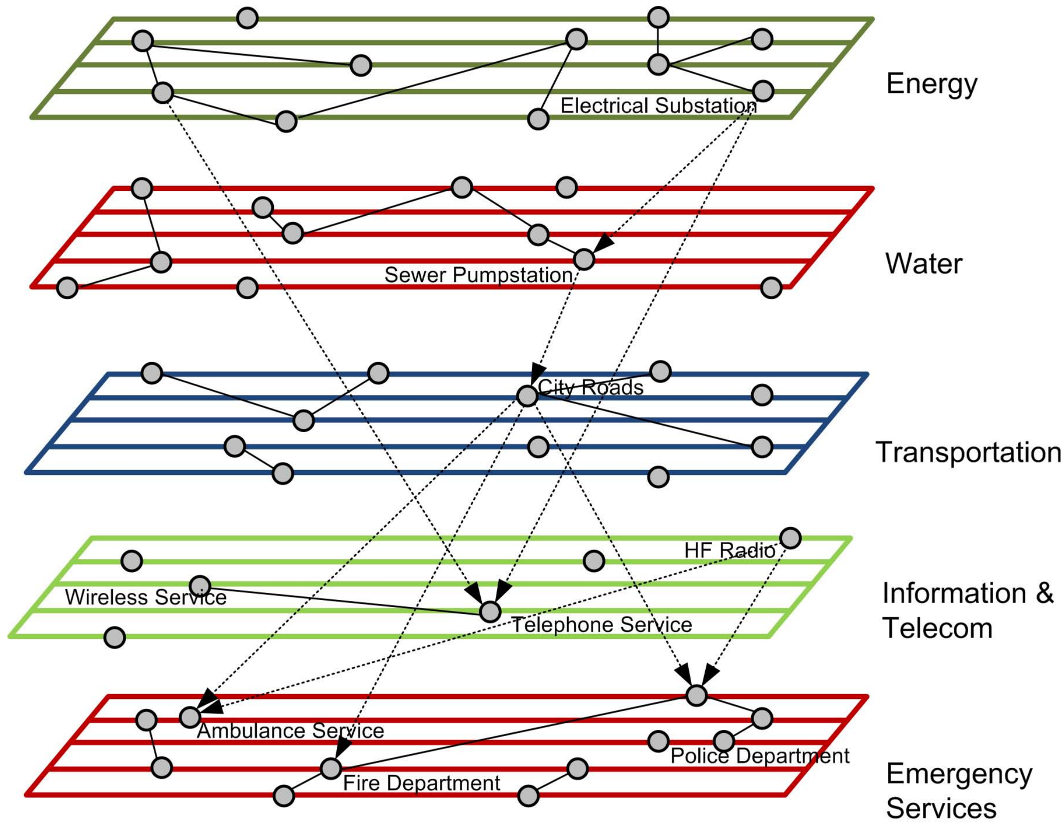

Figure 1.1: Infrastructure Interdependencies

The consequence of relying on this complicated set of interdependencies has been experienced in a number of major events such as the Winter 2000 ice storms in eastern Canada, the 14 August 2003 North American Power Blackout and Hurricane Katrina in 2005. Such events have illustrated not only how interdependencies can collapse a large social system, but also the difficulties they create in the rebuilding process. Following Katrina, for example, it was reported that after one year 'Gas and electricity service is reaching only 41 and 60 percent of the pre-Katrina customer base, respectively' [7], [8]. In emergency management literature, Hollman et al describe this as 'Recovery' stage [6].

The JIIRP is a Canadian national research effort to secure and protect Canada's critical infrastructures [9]. Under this program, the research objective at UBC is to study decision making for critical dependencies in infrastructure networks through modeling and simulation of critical infrastructures and their interdependencies. The culmination of this research at UBC is an infrastructure simulator known as I2Sim [1]. A major effort of the I2Sim development lays in modeling individual infrastructures. It is the focus of this thesis to describe a method for incorporating an electrical power distribution system infrastructure model into the I2Sim multi-infrastructure simulator. In addition, this thesis addresses the related issue of bulk power system recovery and how additional (non-power system) infrastructures necessary for this can be incorporated into the risk models currently used to determine the level of redundancy and maintenance of critical recovery components.

Before discussing this further however, the following subsections review the work that has been done in formally defining and classifying these infrastructures, their interdependencies and the approaches that have been developed to simulate the interdependencies between power systems and other infrastructure networks.

1.2 Infrastructure Interdependency Formalization

The study of infrastructure interdependencies is relatively new. Defining what an infrastructure is and classifying infrastructure interactions has been a non-trivial task of this work [10]. In 1996, following the Oklahoma City bombing and a rapid emergence of computerized control systems, US President Clinton established the President's Commission on Critical Infrastructure Protection (PCCIP), which created what has become a widely used definition for infrastructure [11]:

> "The framework of interdependent networks and systems comprising identifiable industries, institutions (including people and procedures), and distribution capabilities that provide a reliable flow of products and services essential to the defense and economic security of the United States, the smooth functioning of governments at all levels, and society as a whole."

This provides a scope for what may be considered part of the 'infrastructure', however, it does not provide a great deal of insight into how an infrastructure operates or what constitutes an interdependency. To build on this, Rinaldi, Peerenboom and Kelly offer a more functional definition, applicable to infrastructure modeling [12]:

> "An infrastructure network, I, is a set of nodes related to each other by a common function. The network may be connected or disjoint. It may be directional, bi-directional or have elements of both. Internal relationships/dependencies within the infrastructure I are represented by edge (a, b) with $a, b \in I$."

This definition has become quite pervasive in literature and gives a better sense of how infrastructures operate together [10].

With these definitions of what an infrastructure is, it is also important to review the commonly used definition(s) and classifications for infrastructure 'interdependencies'. Dudenhoeffer et al describe a set of four quite widely used dependency classifications that are very useful for classifying the types of services infrastructures provide to one-another. Rinaldi et al paraphrase these succinctly [3], [12], [13]:

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

These are comprehensive and simple classifications for the types of interdependencies that exist in and between infrastructure and are useful for analyzing a system to identify where components depend on one another. Taking a different approach, in their attempt to model post September 11 lower Manhattan, Lee, Mitchell and Wallace also categorized infrastructure interdependencies, however, here they put a stronger focus on the input-output characteristics of dependencies rather than the type of service being shared [2]:

1. *Input dependence* – The infrastructure requires as input one or more services from another infrastructure in order to provide some other service.
2. *Mutual dependence* – At least one of the activities of each infrastructure in a collection of infrastructures is dependent upon each of the other infrastructures. (An example of mutual dependence involving two infrastructures occurs when an output of infrastructure A is an input to infrastructure B, and an output of infrastructure B is an input to infrastructure A.)
3. *Shared dependence* – Some physical components or activities of the infrastructures used in providing the services are shared.
4. *EXCLUSIVE OR dependence* – Only one of two or more services can be provided by an infrastructure. EXCLUSIVE OR can occur within a single infrastructure system or among two or more systems.

5. *Colocated dependence* – Components of two or more systems are situated within a prescribed geographical region.

These are again very useful as they provide a framework for developing mathematical models for the types of interdependencies that exist.

The next fundamental aspect of infrastructure interdependency research is dissecting infrastructure outages themselves to gain insight into how they are managed at a high level. Hollman et al [6] define four stages of management for infrastructure emergencies:

1. Mitigation – Long before the disaster.
2. Preparedness – Long and shortly before the disaster.
3. Response – During and shortly after the disaster.
4. Recovery – Shortly and long after the disaster.

Here, Mitigation refers to sustained actions taken to reduce the prospective risks associated with effects of disasters; Preparedness is the planning done to anticipate the response and recovery actions that will be necessary when a disaster occurs; Response are the actions taken during and immediately following the disaster; and Recovery are the longer term efforts taken to restore the system to its original state. These classifications provide a sense of when and how resources are allocated and spent, which is important for determining how to develop tools for examining and improving their processes. One of these tools, the interdependency simulator, is becoming widely used to study the response and recovery stages of emergencies to optimize the mitigation effort and provide better insight for the preparedness planning. The following section discusses some of the progress that has been made in developing interdependency models and simulations.

1.3 Infrastructure Interdependency Simulation Approaches

In a 2006 review of infrastructure interdependency modeling research efforts, Pederson et al asserted that techniques could generally be classified as one of two approaches: (1) Integrated, or (2) Coupled. They describe *integrated* approaches as modeling infrastructures and their interdependencies in a single model and *coupled* approaches as using multiple cascading simulations of individual infrastructures to model the greater infrastructure in a piecewise fashion. They note that the advantage of integrated models is their tendency towards a larger picture view, while coupled models are better suited to capture component level detail [10].

Within these classifications, a number of techniques exist for modeling and simulating infrastructures and many them have attempted to address power systems, recognizing that energy is among the most critical commodities. Some of the modeling and simulation techniques where electrical power systems have been incorporated include [10], [14]

- **System Dynamics:** This is a continuous integrated modeling approach, developed by Jay W. Forrester, wherein differential equations are employed to model feedback loops, stacks and time-delays of goods and services. The output of such models create a picture of how the system (or infrastructure) changes over time [15]. As described by Rinaldi et al [3], this technique has been used to study the effects of how policies and regulations are applied in 'multiple linked infrastructures including energy (electricity, oil, natural gas), communications, transportation (waterways, highways, rail), emergency services, banking and finance, agriculture, water, shipping and markets.'

- **Petri-Net:** An integrated discrete time-step tool, where graphs are used to model the interdependencies between various parts of a system using tokens. These tokens are transfered between infrastructures to model their states and in this manner Petri-Net models provide a quasi-intuitive way of visualizing flows of services between infrastructures. Petri-Net models have been applied to modeling the interdependencies between multiple infrastructures, including electrical power and its associated SCADA system [16]. Such a simulation was presented by Gurseli et al [17], where it was used to determine the infrastructures that were affected by a loss of power and how tightly the couplings between these infrastructures were. However, a drawback to this approach is its inability to model quantitative information such as the amount of power lost to specific components.

- **Markov Chain:** An integrated, stochastic modeling technique widely used for reliability modeling in electrical power systems [18]. A type of Markov Chain modeling, called Constrained Markov Decision Processes (CMDPs), where the transition probabilities depend on past history and cost constraints are imposed on these decisions [19], has been used to model interdependencies between disruptions to the communication system in a bank and its services. While this study did not explicitly model power systems, this approach could quite easily be adapted to do so. A drawback to Markov Chains, however, is again an inability to capture quantitative system dynamics [18].

- **Agent-Based Model:** This is one of the most pervasive types of infrastructure interdependency simulation approaches. In this type of model, decision makers are modeled as individual agents, which react based on their agent-type and their state (meaning not all agents of the same type will react similarly at the same point in time). Two notable agent based models are the Critical Infrastructure Modeling Software (CIMS) developed by the Idaho National Laboratory [12], and the N-ABLE agent based model from Sandia National Laboratories [10], [12], [20]. In Agent-Based modeling, electrical power is modeled externally, whereby the output of its simulation acts an input to various agents, and in turn those agents make decisions as to how the electrical system is operated. Unfortunately, in the N-ABLE and CIMS models described in [20] and [21] respectively, the specific methods used for simulating the electrical system are left somewhat vague.

- **Cell-Channel:** This is the modeling methodology used in the UBC I2Sim research. As described by Lu Liu [14] and Martí et al [22], in the I2Sim implementation of the Cell-Channel model 'service tokens' represent the goods and services produced, consumed and transferred in and between infrastructures. The other system components involved are 'cells' and 'channels' which are: (1) the entities that perform functions which produce and consume tokens; and (2) the means by which tokens flow between cells, respectively. In this methodology, channels are assigned such parameters as capacity and time delay, while cells are defined as the interactions between infrastructure input(s) and output(s) interfacing with that cell. This modeling technique is further described in Chapter 2.

- **Physics Based:** these models are very pervasive in the modeling of certain individual infrastructures and the interdependencies within them. In particular, a wide variety of well established tools have been developed for modeling electrical power systems to various degrees of granularity in time and for various purposes (e.g. electromagnetic transient program simulations (EMTP), dynamic simulations and load flow modeling). Modeling interdependencies *between* infrastructures with this approach in a non-integrated fashion has also been attempted, however, it has not evolved as a popular method [10], [13]. One reason for this may be that of the amount of processing power necessary to run these models is high and the level of detail that they yield may not be necessary. In addition, constructing and operating such models often requires an expert level of knowledge of the type infrastructure being simulated, which is difficult to attain for simulation of a wide array of infrastructures.

All of these methods clearly have different strengths and weaknesses. With regard to the way they incorporate the electrical power into their models, many of these methodologies assume the power system to be either in or out of service, and allot time and resources to account for its transition from an off state to an on state. This, however, does not fully grasp the complexities of electrical system restoration. In this research, we are particularly interested in this aspect of infrastructure emergencies—restoration of power systems—because it is vital for the restoration of many (if not most) other infrastructures. For I2Sim, our development philosophy is to take advantage of the extensive work that has been done in modeling electrical power systems and, in the following section, some of the work that has been done in the well developed field of electrical power system restoration is discussed.

1.4 Electrical Power Systems Restoration Research

The IEEE Power & Energy Society (PES) is a leading body of electrical power system research. In 1987 the IEEE PES System operation Subcommittee established a power system restoration task force that reported [23]

> "Today's bulk power systems provide a highly reliable supply of electric power. However, due to a combination of unforeseen circumstances, there is the remote possibility of a system wide outage. It is therefore prudent to be prepared for such an unlikely eventuality by developing an up-to-date, readily accessible, and easily understood power system restoration plan to allow a quick and orderly recovery from a system outage, with resultant minimum impact on the public."

Since that time, the industry has taken heed; the North American Electrical Reliability Corporation (NERC) now has policies specifying that the power system operating authorities must have restoration procedure on hand, taking into consideration resources such as personnel, fuel, and communications [24]. However, these plans do not specify the level of necessary redundancy for all services tertiary to power system operation, which may be also be inoperable due to effects other than the loss of power. It is generally assumed that blackouts are due to extraneous conditions affecting components in—and thus the state of—the power system exclusively.

Also in this vein of power system restoration, a great deal of research has been carried out and is presented in a book published in 2000 by one of the field's pioneers and leading authorities M.M. Adibi, titled *Power System Restoration: Methodologies & Implementation Strategies*, containing 87 papers pertinent to the study [25]. In these papers, an abundance of information is presented on electrical bulk and distribution level restoration plans, such as the electrical phenomena that must be taken into account, operator training strategies, restoration optimization, etc.. However, it also highlights the fact that very little attention has been paid to the problem of interdependence between the power system and other infrastructures during the critical restoration process. This further motivates the research being carried out in this thesis.

1.5 Research Objectives

The goal of this research is to use the Cell-Channel and other related methods to model interdependencies among electrical power systems and other infrastructures, to take them into account during the response and recovery stages of an emergency involving an electrical power system blackout. An important consideration of this research is recognizing that the characteristics of distinctive segments of the power system are quite different. Here the power system at the customer delivery level, known as the distribution subsystem, as well as the power generation and transmission level, known as the bulk subsystem [26] are the areas of consideration. For these, two separate, but related, approaches are employed:

Electrical Distribution System Restoration: The UBC I2Sim simulator is an implementation of the Cell-Channel modeling methodology. One goal of this research is to develop a specific methodology for the incorporation of an electrical distribution system model into the I2Sim Simulator. This model must accept damage input and provide electrical capacity output in a hierarchical format compatible with the I2Sim simulator. The philosophy for this model is to adapt an off-the-shelf electrical powerflow modeling tool to perform this task, allowing a high degree of flexibility as well as an extensive array of detail to the I2Sim simulator.

The infrastructure system used for the prototype I2Sim simulator is the UBC campus. Another goal of this research to use this methodology to construct a model of the UBC electrical distribution System for use with I2Sim. A second infrastructure system is considered as well. These two models are combined into a UBC Two-Infrastructure model to simulate earthquakes. The objective of this is to compare how different repair approaches, which consider either one or both infrastructures, are able to recover the system.

Electrical Bulk System Restoration: The goal for this portion of our research is to extend the Cell-Channel approach for simulation of bulk power system interdependencies. This entails creating a simulation method where the sensitivity of bulk system restoration to infrastructure interdependencies can be tested. These results can be used to quantify the risk that failures in interdependent infrastructures pose to such restorations. The British Columbia Transmission Corporation (BCTC) bulk system is used as a test system for this research.

1.6 Organization of this Thesis

In Chapter 2, the architecture of the UBC JIIRP I2Sim simulator and how it can be supplemented with an electrical powerflow model is first discussed. The distinctions between electrical bulk and distribution systems and the different approaches used to model them are elaborated. In Chapter 3, the general Cell-Channel modeling methodology for an electrical distribution system and a software architecture for its implementation are presented. Chapter 4 discusses the implementation of this methodology on the UBC electrical distribution system, the development of the UBC Information Technology (IT) infrastructure model, their amalgamation into the UBC Two-Infrastructure Model and Simulator, a repair model for simulating restoration with the Two-Infrastructure model and metrics for measuring the performance of this tool. In Chapter 5, simulations using the UBC Two-Infrastructure simulator are presented and their results analyzed. In Chapter 6, an electrical bulk system risk study for the BCTC bulk system is presented. This includes the structure of the test system, the development of its restoration strategy, the methodology used and the simulation results. In Chapter 7, a summary of the work done in this thesis and a discussion of future research is offered.

Chapter 2

Electrical Infrastructure Interdependency Modeling Overview

This chapter provides an overview of the approaches taken by our research to model interdependencies in the restoration of distribution and bulk power subsystems. General characteristics of power systems are discussed. An overview of the UBC I2Sim simulator is provided and our electrical power system modeling and our simulation techniques are introduced.

2.1 Electrical Power System Configuration

The general characteristic of all electrical power infrastructures is that they are comprised of three distinct sets of assets: (1) Generation stations, (2) Transmission networks, and (3) Load centres, where electrical power is produced, delivered and consumed, respectively. Within this framework, a transmission network is classified into three subsystems: (1) Transmission, (2) Subtransmission, and (3) Distribution. Typically, a transmission system interconnects all major generating stations and load centers; it typically operates at or above 230 kV; and when combined with the major generating stations is often referred to as a *Bulk Power System.* A subtransmission system transmits power in smaller quantities from transmission substations to distribution substations and operates in voltage levels ranging from 69 kV to 230 kV. A distribution system is the final stage of power transfer, where it is delivered to individual customers, and operates at voltage levels less than 69 kV down to 120 V [26].

The bulk system network is usually well meshed; the components are high in capacity and they are relatively few in numbers. Moving into the subtransmission and distribution levels, the system becomes more spread out and eventually radial, the capacity of individual components decrease and components become more numerous. Because of these physical differences between electrical subsystems, the techniques for operating and studying them also varies quite dramatically. In the following, the I2Sim interdependency simulator, for which this research will model the UBC electrical distribution system using the Cell-Channel modeling methodology, is first discussed. Following this, the extension of Cell-Channel concepts to bulk system interdependency studies for the BCTC bulk system are described.

2.2 I2Sim Interdependency Simulator Description

The general I2Sim simulator is made up of at least two layers of infrastructure, the 'physical layer' and 'decision layer' where tangible objects and decisions by humans flow, respectively. To model the physical layer, three fundamental components are employed [14]:

- *Cell:* an entity that performs a function;
- *Token:* goods or services provided to one entity to perform functions for another.
- *Channel:* the means by which tokens flow from a source cell to a sink cell; and

Cells are used to model critical points in systems such as buildings, hospitals, factories, water pumping stations, etc. Each Cell is modeled as a non-linear system having one or more input(s) and output(s). A Cell accept and produce tokens according to its functionality. The functionality of a Cell i with m inputs $x_{i1} \dots x_{im}$ and n outputs $y_{i1}, y_{i2}, \dots, y_{in}$ is described by a set of non-linear functions $y_{ij} = f_j(x_{i1}, x_{i2}, \dots, x_{im})$ $j = 1, 2, \dots, n$.

Channels model the infrastructure used to move Tokens between Cells, which are goods and services such as foodstuffs, doctors and nurses, electrical power, water, etc. Examples of the infrastructure components that Channels can be used to model include roadways, electric power lines, telephone lines, etc. Channels are modeled by a characteristic function, $f(\cdot)$, that accepts variables of Channel input, output, capacity, time delay and functionality. The input, i, and output, j, of a Channel each describe the Tokens transferred into and out of a cell; the capacity, C_{max}, of a Channel constrains the amount of tokens that it can carry; the time delay, τ, is the length of time it takes for a token to traverse a Channel; and functionality, k_f, describes the damage a Channel has sustained. The characteristic function of a Channel takes the form $x_{ij} = f(y_{jk}, \tau, k_f, C_{max})$, where x_{ij} are the tokens received at Cell i from Cell j and y_{jk} are the Tokens sent from output k of Cell j.

Using these components, I2Sim is designed to model three types of events:

- *Uncontrollable Events:* Infrastructure failures due to disasters. In the model, this event is described as a 'damage' event to each Cell and Channel.

- *Time-dependent Events:* A change in the state of the system due to the parameters or limitations of the system itself. For example, if a diesel generator were to run out of fuel at a certain location, this would be a time-dependent event.

- *Decision Events:* These are decisions made by humans, which impact the state of the system. A good example of this is a decision to make a repair.

These events alter the characteristic functions of the model's Cells and Channels, and because the Token inputs to each of these functions become outputs of another component's function, the effects on individual Cells and Channels ripple through the model to other affect entities, mimicking the real events that exist in real infrastructure systems.

The implementation of I2Sim is complex, involving a database called I2Db, visualization tools, a damage assessment module called I2Dam, and infrastructure models, as Fig. 2.1 shows [27].

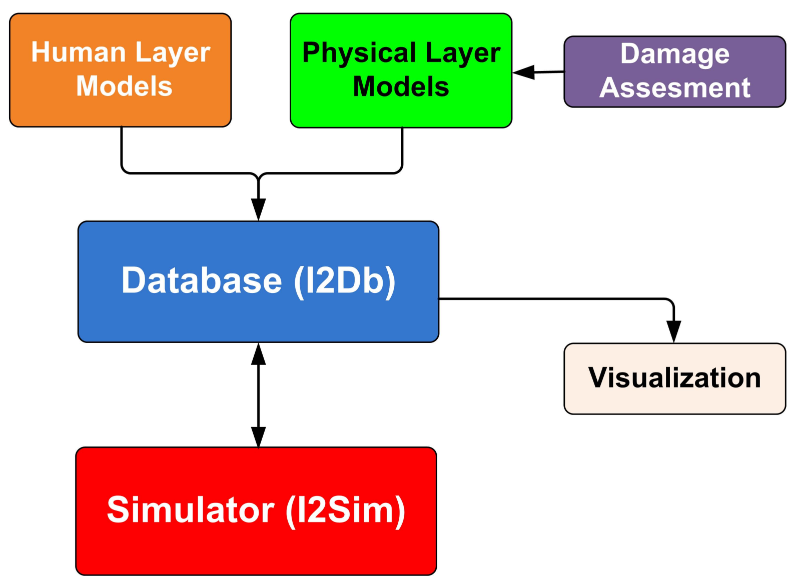

Figure 2.1: I2Sim Simplified Software Architecture

Fig. 2.1 illustrates that damage assessment information of the I2Sim simulator is fed into its physical layer models, which in turn feed information into its database. This information is accompanied by information from human decision models, which moves from the database into main I2Sim simulation component. Information is then returned to the database where it is used by the visualization component to illustrate the simulation results.

An important feature of this simulator is that it is 'scalable', which means that it estimates the state of a system using information from as many or as few infrastructure models as are available.

This is facilitated by the abstract nature of the Cell, Channel and Token components from which it is constructed; if information for a specific infrastructure is unavailable, then it can simply be ignored in the various characteristic functions and conversely, if infrastructure information is available then it can be easily integrated. This also means that a necessary part of integrating an infrastructure is adapting its model to fit the Cell-Channel representation. The following subsection discusses our motivation for using the UBC infrastructure for the I2Sim Simulator prototype and the components that have been, and are currently being, developed for it.

2.3 I2Sim UBC Infrastructure Model

To develop and demonstrate the I2Sim concept, The University of British Columbia Point Grey campus has been considered. Situated on a peninsula, isolated from Vancouver, the UBC campus is approximately 400 hectares, with 60,000 people that includes students, faculty and staff [28] as well as water, gas, steam and electricity networks, plus its own fire department, police station and hospital. The UBC infrastructure system has been considered as a system for modeling because UBC has an isolated infrastructure that is sufficiently complex to be appropriate for the I2Sim research. Further information about UBC's infrastructure was made available to the UBC JIIRP program by the university and its Plant Operations department.

For our modeling of an uncontrollable event at UBC we chose an earthquake. In [27] K. Thibert has developed a database of buildings on the UBC campus. The database contains projected damage-assessments for seven levels of earthquake-intensity for 364 of the 600 campus buildings (excluding single family homes, located on the periphery of the campus). This data was used in our damage-assessment module of I2Sim, shown in Fig. 2.1.

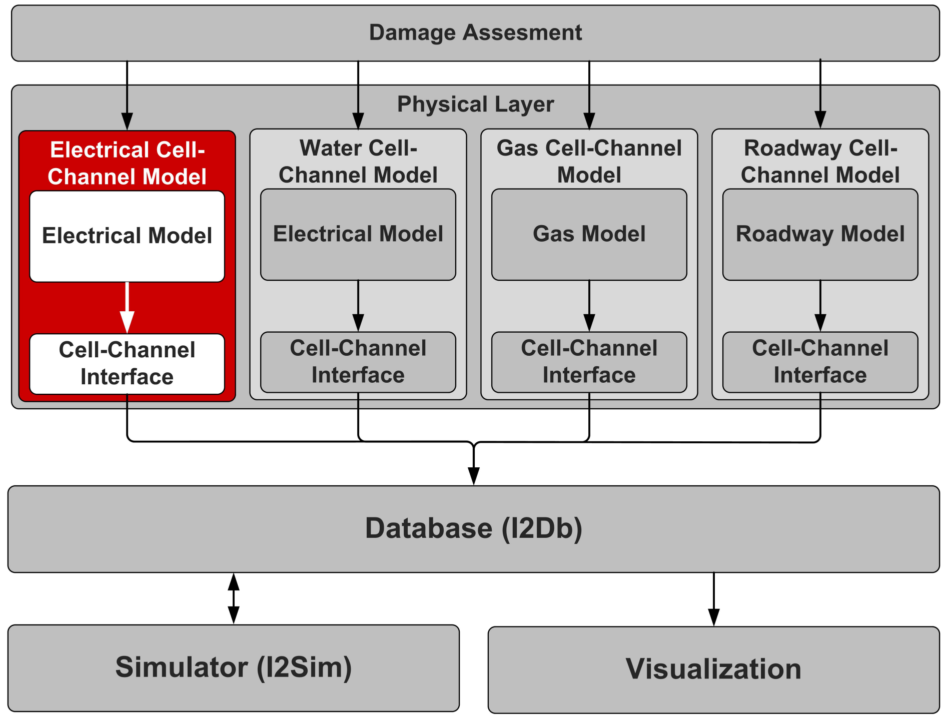

Figure 2.2: I2Sim Simplified Software Architecture: UBC Prototype

For the I2Sim Simulator, models were constructed for the UBC Steam, IT, Water, Hospital and Road networks. Models of the human decision-makers layer have also been developed [14], [29]. Fig. 2.2 highlights how the UBC electrical distribution power system model, and the other models for this research, fit into the overall architecture of the I2Sim simulator. This figure also illustrates the modular approach that the I2Sim Simulator uses for integrating infrastructure models.

2.4 UBC Electrical Distribution System Modeling

Building an electrical distribution system model for I2Sim requires interfacing that model so that it can accept input and produce output that is compatible with the I2Sim architecture, as shown in Fig. 2.2. Our model is intended to simulate the aforementioned recovery and restoration stages, which occur over a time scale on the order of hours, days and weeks [6]. As such, this model does not need to take mid-term, transient or sub-transient effects into account because these occur on the order of only cycles, seconds or minutes. For this reason, we chose the powerflow modeling methodology as our the ‘off-the-shelf’ modeling technique. This powerflow model is integrated into the I2Sim Simulator as depicted in Fig. 2.3.

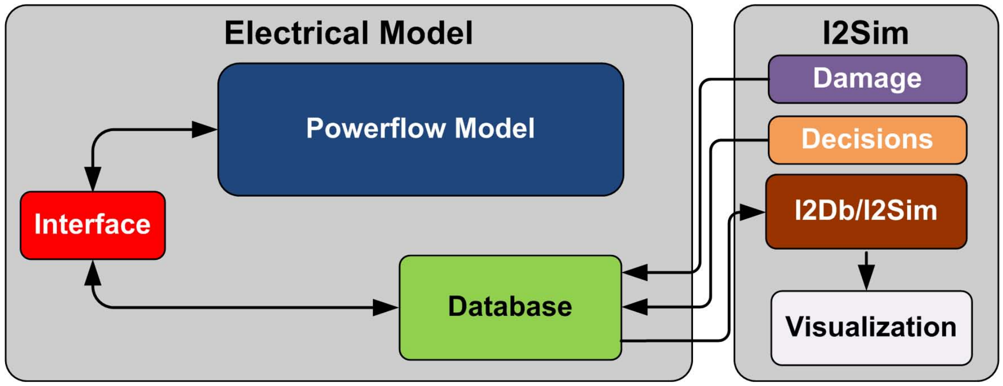

Figure 2.3: Model Component Architecture

Fig. 2.3 shows that the electrical model database accepts input from the damage-assessment component as well as from the human decision component. It models the way that decisions and damages can render electrical system components in or out of service and also models how these affect the state of the overall system. This model structure is applied to the UBC system using a methodology described in Chapter 3.

2.5 BCTC Electrical Bulk System Modeling

The bulk system interdependency modeling carried out in this research extends the work done to model interdependencies in the distribution system. We did this by considering how other infrastructures outages may hinder the system's recovery during an emergency, and how capturing this information could be used to improve the recovery process. In bulk systems, the order in which components are energized following an outage is less flexible than in distribution systems, so developing a wide variety of restoration approaches is unrealistic [25]. In addition, it is assumed that the availability of the bulk power system has a larger impact on the performance of the overall infrastructure than any other system, meaning that the performance of other infrastructures is not taken into account.

These considerations motivate our approach where, instead of optimizing restoration sequences, a single restoration sequence is undertaken, and the *risk* of outages to other infrastructures components which threaten the implementation of this procedure is examined. To carry out this risk analysis we employed powerflow model of the BCTC bulk system and developed a plausible recovery procedure for the blackstart of this system. We then constructed a simulator, incorporating the powerflow modeling tool, to simulate this blackstart procedure and perturbations in it, which were simulated by limiting the availability of supporting infrastructure. We used the results of these simulations and a ‘risk matrix’ to determine the risks of infrastructure unavailability. This work is presented in Chapter 5.

Chapter 3

Electrical Distribution System Modeling and Simulation

In this chapter we describe the general methodology that has been employed for modeling a radial electrical distribution system for integration into the I2Sim infrastructure interdependency simulator. We first present the scope of the methodology and the physical attributes of distribution systems. Following this, we discuss the architecture, components and software of the methodology. We then provide a description of how this methodology can be used in the framework of I2Sim simulations in the chapter's end.

3.1 Model Scope

The model scope, as part of the I2Sim simulator, is to describe the state of a radial electrical distribution system at a single point in time with consideration given to damages caused by a disaster, such as an earthquake or flood. To fulfill this, the model must accept input from the I2Sim damage-assessment module, I2Sim decision inputs which control the operation of specific system components, and provide output in the Cell-Channel format to the I2Sim simulator. A description of this is shown in Fig. 3.1.

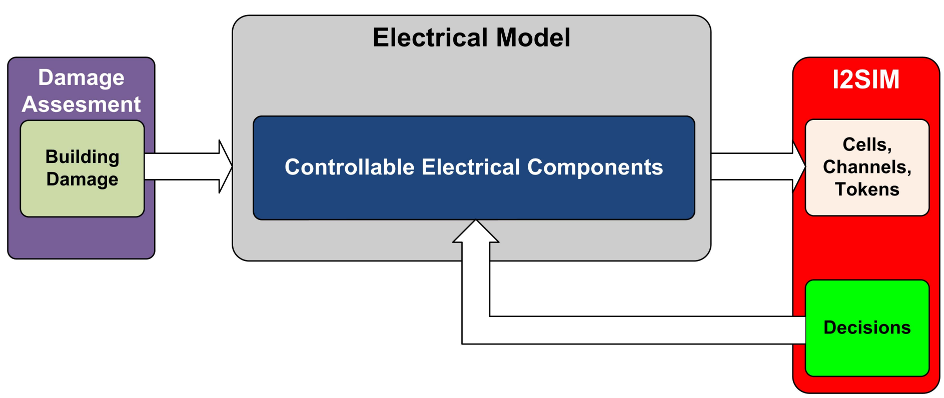

Figure 3.1: General Electrical Model Process Flow with I2Sim

In order to accomplish this, we must directly model the effect of damage to components by placing them out-of-service or at reduced capacity, and represent the interdependencies within the electrical system itself.

3.2 Physical Electrical Distribution System

As described in Chapter 2, an electrical distribution system usually operates at a voltage of 60 kV or less and the purpose of a distribution system is to deliver the energy to end-customers. Because of their distributed nature, a typical distribution system is extremely granular and complex, with hundreds or thousands of circuit breakers, switches, power poles and conductors, all of which can not be modeled to a very detailed level for our purposes. Some of the major physical components that distribution systems contain are the following [30]:

Bus: equipment that is used to physically interface power system devices.

Transformer: a device that statically adjusts voltage levels across a system. High voltages are desirable for transmission of power, but generation and distribution cannot practically be done at these levels and transformers are used to convert these high voltages to low voltages (and vice versa).

Line: Overhead conductors used for transmitting electrical power. These are unshielded and uninsulated conductors suspended in air.

Cable: insulated and shielded conductors used for transmitting electrical power in underground or submarine installations, where overhead transmission lines are not feasible or desirable.

Switch: a device used for disconnecting components from each other. Switches may or may not have the ability to open/close while loaded.

Circuit Breaker: a device whose primary function is to isolate energized components. Circuit breakers are often controlled by protective devices, such as relays, which together are used to mitigate the effects of short circuits.

3.3 Model Overview

Defining boundaries on the components included in our methodology was important because the complexity of distributions systems is too great to include all devices. To accomplish this, we chose to lump some equipment and omit other equipment. The equipment modeled directly by our methodology includes transformers, circuit breakers, lines, cables and loads, while equipment such as switches, protective devices, etc. are not represented.

Our electrical system model must be able to accept input from the damage-assessment and decision module of I2Sim, which contains information about building damage and decision information for electrical components, and also have the ability to output data that conforms to the I2Sim Cell/Channel/Token format. We accomplished this by interfacing the input and output data with the I2Sim and damage-assessment modules as shown in Fig. 3.2.

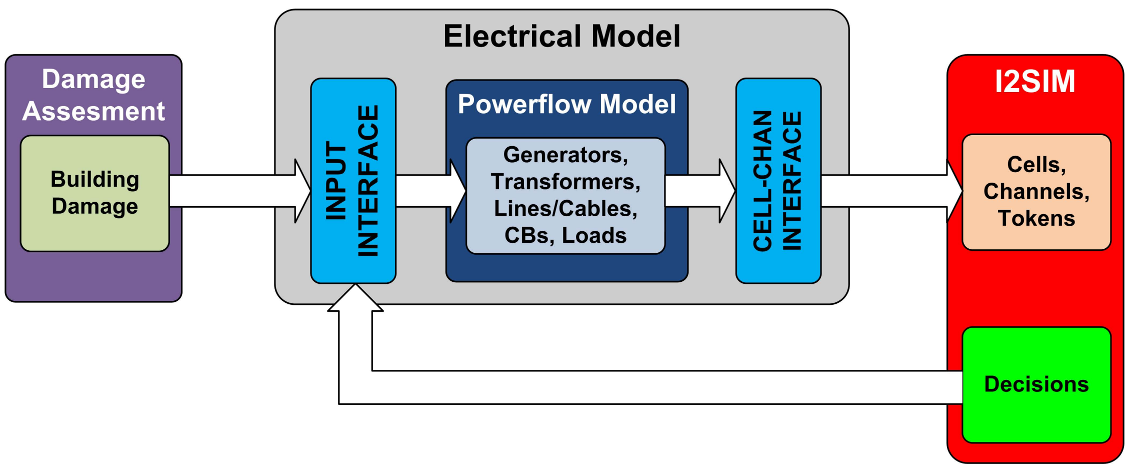

Figure 3.2: Detailed Electrical Model Process Flow with I2Sim

As Fig. 3.2 illustrates, the model requires interfaces at the input and output of the powerflow model. The input interface allows the model to accept abstracted input, in the form of damage and decision information, used to control its electrical components. In turn, the output interface abstracts information into a Cell/Channel/Token representation. The following Sections 3.4 and 3.5 discuss the component abstractions we used to create these interfaces.

3.4 Models of Components

At the input interface of the model, the distribution system appears as four entities: (1) Generators, (2) Buildings, (3) Substations and (4) Branches, which are designed to accept input from both the I2Sim damage assessment and decision modules. Partitioning the system in this way permitted us to create a model with a geographical/civil component in order to accommodate the geographic nature of the I2Sim damage-assessment. This differs somewhat from typical electrical power system models, which are constructed purely from the perspective of electrical connectivity.

In the following subsections, each of these components is defined by variables describing its properties as well as its input and output. In addition, two subcategories of Buildings and a construct of Branches, named ‘Lines’, are defined.

3.4.1 Generators

Power to a distribution system is typically provided externally from a subtransmission system. Thus, we assumed that at interfaces between the distribution and subtransmission systems infinite and infallible generators exist. The model for the Generator component then is simply a generator of unlimited power capacity connected to a bus, as shown in Fig. 3.3.

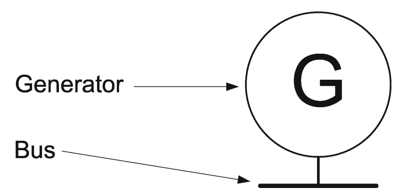

Figure 3.3: Generator Component

Generators possess one property variable, generator voltage denoted V_g, which has units of kV:

$$V_{gen} \in \mathbb{R}^+ \tag{3.1}$$

Generators are the only active component in this modeling methodology, meaning that the voltage in every other part of a model is dictated by the voltage of its generator(s). This voltage is modeled as a permanent property of the generator component to reflect that, in a real system, the voltage would be dictated by the subtransmission system. In a distribution system, transformer tap-changers and switched shunts also have the ability to adjust voltages. However, in this model such components were not included because generally this control would be used to enhance for power quality and efficiency, which are not issues of concern here. Generators have one output, generator power output P_{gen}^{out}, which has units of MW and describes the amount of electrical power a generator is producing. We note here that Generator components are defined as being unable to absorb power.

It should also be noted that systems which include generators within the distribution systems (i.e. micro-generation facilities and emergency diesel generators) are not uncommon, but are not modeled using our methodology. This is recognized and is discussed in Section 7.2 on Future Research.

3.4.2 Buildings

We define Buildings as entities that may sustain damage, house loads and contain infrastructure including transformers, busses, and circuit breakers. Buildings are controllable power sinks, but can also act as intermediaries between power sources and other components. In this methodology, we define two Building subclassifications:

Principal Buildings: This classification is used to represent a Building containing a transformer, which would affect downstream Buildings if it were to be become inoperable. Principal Buildings are represented as two or more busses, one or more loads and one or more transformers. Typically, Principal Buildings have Secondary Buildings connected downstream from them, but there is no restriction on their position in the electrical topology. So a Principal Building may also be downstream of a Principal Building or Secondary Building.

Secondary Buildings: This classification is used to represent a Building that does not contain transformers and cannot interrupt power to the downstream Buildings if removed from service. Secondary Buildings are represented as one bus and one load. These always occur downstream of a Principal Building or Substation, but may have Buildings connected downstream from them.

The models of these Building types are shown below in Fig. 3.4.2.

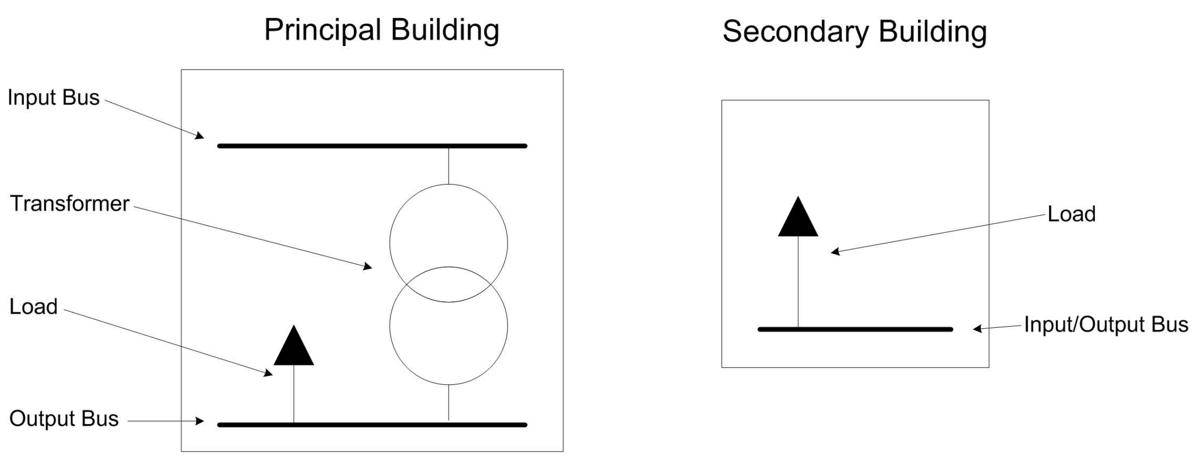

Figure 3.4: Primary and Secondary Buildings Models

The properties of a Building are normal power capacity, P_{bld}^{nom}, and building damage threshold h_{bld}. We define these as

$$\begin{aligned} P_{bld}^{nom} &\in \mathbb{R}^{+} \\ h_{bld} &\in [0 \ldots 100] \end{aligned} \tag{3.2}$$

Normal power capacity is the maximum amount of power a Building is likely to consume, in MW, and is represented by its load, which is assumed to be of a constant power at 0.95 power factor lagging. The intention of this variable is not to represent the amount of power a Building is *capable* of consuming, but to represent the amount of power it would be likely to consume if its performance was not degraded by damage. Building damage threshold is a variable indicating the resilience of a Building to damage: the higher the threshold, the higher the resilience.

Principal Buildings have three additional attributes to described their transformers, which Secondary Buildings do not. These are: transformer capacity, S_{tr}^{max}; transformer reactance, X_{tr}; and transformer ratio, N_{tr}. These are described as

$$\begin{aligned} S_{tr}^{max} &\in \mathbb{R}^{+} \\ X_{tr} &\in \mathbb{R}^{+} \\ N_{tr} &\in \mathbb{R}^{+} \end{aligned} \tag{3.3}$$

Transformer capacity represents the amount of apparent power, in MVA, that can be drawn through a Building's transformer(s) to serve both the Building itself and the Building(s) fed by it. Transformer reactance is the reactance of the Building's transformer(s), in pu, and transformer ratio is the ratio of a transformer's input line voltage to its output line voltage.

The input variables of a Building model are: building damage, d_{bld}, and requested power, P_{bld}^{req}, which are described as

$$\begin{aligned} d_{bld} &\in [0 \ldots 100] \\ P_{bld}^{req} &\in [0 \ldots P_{bld}^{nom}] \end{aligned} \tag{3.4}$$

Building damage represents the amount of damage a Building has suffered to its structure and internal components, which is input from the I2Sim damage-assessment. Requested power represents the amount of power, in MW, a Building is being called upon to consume. This variable allows, for example, the model to reflect a deliberate decision to curtail a Buildings' consumption during a disaster, but it could also be used to reflect the time-of-day variance in load, or any other number of considerations.

Buildings have two output variables: available power, P_{bld}^{avl}, and consumed power, P_{bld}. Principal Buildings are also defined as having three additional output variables: power throughput,

P_{bld}^{thr}; available transformer capacity, S_{tr}^{avl}; and transformer status, s_{tr}.

A Building's available power is the amount of power it has available for consumption at the present time. This variable is defined as a function of a Building's normal power capacity, building damage threshold and building damage, as described by the following equation

$$P_{bld}^{avl} \triangleq \begin{cases} P_{bld}^{nom} \cdot (1 - \frac{d_{bld}}{h_{bld}}) & \text{if } d_{bld} < h_{bld} \\ 0 & \text{if } d_{bld} \geq h_{bld} \end{cases} \tag{3.5}$$

According to this model, if a Building's damage is less than its damage threshold then the capacity of the Building to consume power is proportional to the compliment of the ratio of its damage divided by its damage threshold. If a Building's damage exceeds its damage threshold, its available power becomes zero.

A Principal Building's power throughput is the amount of power, in MW, flowing through it. This is calculated as

$$P_{bld}^{thr} = \begin{cases} P_{bld} + P_{bld}^{out} & \text{if } s_b = 1 \\ 0 & \text{if } s_b = 0 \end{cases} \tag{3.6}$$

where P_{bld}^{out} represents the real power the Building is delivering to the power network.

A Building's transformer(s) status is open or closed and is defined by

$$s_{tr} \triangleq \begin{cases} 1 & \text{if } d_{bld} < h_{bld} \\ 0 & \text{if } d_{bld} \geq h_{bld} \end{cases} \tag{3.7}$$

Equations 3.6 and 3.7 show that the condition $d_{bld} \geq h_{bld}$ in a Principal Building represents that the Building is too damaged to supply power to itself or other Buildings, causing its transformer throughput to become zero.

The available transformer capacity of a Building is the available capacity, in MVA, of its transformer(s). This is defined by

$$S_{tr}^{avl} \triangleq S_{tr}^{max} - (\frac{P_{bld}}{\text{pf}} + S_{tr}^{out}) \tag{3.8}$$

where S_{tr}^{out} represents the apparent power the Building is delivering to the downstream power network and pf is the power factor of the Building's load(s).

The situation for Secondary Buildings is different, because we have assumed that regardless of its level of damage a Secondary Building can always be used to wheel power to downstream Buildings.

Consumed power is the amount of power a Building is presently consuming. For either a Principal Building or Secondary Building, this is calculated by taking the lesser of its available power and requested power, as the following equation describes

$$P_{bld} \triangleq min\{P_{bld}^{avl},\ P_{bld}^{req}\} \tag{3.9}$$

This implies that a Building cannot be requested to consume power in excess of its available power.

3.4.3 Substations

Substations are interfaces between major sections an electrical system. Substation contain a variety of equipment (e.g. measurement, control, protection, etc) crucial to distributing electricity, however, they do not contain loads. For the purpose of this thesis, this complexity is abstracted by representing substations as Principal Buildings without load. Thus, substations are described by the same variables as Principal Buildings, with the exception that their normal power capacity is restricted to zero, i.e. $P_{bld}^{nom} = 0$. This is reasonable given that the Principal Building component models transformer damage, and transformers are the most critical substation assets.

3.4.4 Branches

Branch components are used in powerflow models to represent physical cables and overhead lines. The Branch components in powerflow models usually have two switchable ends, and we have followed this convention here. Fig. 3.5 is an example of how Branches are used to model a system. It shows 26 Branches connecting a network containing a Substation and six Buildings and it illustrates that each Branch has exactly two ends.

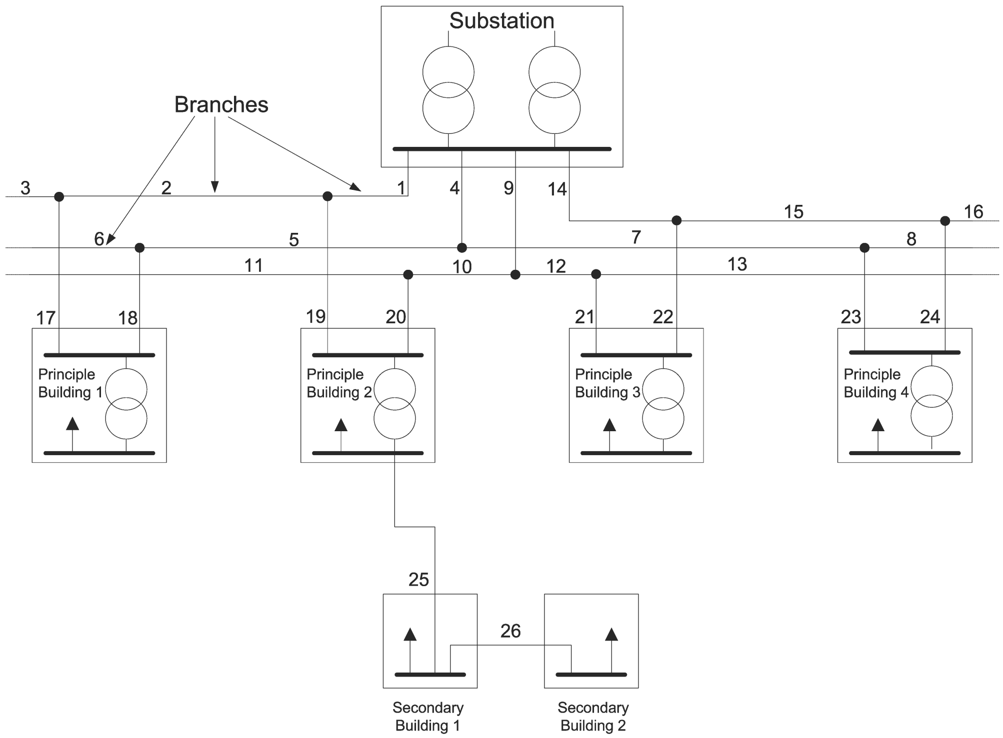

Figure 3.5: Branch Layer of an Example System

A Branch object has the following parameters: branch capacity, S_{br}^{max}; branch reactance, X_{br}; normal branch status, s_{br}^{nom}; and branch damage threshold, h_{br}. These parameters are defined as

$$\begin{aligned} S_{br}^{max} &\in \mathbb{R}^+ \\ X_{br} &\in \mathbb{R}^+ \\ s_{br}^{nom} &\in \{0 = \text{open}, 1 = \text{closed}\} \\ h_{br} &\in [0 \ldots 100] \end{aligned} \tag{3.10}$$

Branch capacity is the maximum amount of apparent power, in MVA, a Branch can carry. Branch reactance is the equivalent impedance of a Branch in pu. Normal branch status indicates whether a Branch is designed to be open or closed; its significance will be explained in the following subsection. Branch damage threshold is akin to building damage threshold, as it describes the amount of tolerance the Branch has for damage.

The input variables of a Branch are branch damage, d_{br}, and requested branch status, s_{br}^{req}, which can take the following ranges of values

$$\begin{aligned} d_{br} &\in [0 \ldots 100] \\ s_{br}^{req} &\in \{0 = \text{open}, 1 = \text{closed}\} \end{aligned} \tag{3.11}$$

Branch damage is again akin to building damage and represents the amount of damage associated with a Branch. Requested branch status is a decision variable for the open or closed status a Branch has been requested to take.

Branches have two outputs: branch status, s_{br}, and available branch capacity, S_{br}^{avl}. Branch status is a function of branch damage and requested branch status as following equation describes

$$s_{br} \triangleq \begin{cases} 1 & \text{if } d_{br} < h_{br} \quad \text{and} \quad s_{br}^{req} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{3.12}$$

In this model, if a Branch has the branch status of 'open', i.e. $s_{br} = 0$, both of its ends are open; and if it has a branch status of 'closed' both of its ends are closed. Available branch capacity is defined as

$$S_{br}^{avl} \triangleq S_{br}^{max} - |S_{br}| \tag{3.13}$$

where S_{br} is the apparent power, in MVA, flowing through the branch.

3.4.5 Lines

In physical systems, overhead lines and cables may have zero, one, two or more switchable ends. This is because the end of one cable or overhead line may be connected to the middle of another at a tap. The Branch component we have defined, however, has exactly two switchable ends. To resolve this inconsistency we introduce an additional component: the Line component.

A Line is defined as an aggregation of Branches which are switched synchronously. This means Lines behave as multi-ended Branches. This concept is depicted in Figs. 3.6 and 3.7. The network shown in Fig. 3.6 is the same as the 26 Branch network shown in Fig. 3.5, however, aggregations of Branches are depicted as Lines in the former. Table 3.6 describes how the Branches in Fig. 3.5 map to the Lines in Fig. 3.6. As this illustrates, all Branches are exclusive members of one Line.

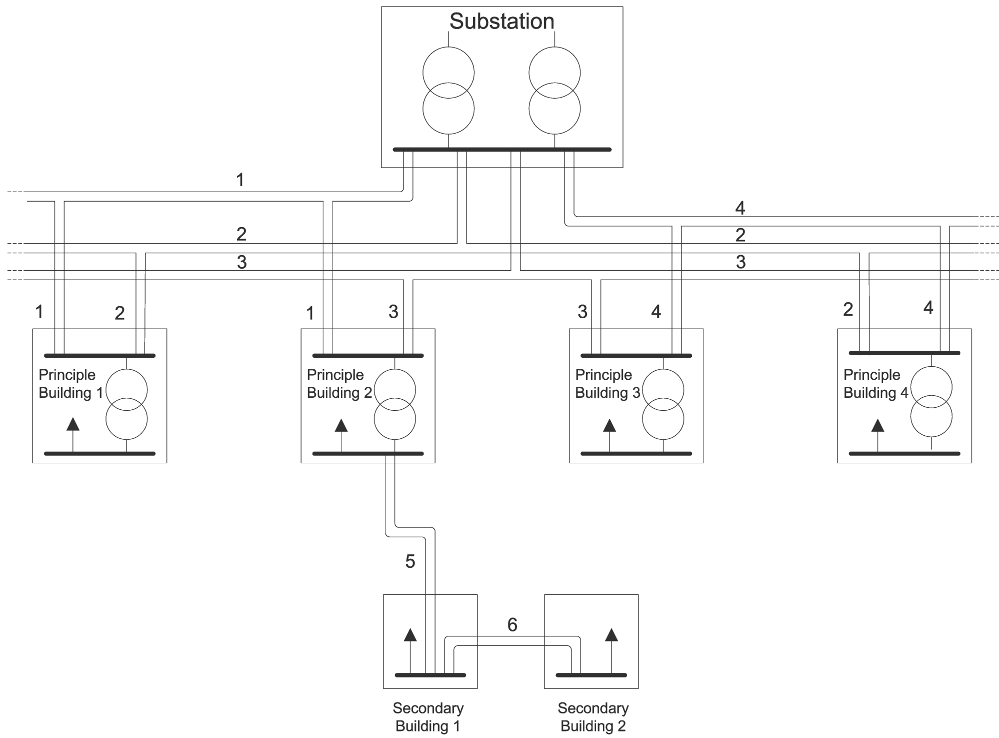

Figure 3.6: Line Layer of an Example System

		BRACNHES																									
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
L	1	X	X	X														X		X							
I	2				X	X	X	X	X										X					X			
N	3									X	X	X	X	X							X	X					
E	4														X	X	X						X		X		
S	5																									X	
	6																										X

Table 3.1: Branch-to-Line Map

Fig. 3.7 illustrates the way in which Branches' switching conditions are restricted when they are aggregated as a Line.

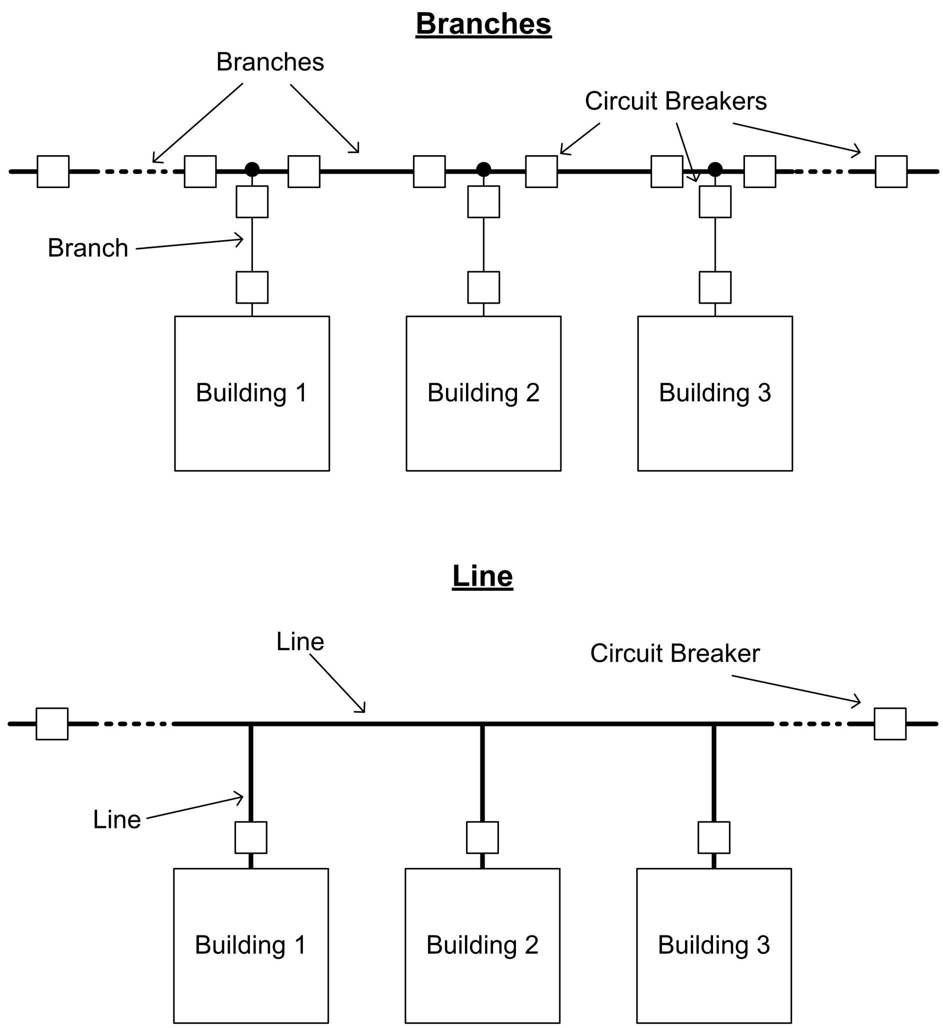

Figure 3.7: Diagram Branch vs. Line

Line status, s_l, is a Line's open or closed status and is defined by the equation

$$s_l \triangleq \begin{cases} 1 & \text{if} \quad \forall i \in \{1 \ldots n\} \; s_{br_i}^{nom} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{3.14}$$

This equation states that if the statuses of all the normally closed Branches making up the Line are closed then the Line is also closed, otherwise the Line is open. An open Line is modeled by assigning open statuses to all the Branches of which it is composed. This has the effect of opening all the breakers associated to that Line.

3.5 Cell-Channel Interface Components

A purpose of this methodology is to provide an output conforming to the I2Sim Simulator's Cell/Channel/Token structure, which are defined as follows:

Cell: An entity that consumes and/or delivers electrical power.

Channel: The electrical path from on Cell to another.

Token: The energy, in MWh, delivered from one Cell to another.

3.5.1 Cells

Cells encompass Generators, Buildings and Substations and have the properties cell index, c, and cell type, m:

$$\begin{aligned} c &\in \{1, 2 \ldots I\} \\ m &\in \{1, 2, 3, 4\} \end{aligned}$$

These variables allow Cells to be mapped back to their respective components. Cell types 1-4 correspond to Generator, Principal Building, Secondary Building and Substation, respectively.

A Cell is also defined to inherit the properties of its constituent component, which for brevity will not be re-stated here. As such, in this thesis the term 'Cell' will be used in the place of the terms 'Building', 'Substatation' and 'Generator' where it simplifies the discussion. This means that in describing components or component properties, such as 'building damage' or 'generator power output' we assume the terms 'cell damage' or 'cell output power' to have the same meanings, respectively.

3.5.2 Channels

A Channel is defined to have two ends [14], which we refer to as its parent and child ends. Similar to a Line, a Channel is constructed from a number of Branches. The difference between a Channel and a Line though, is that a Line emulates the behavior of a physical line, while a Channel is a theoretical construct used to describe how power flows from one Cell to another. Fig. 3.8 shows another view of the system shown in Figs. 3.5 and 3.6, however, instead of Branches or Lines, the network is shown in terms of Channels.

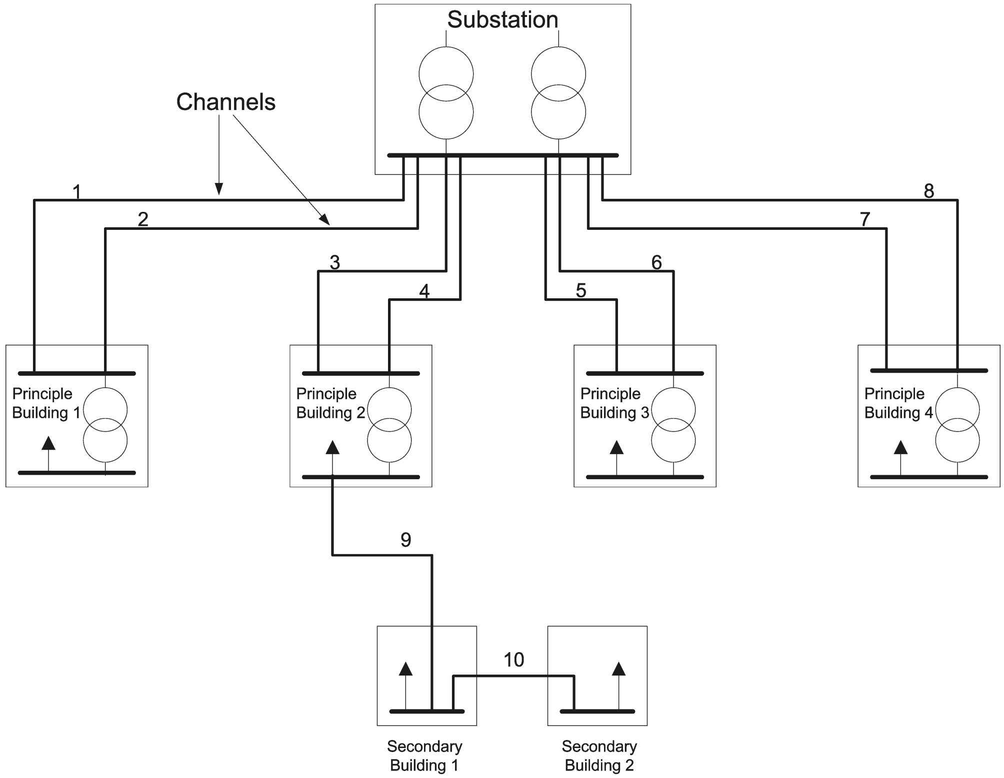

Figure 3.8: Channel Layer of an Example System

In this figure, the 'Substation' is the parent of the four Principal Buildings, 'Secondary Building 1' is the child of parent 'Principal Building 2' and 'Secondary Building 2' is the child of 'Secondary Building 1'. The mapping from the Branches of Fig. 3.5 to the Channels of Fig. 3.8 is shown in Table 3.2.

		BRANCHES																									
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
C	1	X	X															X									
H	2				X	X													X								
A	3	X																		X							
N	4									X	X										X						
N	5									X			X									X					
E	6														X								X				
L	7				X			X																X			
E	8	X													X	X									X		
S	9																									X	
	10																										X

Table 3.2: Channel-to-Branch Map

The strength of this Cell-Channel representation is that it allows the relationships among components to be easily seen. The Cell-Channel representation alone, however, cannot fully convey the interdependencies of an electrical network.

The properties of Channels are inherited from their underlying Branches. In Table 3.2, it is interesting to note that Branches 1, 4, 9 and 14 are mapped to multiple channels, illustrating that, unlike in Line representations, a Branch may be a part of more than one Channel.

We have assigned five Channel property variables: channel number, n; parent cell, i; child cell, j; channel capacity, S_{ch}^{max}; and normal channel status, s_{ch}^{nom}. Channel number, parent cell, child cell are defined as

$$\begin{aligned} n &\in [1, 2 \ldots N] \\ i &\in [1, 2 \ldots I] \\ j &\in [1, 2 \ldots I] \end{aligned} \tag{3.15}$$

respectively, where N is the number of Channels and I is the number of Cells in the model. These property variables are used to index the Cells that Channels are connected to.

Channel capacity is defined as

$$S_{ch}^{max} \triangleq min\{S_{br_1}^{max}, S_{br_2}^{max} \ldots S_{br_m}^{max}\} \tag{3.16}$$

where the Channel is assumed to be composed of m branches $b_1, b_2, \ldots, b_m$. This equation illustrates that channel capacity is the maximum capacity of the lowest capacity Branch of which a Channel is composed. Because the Branches composing a Channel must be series connected, this is the maximum amount of apparent power that can be drawn from one end of a Channel to the other. We note, however, that because Branches can be a part of multiple Channels, the actual present capacity of a Channel may be less than its nominal channel capacity.

Normal channel status is defined as

$$s_{ch}^{nom} \triangleq \begin{cases} 1 & \text{if} \quad \forall i \in \{1 \ldots m\} \; s_{br_i}^{nom} = 1 \\ 0 & \text{otherwise} \end{cases} \tag{3.17}$$

where the normal branches statuses of the Branches a Channel is composed of are used to determine if there is a normally a closed path from its parent to its child end.

Channels have three outputs: channel status, s_{ch}; available channel capacity, S_{ch}^{avl}; and time delay, τ_{ch}. Channel status describes whether there is a closed path from one end of a Channel to the other, and for Channels which are normally closed this is determined by the following equation

$$s_{ch} = \begin{cases} 1 & \text{if} \quad \forall i \in \{1 \ldots m\}\ s_{br_i} = s_{br_i}^{nom} \\ 0 & \text{otherwise} \end{cases} \tag{3.18}$$

For a normally-opened Channel, the only way to confirm closure is when all of its Branches are closed.

Available channel capacity is defined as the minimum available branch capacity of any constituent branch of a Channel. For the same Channel considered above, if $S_{br_1}^{avl}, S_{br_2}^{avl}, \ldots S_{br_m}^{avl}$ are the available capacities of branches $b_1, b_2, \ldots b_n$, respectively, then its available channel capacity is defined as

$$S_{ch}^{avl} \triangleq min\{S_{br_1}^{avl}, S_{br_2}^{avl}, \ldots S_{br_m}^{avl}\} \tag{3.19}$$

It is important to note that because Branches can be assigned to multiple Channels, the available channel capacity of one Channel can be affected by a change in the powerflow to another.

Time delay is a parameter defined in [14] as the amount of time for a Token to travel from one Cell to another. While electrical energy does not travel instantaneously, for the purposes of this model we assume the time delay of electrical Tokens flowing through Channels is zero:

$$\tau_{ch} \equiv 0 \tag{3.20}$$

3.6 Software Description

To implement a model with this methodology, we used three types of software tools: (1) a powerflow modeling tool for providing a steady-state description of an electrical system; (2) a database for storing model parameters, input and output; and (3) a data processing tool, for adapt the input and output of the powerflow model to achieve our modeling methodology. The software we used for these three tasks is listed in Table 3.3.

Software Tool	Description
PowerWorld	Powerflow Modeler
Matlab	Data Processing Tool
Microsoft Excel	Database

Table 3.3: Software Components

PowerWorld, MS Excel and Matlab are common engineering tools. We provide descriptions of them, as they are applied in this research, in the following subsections.

3.6.1 Powerflow Modeler

PowerWorld© is a software tool that is used to compute powerflow solutions for electrical power networks. This solution includes a complete set of parameters for the system (e.g. bus voltages, branch flows, power flows, etc.). A number of other software packages able to perform this task are available including ETAP Load Flow Analysis©, PSS/E Load Flow Simulator© and CYMFLOW©. We chose PowerWorld because it is relatively easy to use and because it provides two useful features: (1) A graphical user interface (GUI) that provides a visualization of its powerflow solution with which a user can interact; and (2) the ability to access and change data through an external program using an add-on tool named SimAuto. These two features are discussed further below.

The model components described in Section 3.4 were conceived with a powerflow simulator in mind, meaning that implementing our modeling methodology with a powerflow simulator is straightforward. Five PowerWorld components are necessary to do this: busses, transformers, circuit breakers, branches and generators. In PowerWorld this equipment is defined as follows [31]:

Bus: A bus is a passive element, which is used at the interface of every piece of equipment. The basic properties of a bus are:

- *Bus Number:* a unique identification number;
- *Nominal Bus Voltage:* the nominal voltage of a bus and the equipment connected to it, in kV;
- *System Slack Bus:* a boolean variable used to designate a bus as the voltage reference bus for the system;
- *Bus Voltage:* the calculated voltage at a bus, in kV.

Branch: A branch in PowerWorld is analogous to the Branches and Transformers we defined in Section 3.4. The Basic PowerWorld branch properties are:

- *To Bus:* the 'Bus Number' of the bus connected at the 'to' end of a branch;
- *From Bus:* the 'Bus Number' of the bus connected at the 'from' end of a branch;
- *Circuit Number:* a number that differentiates branches connected to the same pairs of busses;

- *Transformer:* a boolean variable that specifies whether a branch is a transformer or branch;
- *Status:* the open/closed status of a branch;
- *Reactance:* the equivalent series reactance of a branch, in per-unit;
- *Lim:* the capacity of a branch, in MVA.

If the device is a transformer, its ratio is defined by the 'Nominal Voltages' of the busses at its ends.

Generator: This is analogous to the generator defined in our methodology. Basic PowerWorld generator properties are:

- *Generator ID:* a number used to differentiate generators connected to the same bus;
- *Voltage Setpoint:* a per-unit value, which defines what voltage the generator should maintain relative to its bus' 'Nominal Bus Voltage';
- *Min MW:* the minimum amount of power the generator can deliver, in MW;
- *Max MW:* the maximum amount of power the generator can deliver, in MW;
- *Min MVAR:* the minimum amount of reactive power the generator can deliver, in MVAR;
- *Max MVAR:* the maximum amount of reactive power the generator can deliver, in MVAR;
- *AGC Available:* a boolean parameter controlling whether the generator is operating in Automatic Generation Control (AGC) Mode;
- *Participation Factor:* a number that determines the percentage of power a particular generator will contribute to changes in load demand (if its AGC is Available);
- *AVR Available:* a boolean parameter controlling whether a generator operates in Automatic Voltage Regulation (AVR) Mode, used to automatically control the generator field;
- *Status:* a boolean parameter which determines if the breaker between a generator and its bus is open or closed.
- *Power Output:* the amount of power a generator is delivering;
- *Reactive Power Output:* the amount of reactive power a generator is delivering.

Load: This is used to represent system loads and has the following properties in PowerWorld:

- *Constant Power:* the quantity of complex power the load consumes (independent of bus voltage);
- *Status:* the open/closed status of the load.

Circuit Breaker: This piece of equipment is an integrated part of other PowerWorld components. Circuit breakers do not have their own references or properties, but represent the mechanism by which equipment is open and closed.

The complete list of PowerWorld parameters is much more extensive than the list presented here. We have only discussed the parameters necessary for implementing our model components.

PowerWorld component parameters are defined a binary file, which can be constructed either through PowerWorld directly, or through SimaAuto. Table 3.4 shows how we set these parameters to realize our Generator, Principal Building, Secondary Building and Branch components.

Model Component Variable		PowerWorld Component Parameter	
Generator	V_{gen}	Nominal Bus Voltage	Bus
	*	System Slack Bus	
	P_{gen}^{out}	Power Output	Generator
	1.0	Voltage Setpoint	
	0	Min MW	
	99,999	Max MW	
	-99,999	Min MVAR	
	99,999	Max MVAR	
	Yes	AGC Available	
	$\frac{1}{num\ gens}$	Participation Factor	
	Yes	AVR Available	
	Closed	Status	
Building (Principal)	Yes	Transformer	Branch
	s_{tr}	Status	
	X_{tr}	Reactance	
	S_{tr}^{max}	Lim	
	N·Nominal Voltage (input bus)	Nominal Voltage (Output bus)	Bus
(All)	No	System Slack Bus	
	P_{bld} @ .95 Power factor lagging	Constant Power	Load
	Closed	Status	
Branch	No	Transformer	Branch
	s_{br}	Status	
	X_{br}	Reactance	
	S_{br}^{max}	Lim	
	Nominal Voltage (From Bus)	Nominal Voltage (to Bus)	Bus

Table 3.4: Building Data Sheet

As Table 3.4 illustrates, implementing a component from our methodology required multiple PowerWorld components. For example, to model our Generator a PowerWorld bus *and* generator were required. This table also shows how assumptions from our methodology, such as infinite generation capacity, were realized.

Most of the implementation shown here is straightforward, but there are exceptions to note: (1) to model a Branch, the PowerWorld nominal bus voltages must be the same value at each of its ends; (2) the bus voltages at the ends of a transformer define its ratio; (3) PowerWorld will choose a slack bus automatically and if the participation factors are the same for each generator it should not matter which one is chosen; and (4) component ID's and component numbers are not listed in this table as they will be discussed in the following section.

PowerWorld GUI The PowerWorld GUI is a part of the PowerWorld Simulator that allows the user to rapidly access the needed information such as the system topology, available branch capacities, and the system voltage profile. This is illustrated in Fig. 3.9, where a portion of an electrical model is shown with a colour gradient indicating the voltage levels in different parts of the system. Blue indicates a low voltage (less than 0.95 pu) while red indicates a high voltage (greater than 1.05 pu). This is one of the many options that PowerWorld offers for graphically displaying information about a model.

The GUI is also a mechanism for directly making changes to parameters such as line statuses or load levels and immediately seeing the effect. This functionality, however, is only accessible by a person accessing the display in real-time.

SimaAuto SimAuto© is a PowerWorld Simulator add-on tool, which provides access to PowerWorld parameters through external software programs. Using SimAuto, these parameters can be accessed through C++, Matlab or VisualBasic programs. The actions that can be carried out include changing the state of a branch, determining the amount of power flowing through a transformer, increasing or decreasing the consumption of a load, etc [31].

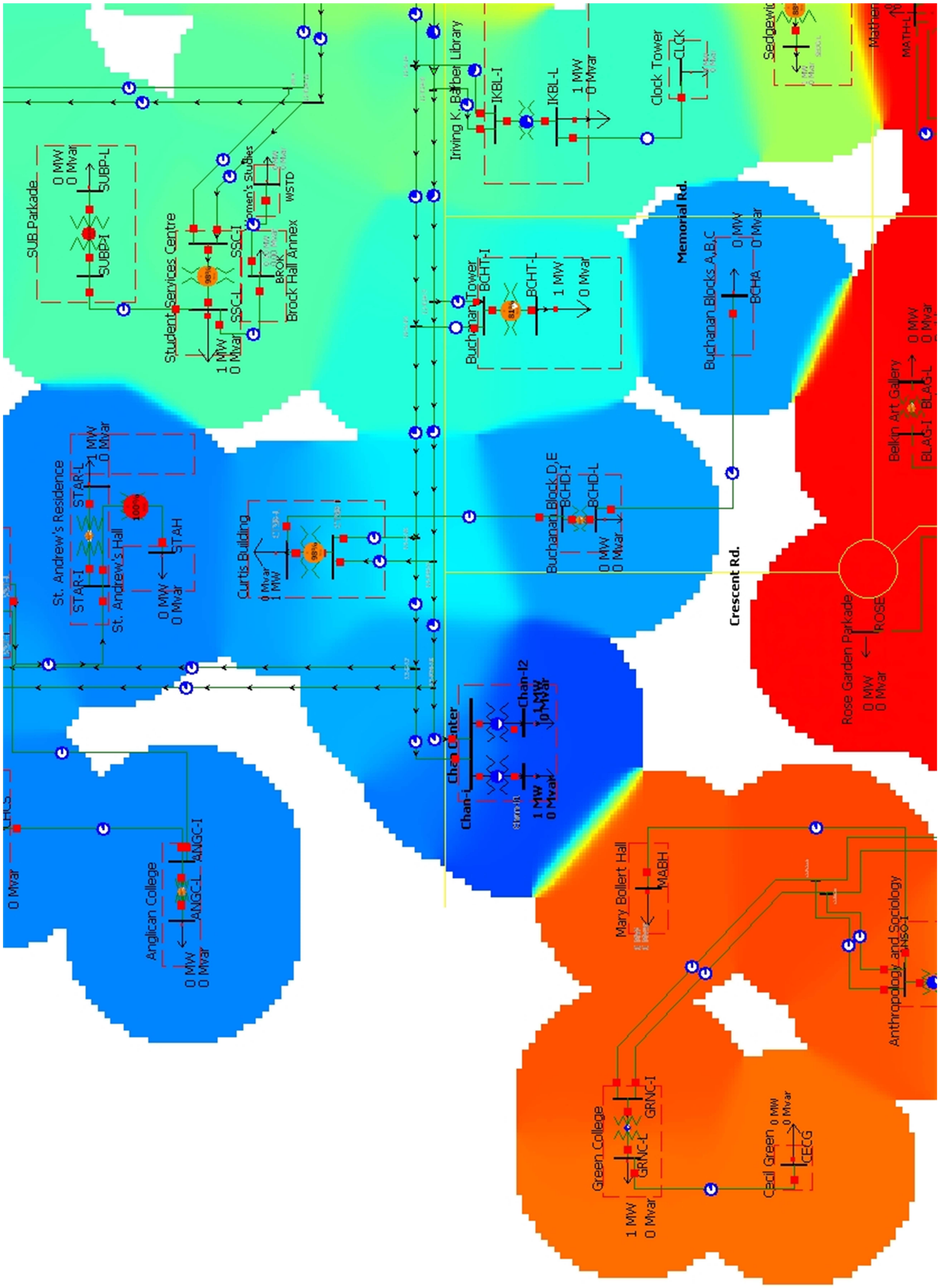

Figure 3.9: Electrical Model Voltage Contour

3.6.2 Database

We chose Microsoft Excel© for this purpose because of its familiarity and convenience. The Excel database acts as both a vessel for simulation parameters, such as mappings from Branches to Lines, and as an interface for the I2Sim Simulator and for Matlab to access input and output data.

We used the Excel database as a 3-dimensional array, where different sheets are used to gain the 3$^{\text{rd}}$ dimension. A total of six Excel sheets are necessary to implement the required database:

1. Branch List Sheet
2. Line to Branch Mapping Sheet
3. Channel to Branch Mapping Sheet
4. Building to Channel and Bus Mapping Sheet
5. Building Data Sheet
6. Channel Data Sheet

Tables 3.5 to 3.10, shown below illustrate the data contained in these sheets.

From Bus	From Bus Name	To Bus	To Bus Name	Circuit Number	Damage	Normal Status	Status	Requested Status	Transformer
1	Hydro 1	3	Main L1	1	0	1	1	1	No
2	Hydro 2	4	Main L2	1	0	1	1	1	No
5	Main L	485	12-F13-1	1	0	1	1	1	No
5	Main L	76	12-F23-1	1	0	1	1	1	No
5	Main L	407	12-F21-1	1	0	1	1	1	No
259	BKST-I	260	BKST-L	1	0	1	1	1	Yes
464	12-S-29	420	12-F20S	1	0	0	0	0	No
.	.	.	.	.	.	.	.	.	.

Table 3.5: Branch Data Sheet

Line Name	From Bus 1	To Bus 1	Circuit 1	From Bus 2	To Bus 2	Circuit 2	From Bus 3	To Bus 3	Circuit 3	. . . . . .	From Bus 29	To Bus 29	Circuit 29
1	5	490	1										
1.1	490	236	1										
10	98	5	1	98	99	1	99	371	1	. . .			
10.1.T	283	284	1										
9	5	373	2	373	374	1	374	375	1	. . .	405	406	1
.	.	.	.	.	.	.	.	.	.	.	.	.	.

Table 3.6: Line to Branch Mapping Sheet

Channel Name	From Bus 1	To Bus 1	Circuit 1	From Bus 2	To Bus 2	Circuit 2	From Bus 3	To Bus 3	Circuit 3	. . . . . .	From Bus 59	To Bus 59	Circuit 59
1	473	256	1	471	5	1	471	472	1	. . .			
2	427	256	1	5	424	1	424	429	1	. . .			
12	266	267	1										
114	84	86	1	91	84	1	83	368	1	. . .	366	367	1
.	.	.	.	.	.	.	.	.	.	.	.	.	.

Table 3.7: Channel to Branch Mapping Sheet

Cell Name	Cell Number	Parent Cell	Connecting Channel	Input Bus	Output Bus	Cell Type
Substation A	188			3	4	4
Building P	520	188	61	7	8	2
Building P	45	188	53	15	16	2
Building R	45	188	54	15	16	2
Building S	44	45	56	20	20	3
.	.	.	.	.	.	.

Table 3.8: Cell and Channel Mapping Sheet

Cell Number	Cell Damage	Cell Damage Threshold	Normal Cap. (MW)	Consumed Power (MW)	Requested Power (MW)	Xfrmr Cap. (MVA)	Avail. Xfrmr Cap. (MVA)	Xfrmr Status
188	18.8	30	0	0	0	30	15	1
520	0	30	1.4	1.4	1.4	3	.2	1
45	0	30	1.3	1.3	1.3	2	.1	1
44	0	30	1.3	1.3	1.3	0	0	2
312	18.8	30	1.4	0.52	1.4	0	0	2
.	.	.	.	.	.	.	.	.

Table 3.9: Cell Data Sheet

Channel Number	Channel Capacity (MVA)	Available Channel Capacity (MVA)	Normal Channel Status	Channel Status
1	10	4.079348	1	1
2	1	0.894967	1	1
3	10	4.079348	1	1
4	1	0.894967	1	1
5	1	-0.158371	1	1
.	.	.	.	.

Table 3.10: Channel Data Sheet

The sheets depicted in Figs 3.5–3.10 are used for the following:

Branch Data Sheet: We used this sheet to store Branch data used during runtime. As Table 3.5 shows, it includes the PowerWorld identification information—to bus, from bus, circuit number and transformer—as well as the normal branch status, branch status, requested branch status and branch damage variables.

Line to Branch Mapping Sheet: This sheet simply contains our Line-to-Branch map. In this sheet, Line names are cross referenced to the PowerWorld branch identifiers: to bus, from bus and circuit number.

Channel to Branch Mapping Sheet: This sheet contains our Channel-to-Branch Map described in Table 3.2. In it, Channels numbers are cross referenced to their associated Branch identifiers: to bus, from bus and circuit number.

Cell and Channel Mapping Sheet: This sheet contains the mappings of Cells to Buildings, Substations and Generators, as well of Channels to Cells. As Table 3.8 illustrates, we mapped cell numbers to Buildings, Substations and Generators by referencing their PowerWorld bus numbers. We set the input bus of a Secondary Building or Generator to be the same as its output bus.

To map a Channel, we referenced its parent cell and child cell to its channel number.

Cell Data Sheet: This sheet contains a Cell input and Cell output as well as Building, Substation and Generator data used during run-time. The variables included are cell number, building damage, building damage threshold, normal power capacity, consumed power, requested power, transformer capacity, available transformer capacity and transformer status. Note that in this sheet, we set damage and damage threshold for Generators to 0 and 100, respectively, and the status of a Cell without a transformer to 2.

Channel Data Sheet: This sheet contains Channel output variables including channel number, channel capacity, available channel capacity, normal channel status and channel status.

3.6.3 Pre and Post Processor

The pre and post-processing of data is the essence of the simulator. The pre-processor carries out the functions of extracting data from the database, processing it, loading it into PowerWorld and directing PowerWorld to execute a powerflow solution. Likewise, the post-processor interprets the PowerWorld output and converts it into the I2Sim Simulator data format.

The program used for this pre and post-processing is Matlab. Matlab is a widely used rapid prototyping application program with a very large amount flexibility. The attractions to it are its ability to interface easily with both MS Excel and SimAuto and its built in g++ compiler, allowing its programs to be converted into standalone executable files.

Eleven Matlab functions were developed:

1. Cell Property Populate: A function that populates the normal power capacity and transformer capacity columns of the Building Data Sheet, based on the state of the PowerWorld binary file loaded into the simulator.

2. Branch Property Populate: A function that populates the normal branch status and maximum branch capacity columns of the Branch Data Sheet and Channel Data Sheet based on the state of the PowerWorld binary file loaded in the simulator.

3. Cell Damage Simulation: A function that accepts the load and input bus mappings, building damage, building damage threshold as well as normal power and requested power for a model's Cells. This function simulates cell damage by changing the state of the PowerWorld binary file through load adjustments and transformer switching.

4. Branch Damage Simulation: A function that accepts branch damage, branch damage threshold, and requested branch status input. Using this, it simulates damage in Branches by adjusting their statuses appropriately.

5. Line Status Reconcile: Using the Branch-to-Line map and normal branch status data, this function determines whether Lines are closed according to Equation 3.14. If a Line is deemed as open, this function opens *all* the Branches of that Line.

6. Open/Close PowerWorld Case: A function that accepts a PowerWorld binary file name input, opens that file in PowerWorld and allows it to be accessed by the simulator. This function can also close a binary file.

7. Open/Close PowerWorld Drawing: A function that accepts a PowerWorld drawing file and loads it. Again, this function can also close a PowerWorld drawing file.

8. PowerWorld Drawing Animate: A function that animates, or stops the animation of, a PowerWorld drawing file.

9. Cell Data Output: A function that outputs cell power consumed and available transformer capacity into the database based on the state of a PowerWorld Binary file. This function requires the Building-to-Bus map.

10. Branch Data Output: The Branch counterpart to the Cell Data Output function, this function outputs branch status, available branch capacity, available channel capacity and channel status data into the database based on the state of the PowerWorld Binary file. This function requires the Branch-to-Channel map.

11. Save PowerWorld Binary: This function accepts a file name and saves the current state of the PowerWorld Binary file under that name.

3.7 Software Architecture

The software tools discussed above interact with each other as shown below in Fig. 3.10.

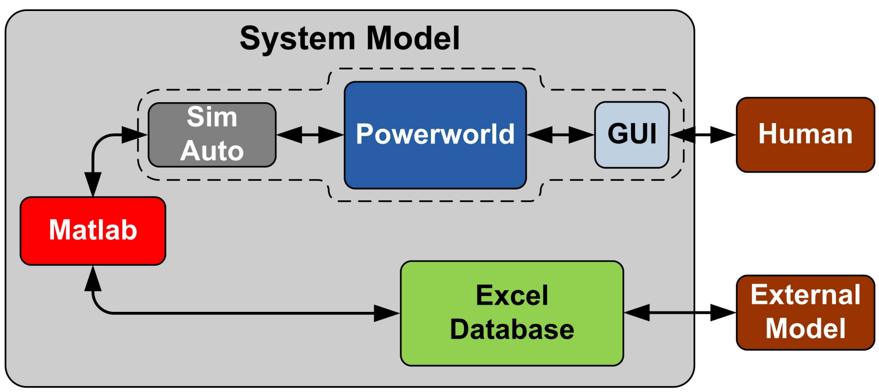

Figure 3.10: Model Component Architecture

Fig. 3.10 illustrates that the Matlab executable and the database can be circumvented through the graphical user interface. The GUI, however, is only accessible by a person (using a monitor and mouse), while the Excel database can be accessed by an external software process. This figure illustrates that the model is bi-directional because the input and output come from and go to the same entities. The Matlab executable function processes data and passes it between Excel and the PowerWorld Simulator through SimAuto. Matlab reads damage and decision input from the Excel database and delivers the various output variables back. Passing the data to and from the Excel database allows it to be stored, written and read by the I2Sim Simulator. In addition, Fig. 3.10 shows that the PowerWorld GUI continuously displays the electrical topology, which can be read and changed by a human user.

3.8 Simulation Process

To carry out a simulation, the Matlab functions are executed in four stages: (1) Initialization; (2) Execution; (3) Output; and (4) Termination. This progression is shown in Fig. 3.11, where it is illustrated that if the simulator is being used in an iterative loop the initialization process is not necessary after the first iteration and the termination stage is not executed until the final (nth) iteration.

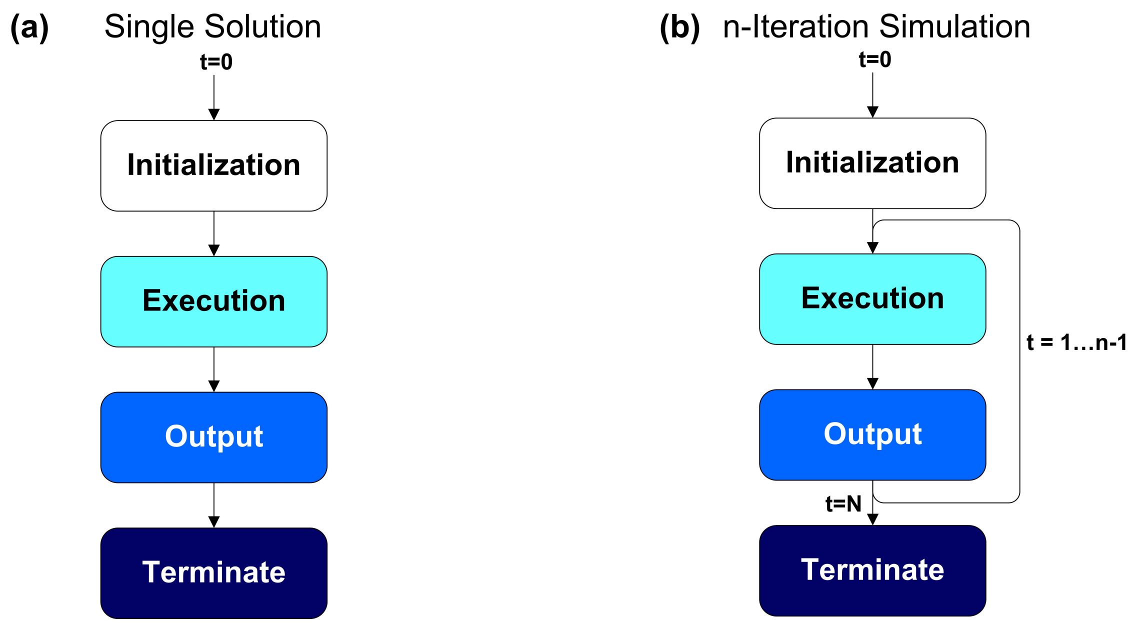

Figure 3.11: Process Stages for (a) Single Solution and (b) Iterative Solutions.

We describe the processes carried out in these simulation stages in the following subsections.

3.8.1 Initialization Stage

In the initialization stage the user must load the PowerWorld binary file, the Excel database sheets and the necessary initialization data. With these in place, Matlab functions then use these files to propagate additional information into the database. The files that are required by the user are

1. PowerWorld binary file;

2. PowerWorld drawing file;

3. Database sheets.

The columns of the database, which must be populated in the initialization stage are outlined in Table 3.11.

Table	Data Type
Branch Data Sheet	From Bus To Bus Circuit Number
Line to Branch Mapping Sheet	All Columns
Channel to Branch Mapping Sheet	All Columns
Cell and Channel Mapping Sheet	All Columns
Channel Data Sheet	Channel Number Normal Status

Table 3.11: Initialization Stage Data Required

The initialization stage procedure is depicted in Fig. 3.12. This figure shows the Matlab functions, the Database sheets and variables, the user input files and the pertinent memory objects that are employed in this process.

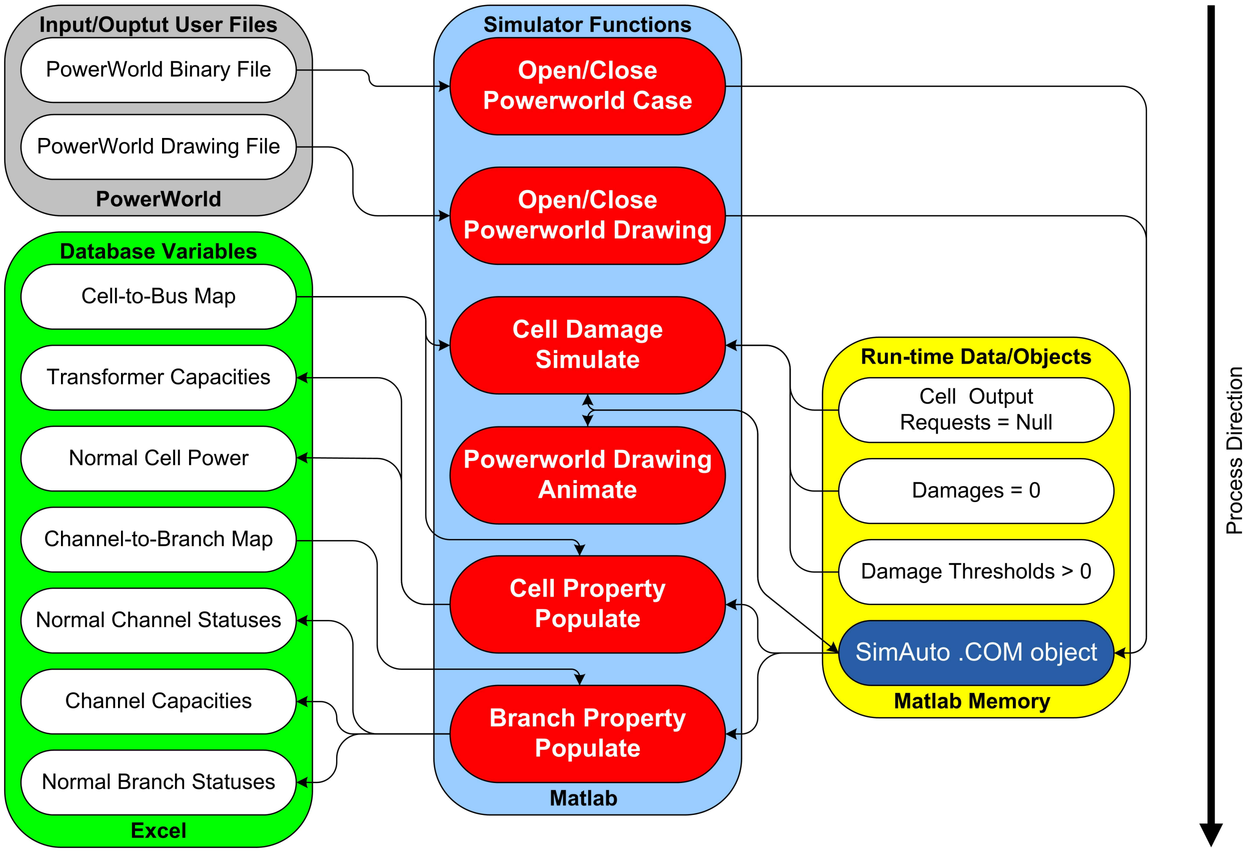

Figure 3.12: Initialization Stage of the Simulation Process

The left column of Fig. 3.12 contains PowerWorld files and database data, the centre column contains Matlab functions and the right column contains data created in Matlab's memory that is used by these functions. In this figure, a memory object called the 'Simauto .COM object' is shown. This object is created by the 'open/close PowerWorld Case' function, and is the mechanism that SimAuto uses to allow the Matlab functions to access PowerWorld.

Fig. 3.12 illustrates that six of the eleven available Matlab functions executed in the initialization stage. We describe the purpose of each function in this stage in the following list:

1. Open/Close PowerWorld Case: opens a the PowerWorld binary file input by the user and creates the SimAuto .COM object.

2. Open/Close PowerWorld Drawing: opens the PowerWorld drawing file drawing associated with the PowerWorld binary file using the SimAuto .COM object.

3. PowerWorld Drawing Animate: animates the simulation graphical user interface using the SimAuto .COM object.

4. Cell Damage Simulation: verifies that the powerflow solution reflects an undamaged system. To accomplish this, damage values of zero, damage thresholds greater than zero and requested powers of zero for all Cells and Branches are input to the function.

5. Cell Property Populate: inserts the normal Cell power and transformer capacities into the database.

6. Branch Property Populate: uses the initial statuses of the Branches in the PowerWorld binary file to populate the capacity and normal status columns of the database.

3.8.2 Execution Stage

With the initialization data in place, the framework of the model is constructed. The execution stage is where Matlab performs pre-processing of input data, passes it to PowerWorld and executes commands to calculate a powerflow solution. Table 3.12 lists the input data which the simulator requires at each iteration of the execution stage.

Table	Data Type
Branch Data Sheet	Damages Decisions Statuses
Building Data Sheet	Damages Requested Outputs

Table 3.12: Execution Stage Data Required

The execution stage of the simulation process involves only three functions: (1) Branch Damage Simulation; (2) Line Status Reconcile; and (3) Cell Damage Simulation. The execution of these function is illustrated in Fig. 3.13.

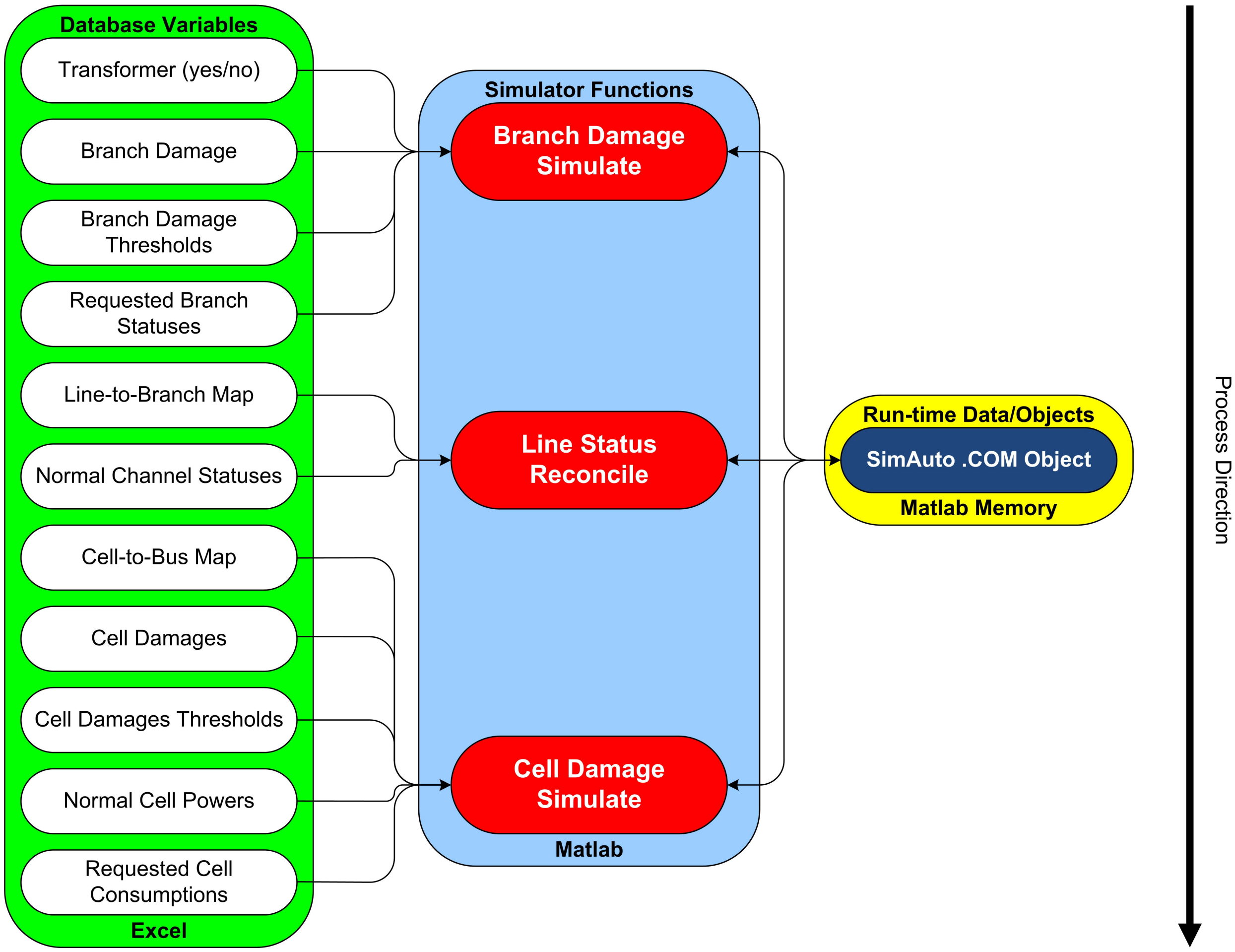

Figure 3.13: Execution Stage of the Simulation Process

The functions executed in this stage of the simulation process are the following:

1. Branch Damage Simulation: simulates damage to the model's Branches and implements the requested branch statuses in PowerWorld case through SimAuto.

2. Line Status Reconcile: reconciles branch statuses in the PowerWorld case based on their Line affiliations according to Equation 3.14 through SimAuto.

3. Cell Damage Simulation: simulates cell damage and requested cell outputs in PowerWorld through SimAuto.

3.8.3 Output Stage

The output stage entails post-processing the output data from PowerWorld, mapping it into the database and saving the solved powerflow solution. Table 3.13 lists the five outputs produced by the model in this stage.

Table	Data Type
Branch Data Sheet	Actual Statuses
Building Data Sheet	Actual Outputs Available Transformer Capacities
Channel Data Sheet	Available Transmission Capacities Present Statuses

Table 3.13: Output Stage Data Required

Fig. 3.14 illustrates the output stage procedure in which three functions are executed: (1) Cell Data Output; (2) Branch Data Output; and (3) PowerWorld Save Binary.

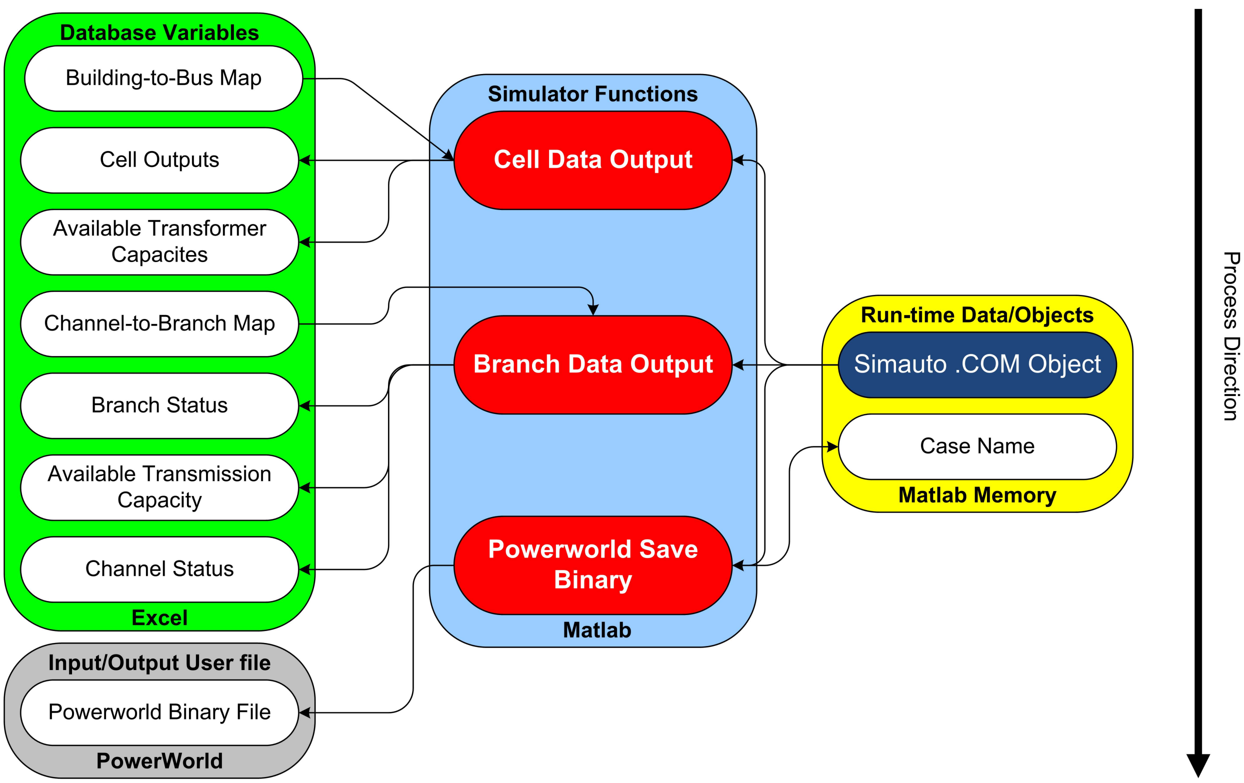

Figure 3.14: Output Stage of the Simulation Process

The Matlab functions executed in the output stage are the following:

1. Cell Data Output: delivers the Cell consumed power and available transformer capacities to the database.

2. Branch Data Output: delivers the Branch and Channel available capacity and status data to the database.

3. PowerWorld Save Binary: saves the solved PowerWorld binary file.

3.8.4 Termination Stage

In the termination stage, the model and its associated programs are shut down. Fig. 3.15 illustrates termination stage procedure, in which three functions are executed: (1) PowerWorld Drawing Animate; (2) PowerWorld Drawing Open/Close; and (3) PowerWorld Case Open/Close.

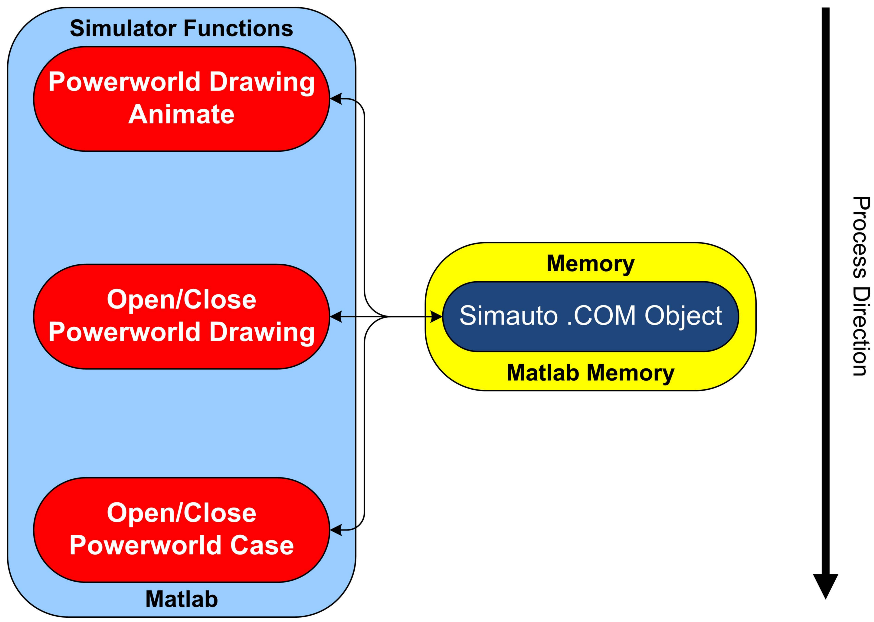

Figure 3.15: Termination Stage of the Simulation Process

The the functions executed in this stage of the simulation process are the following:

1. PowerWorld Drawing Animate: stops the PowerWorld drawing animation in preparation for it to be closed.

2. PowerWorld Drawing Open/Close: closes the PowerWorld drawing file.

3. PowerWorld Case Open/Close: closes the PowerWorld binary file.

The execution of this process stage concludes the simulation.

Chapter 4

The UBC Two-Infrastructure Restoration Simulator

Two objectives of this research are: to build a model of the UBC electrical power distribution system that could be integrated in to the I2Sim Simulator; and to test the usefulness of this model as a tool for restoration and recovery planning. In this chapter, we present the 'UBC Two-Infrastructure Simulator' (UTIS) and discuss how it may be used to test the effectiveness of restoration and repair approaches in recovering a *system* of infrastructures.

UTIS is a combination of two infrastructure models, one model of the UBC electrical distribution infrastructure and another model of the UBC information technology infrastructure. Our motivation for developing this Two-Infrastructure Simulator was to allow the UBC electrical distribution infrastructure model to be tested in multi-infrastructure simulations *independently* of the I2Sim Simulator. The steps we present in this chapter for the UTIS development are:

1. Modeling the UBC electrical power distribution infrastructure using the methodology and simulator-architecture described in the previous chapter;

2. Modeling the UBC IT infrastructure using a similar, but simplified, methodology;

3. Combining these models to create the UBC Two-Infrastructure Simulator;

4. Developing an infrastructure repair approach for use with this simulator.

In this chapter we also present an evaluation criteria that we developed for comparing the success of simulations performed with UTIS. Before we discuss the UBC campus infrastructure models, however, we present the following two sections on the physical characteristics of the UBC electrical and information technology infrastructures.

4.1 UBC Electrical Distribution Infrastructure

The information available for the UBC electrical distribution infrastructure describes a radial-architecture, with two 60 kV transmission lines feeding power through a pair of distribution transformers into the campus. Downstream of the transformers is a 12 kV distribution bus, from which 13 cables feed the numerous campus buildings. A typical distribution setup downstream of this is a bus within a large building. Each contains a step-down transformer that is fed by two conductors tapped from the main cables. These buildings, in turn, feed power at 600 V or 230 V to small adjacent buildings, and to tertiary devices (e.g. street lights). An example of this setup is depicted in Fig. 4.1, which shows UBC's main substation, four of its large buildings and two of its tertiary buildings. As the figure shows, tertiary buildings sometimes provide power to each other [32].

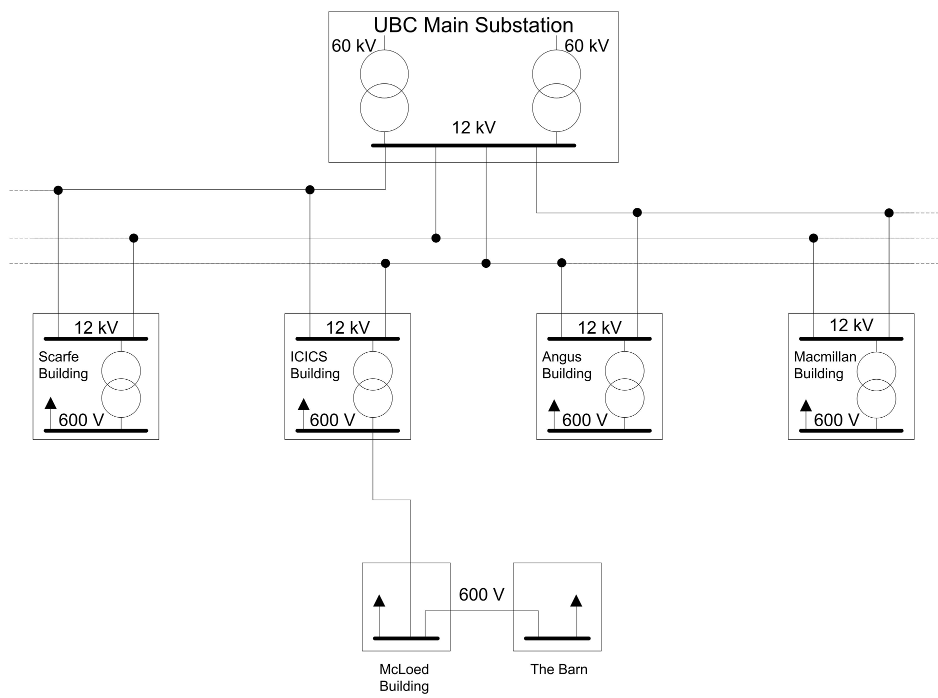

Figure 4.1: Typical UBC Electrical System Topology

While the setup shown in Fig. 4.1 is typical, there are exceptions: Some buildings include multiple transformers; one substation contains two 12/4 kV transformers, and serves a small number of campus buildings; and some main feeders are terminated at distribution busses before they reach buildings, as opposed to being tapped [32].

Information was available for 191 buildings that are designated in or above the 600 V voltage class. However, below this, the architecture of the system is unknown. It is clear after having compared electrical drawings to civil drawings, however, that some of the single buildings depicted in the electrical drawings are abstractions of multiple civil buildings. We discuss this later on in this chapter.

The complete UBC Electrical infrastructure has been modeled using PowerWorld as shown in Fig. 4.2. In this representation, buildings have been numbered according to a Graphical-Information-System (GIS) numbering index that we also discuss later in this chapter. Fig. 4.3 shows a GIS representation of the electrical system that provides a sense of its geographic complexity.

4.2 IT Network Infrastructure

The UBC IT network controls the campus' telephones and computer networks. The information available for UBC IT network is shown in Fig. 4.4. This figure depicts that the IT network has a hierarchical structure on four levels, which are denoted L1 to L4. At the top echelon, Level 1, there are three buildings. These buildings are labeled 493, 486 and 428, respectively. Here, the buildings have been numbered according to the GIS numbering scheme used in Fig. 4.2. The levels of buildings in this infrastructure are assigned according to the number of network nodes above them in the hierarchy. At the lower echelons, 'child' buildings are typically fed by one 'parent'.

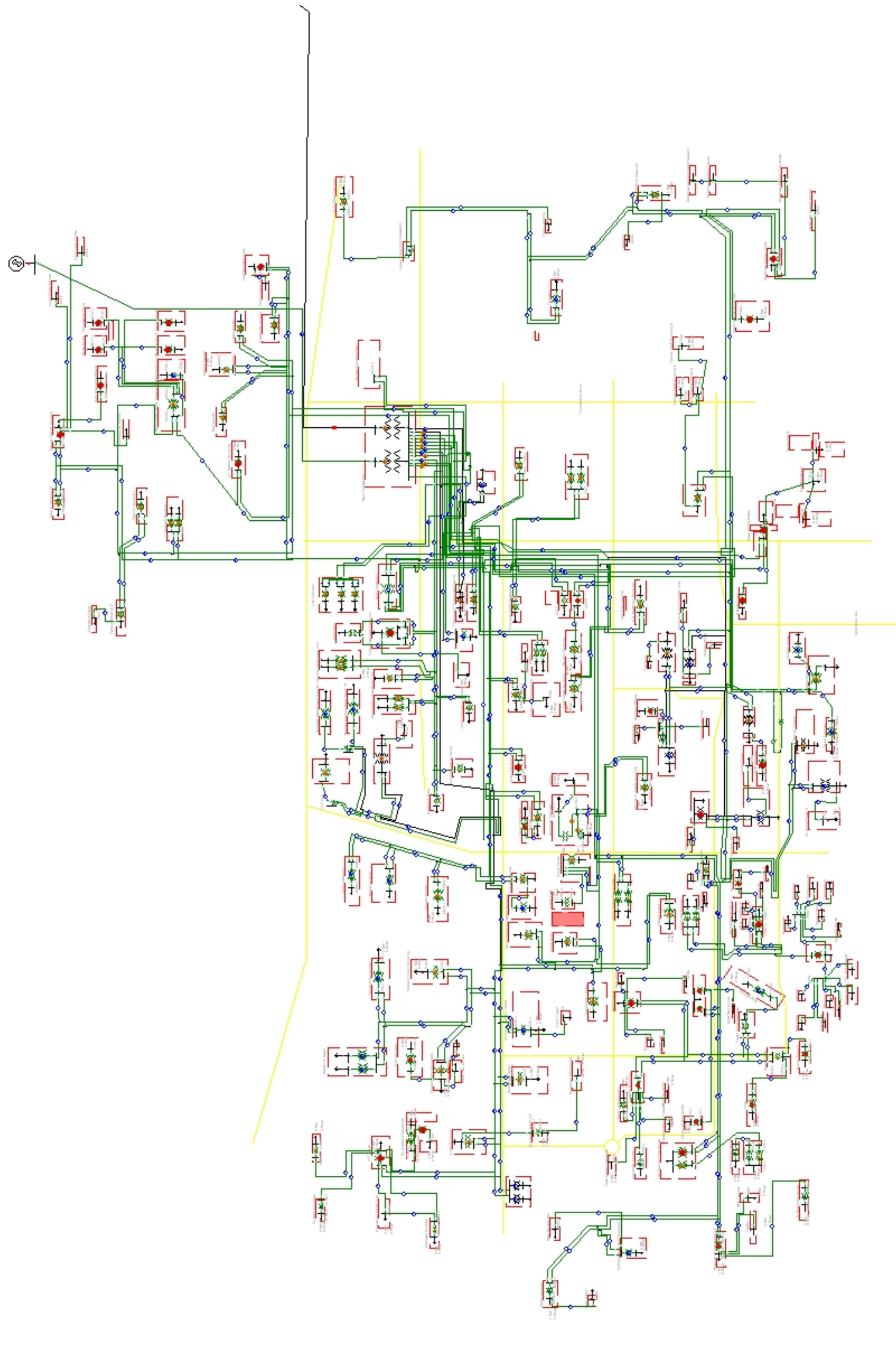

Figure 4.2: Electrical Network Model

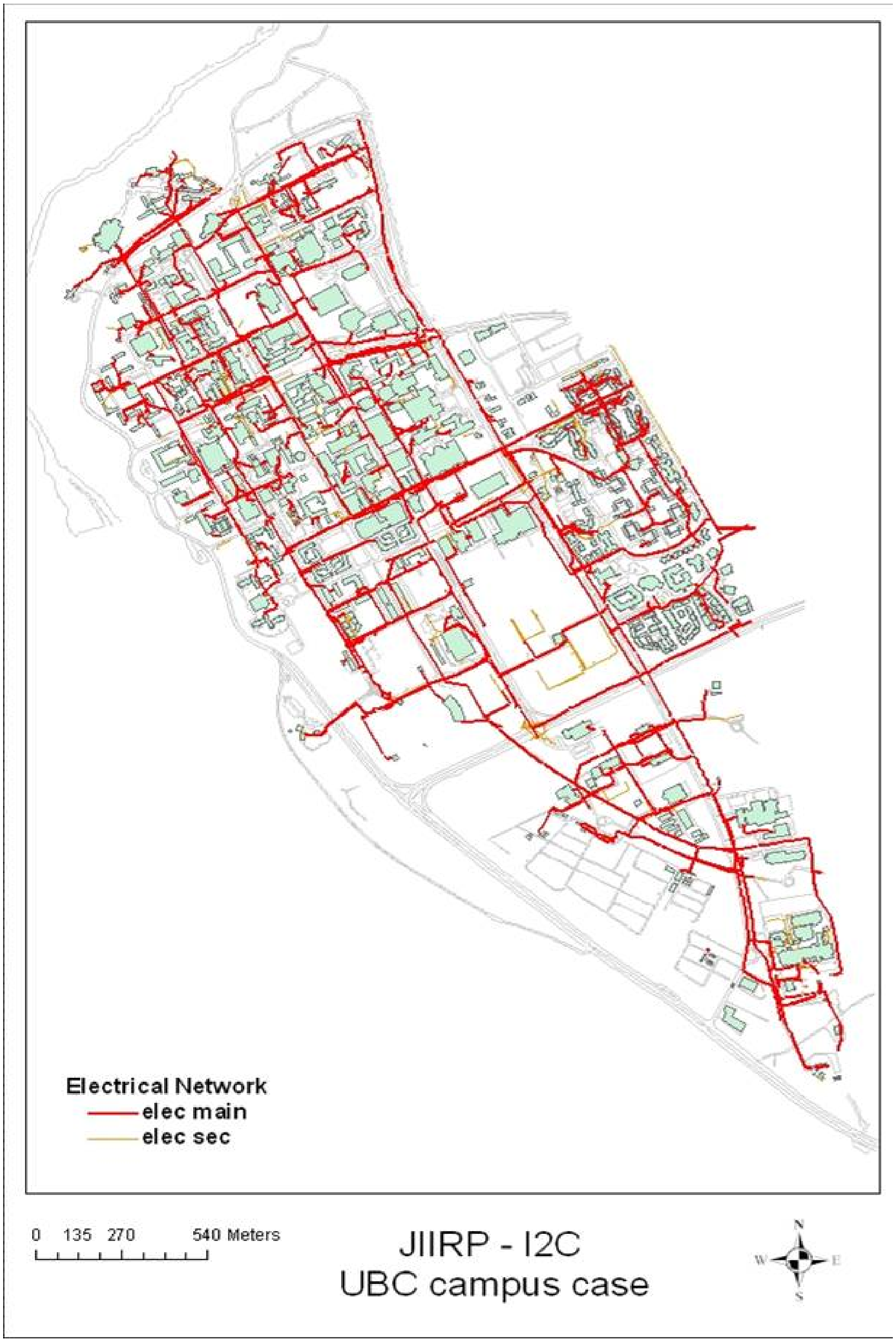

Figure 4.3: UBC Campus Electrical Overview

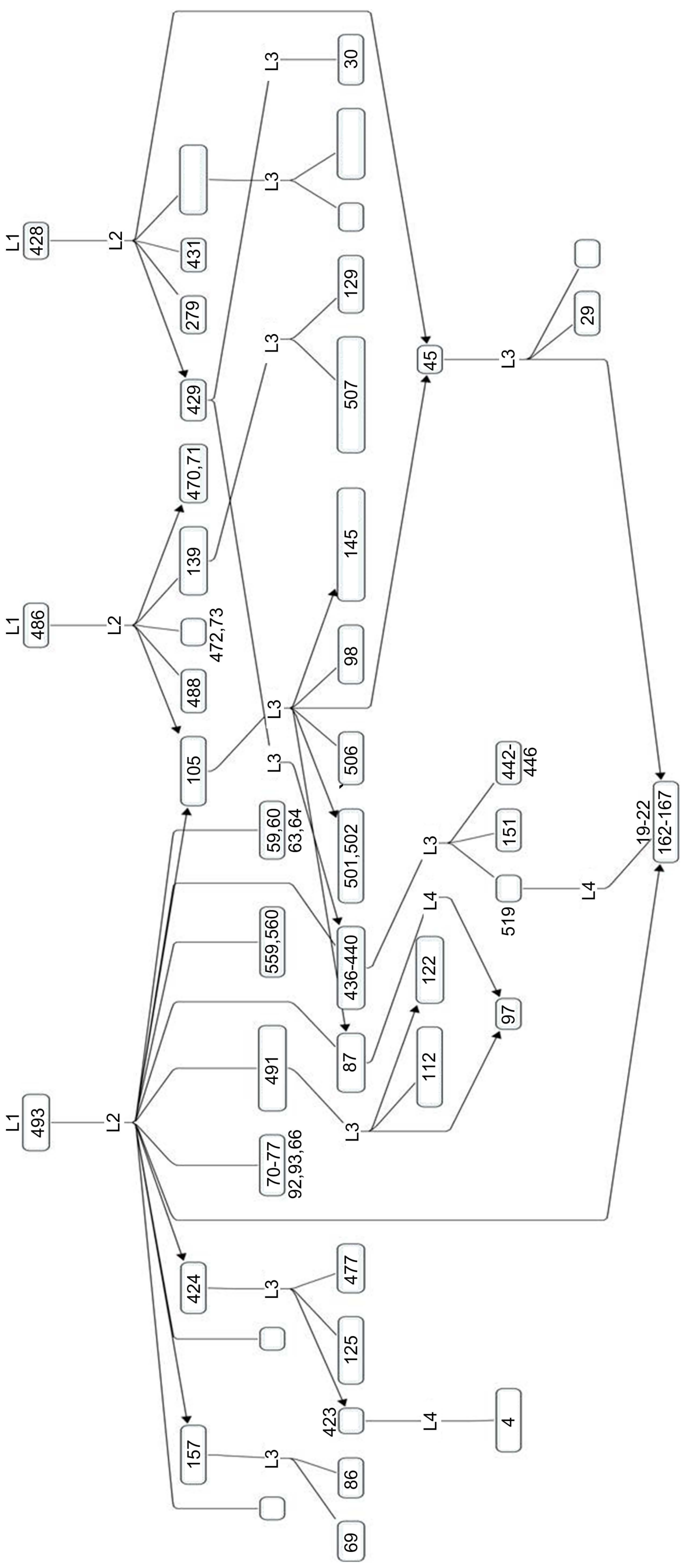

Figure 4.4: IT Network Hierarchy

4.3 UBC Damage Assessment

In the damage-assessment carried out by K. Thibert in [27] she projected the damage to 364 UBC buildings and substations for seven intensities of earthquakes. She classified buildings and substations according to their type and materials and calculated the damage to both their structural and nonstructural components. In this research, we have employed this damage-assessment for the following models.

4.4 UBC Electrical Model

The UBC electrical distribution system has been modeled according to the methodology described in the Chapter 2. However, the mapping of the damage-assessments to electrical Cells requires clarification. 364 Cells were described in the damage-assessment but only 191 Cells were included in the UBC electrical model, meaning not all Cells with damage-assessments were described in the electrical model. Furthermore, not all Cells described in the electrical model were included in the damage-assessment. As a result, it was often difficult to assign damage-assessment information to electrical Cells. To cope with this, we have developed the following criteria for mapping damage-assessments to the appropriate electrical Cells:

1. We assigned electrical Cells which were not included in the damage-assessment a cell damage of zero.

2. Where it was clear that one Cell in the electrical infrastructure corresponded to a number of Cells individually represented in the damage-assessment, we included the entire group of damage-assessment Cells in the model by:

    (a) choosing one Cell from the group, the 'Representative Cell', to be the Cell represented directly in the electrical model.

    (b) including each 'Non-Representative Cell' in the Database and creating Channel components connecting each of them to the Representative Cell as its child Cells.

    (c) assigning normal power to each Non-Representative Cell equal to 1% of the Representative Cells' normal power, i.e. if Cell a is represented by Cell b then $P_b^{nom} = 0.01 \cdot P_a^{nom}$.

    (d) assigning the damage of the Representative Cell to each Non-Representative Cell in its group throughout the simulation, i.e. if the Representative Cell has 20 units of damage, all of its Non-Representative Cells also have 20 units of damage.

(e) assuming that throughout the simulation if the Representative Cell's available power was equal to zero then each of its Non-Representative Cell's available power was also equal to zero, i.e. $P_b^{avl} = 0$ if $P_a^{avl} = 0$.

While it would have been simpler to omit these rogue Cells, the objective of our research was to create a model that could accept data from other infrastructures, so it seemed prudent to make an attempt to include as many Cells as possible from the damage-assessment. Assigning a normal power to these Non-Representative Cells allowed them each to be part of the simulation. However, the amount of power assigned was small because they are numerous and their consumption may have already been lumped into the Buildings shown in the electrical drawings we were provided.

We included a total of 395 Cells in our model, making it impractical to discuss specifics for each. However, detailed information in [33] including the diagrams depicting the PowerWorld model, a list of cell damages and other Cell data. In these appendices, we represent each Cell by a cell ID number between 0 and 565. These correspond to the numbers used in the GIS model employed by the damage-assessment research.

4.5 UBC IT Model

In this section, we present an IT infrastructure modeling methodology and its application to our infrastructure model.

4.5.1 IT Modeling Methodology

The modeling methodology we discuss here is similar to the methodology we developed in Chapter 3 for an electrical infrastructure. However, here we assume that: if a Cell can receive data from at least one operational parent cell, and it itself is operational, it can process and transfer data at its normal capacity; the operation of an IT Cell is dependent on its electrical power input and the amount damage it has sustained; and the data capacity of a network is defined by the number of IT Cells being served. In our model we do not take into account considerations such as network delay and service quality.

As with the electrical system methodology, this methodology describes the system geographically, with Buildings as its main components.

IT Building Model: Here we define the properties of an IT Building by the following variables: normal data capacity, L_{it}^{nom}; and IT damage threshold, h_{it}:

$$\begin{aligned} L_{it}^{nom} &\in \mathbb{R}^{+} \\ h_{it} &\in [0 \ldots 100] \end{aligned} \tag{4.1}$$

Normal data capacity, with units of Megabytes per second (MBps), and IT damage threshold are analogous to their electrical model counterpart variables: P_{bld}^{nom} and h_{bld}, respectively.

The inputs to an IT Building are assumed to be IT building damage, d_{it}; and electrical power available P_{it}^{avl}, which we describe as

$$\begin{aligned} d_{it} &\in [0 \ldots 100] \\ P_{it}^{avl} &\in \{0 = \text{no}, 1 = \text{yes}\} \end{aligned} \tag{4.2}$$

where IT building damage is again analogous to d_{bld}, and electrical power available represents an IT Building's dependence on the electrical system for power. The output of an IT Building is assumed to be data consumed L_{it}. We define this as

$$L_{it} = \begin{cases} L_{it}^{nom} \cdot (1 - \frac{d_{it}}{h_{it}}) \cdot P_{it}^{avl} & \text{if } d_{it} < h_{it} \\ 0 & \text{if } d_{it} \geq h_{it} \end{cases} \tag{4.3}$$

Thus, the IT Building model closely resembles its electrical counterpart. As in the electrical model, any IT Building must have data available to it from a parent building to be considered operational.

IT Channels: To connect IT Buildings, the identical concept of Channels is also used here. However, in the IT model capacity is not considered and Channels cannot be opened or closed; IT Channels are simply a path from one IT Cell to another. As Fig. 4.5 illustrates, the information we have for the physical UBC IT network shows that it conforms to a structure where all IT child and parent buildings are connected by individual Channels. Thus, no complicated mappings are required to convert the IT Network Model into the Cell-Channel format.

4.5.2 IT Model Implementation

The information we have for the IT system does not contain all of the Cells represented in our UBC electrical model. We have added the omitted Cells, as shown below in Fig. 4.5, to make our IT model more comprehensive. In this figure the groups of Cells that have been added appear with a dark-grey tone. According to the ranges of Cell numbers, however, Fig. 4.5 seems to indicate that certain Cells were represented twice, which is not the case. We added only those Cells that were not already represented in the IT Model. We also point out here that all of the Cells in the original IT hierarchy have been mapped to 'Representative Cells'.

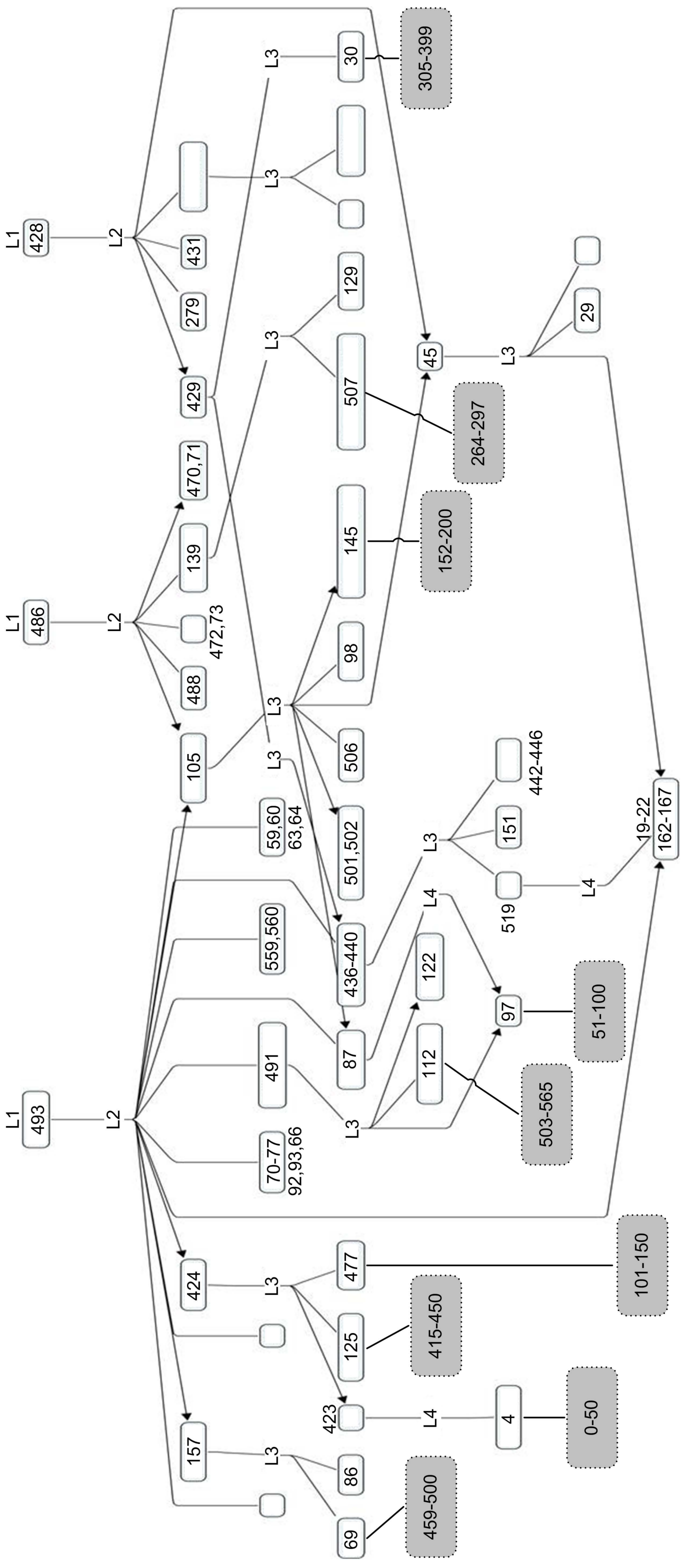

Figure 4.5: IT Network Hierarchy Model

The final UBC IT model is much simpler than our UBC electrical model because it does not involve an external simulator. It was executed entirely through a Matlab executable file and the Excel database. We stored the data for the IT model in two sheets as depicted in Table 4.1, which shows the mapping between IT parent and child Cells.

IT Cell Name	IT Cell Number	IT Cell Parent
Substation A	188	15
Building P	520	49
Building P	45	73
Building R	45	81
Building S	44	45
.	.	.

Table 4.1: IT Cell Channel Mapping Sheet

In contrast to electrical Channels, IT Channels were not assigned numbers. This is because IT Channels do not have any inherent properties and thus need not be referenced. The 'IT Cell Number' and 'IT Cell Parent' entries are necessary, however, while the 'IT Cell Name' is optional. We should note that it is possible for a Cell to have multiple IT Parents, in which case it was given multiple entries in the table.

IT Cell Number	IT Damage	Damage Threshold	Normal Data Capacity	Data Consumed	Electrical Power
188	18.8	30	0	0	Yes
520	0	30	1.4	1.4	Yes
45	0	30	1.3	0	No
44	0	30	1.3	1.3	Yes
312	18.8	30	1.4	0.52	Yes
.	.	.	.	.	.

Table 4.2: IT Cell Data Sheet

Table 4.2 depicts the IT Cell Data Sheet, where we contained the input, output and parameter data for the IT Model. In this table, IT damage and electrical power available comprise the input for the model, while data consumed comprises its only output. This concludes our discussion of the UBC IT model.

4.6 UBC Two-Infrastructure Model

The UBC Two-Infrastructure model is the combination of our electrical model and IT model. In combining these models, we made certain assumptions:

1. The damage thresholds of all Cells in the electrical model are equal. i.e. $h^1_{bld} = h^2_{bld} = \ldots = h^{395}_{bld}$. This global threshold is denoted H.

2. The damage thresholds of all IT Cells' models are equal to the damage thresholds of their respective electrical Cell models. i.e. $h^i_{it} = H \; \forall i \in \{1 \ldots 395\}$.

3. The damage of each Cell is the same for its respective electrical and IT model. i.e. $d^i_{bld} = d^i_{it} \; \forall i \in \{1 \ldots 395\}$.

4. The requested power of all Cells is equal to their normal power capacity. i.e. $P^{req}_{bld_i} = P^{nom}_{bld_i} \; \forall i \in \{1 \ldots 395\}$.

5. The normal data capacity of all Cells is equal to their respective normal power capacity. i.e. $w_l L^{nom}_{it_i} = w_p P^{nom}_{bld_i} \; \forall i \in \{1 \ldots 395\}$. Here we define the weighting factors w_p and w_l as having values of $\frac{1}{\text{MW}}$ and $\frac{1}{\text{MBps}}$, respectively. These allow us to equate data capacity and electrical power.

Assumptions (1) and (2) were made because the damage-assessments were already tailored to each Cell, thus varying the damage thresholds would have created a degree of freedom which was unnecessary at this stage of research. Assumption (3) was reasonable because the damage a Cell's electrical equipment would sustain during a disaster would be similar to the amount of damage its IT equipment would sustain. Assumption (4) was used because the requested power output is a variable that takes human decision into account. Finally, assumption (5) implies that the importance of IT services is similar to electrical services. Giving these services equal importance was deemed to be a reasonable assumption.

With these assumptions, the UBC Two-Infrastructure Model can be depicted as shown in Fig. 4.6. As this figure shows, both the IT model and electrical model receive input from the damage-assessment, while the IT model also receives input from the electrical model. Fig. 4.6 also illustrates that the two models produce separate output-data sets.

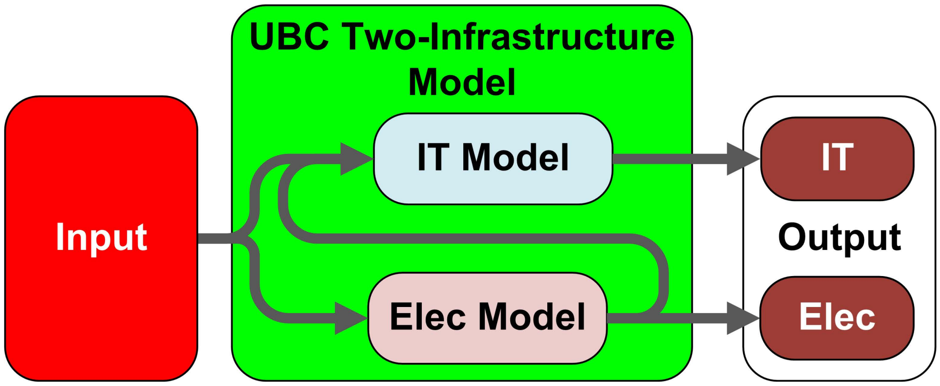

Figure 4.6: Test Simulation Process

The following section discusses how this Two-Infrastructure UBC model was adapted into a simulator.

4.7 UBC Two-Infrastructure Simulator

Simulations with the UBC Two-Infrastructure Model were done by applying damage to the system at the first iteration, and carrying out repairs on that system at each subsequent iteration by reducing the damages to Cells. This process is depicted in Fig. 4.7. As this figure shows, the repair procedure was implemented using a feedback loop.

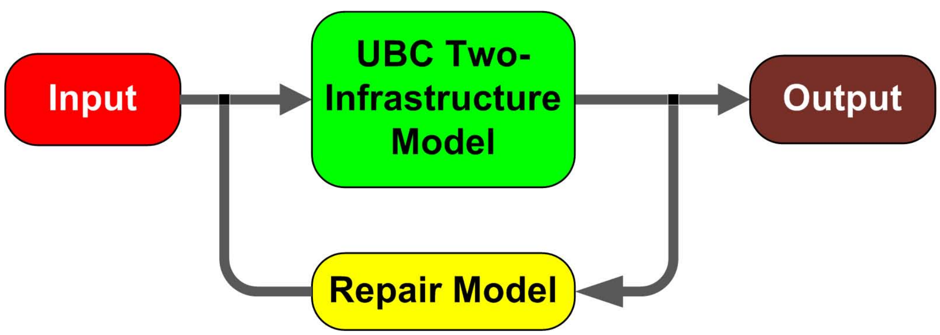

Figure 4.7: Test Simulation Processes

To test a particular repair approach a repair model is necessary. The repair model we developed is described in the following subsection.

4.7.1 Repair Model

The repair model we define here is the process in which Cells are repaired. According to this repair model, one Cell is repaired at each iteration by re-assigning it a damage value of zero. In this thesis we have attempted to create a repair approach that would recover the system efficiently. However, it was not our objective to search for an *optimal* repair procedure. This would be a subsequent topic of research. Our approach is defined by the following assumptions:

- All the services for one Cell can be repaired to full capacity at each iteration
- The importance of IT service and Electrical service is equal
- The Cell that is likely causing the most lost service to the system is repaired first

To implement this repair model six variables were used:

1. Cell lost power output, P_{clp};
2. Cell lost data capacity, L_{cld};
3. Lost downstream power output, P_{dslp};
4. Lost downstream data capacity, L_{dsld};
5. Cell lost combined capacity, C_{clc};
6. Lost downstream combined capacity, C_{dslc}.

We define cell lost power output and cell lost data capacity as follows:

$$P_{clp} \triangleq P_{bld} - P_{bld}^{nom} \tag{4.4}$$

$$L_{cld} \triangleq L_{it} - L_{it}^{nom} \tag{4.5}$$

As Equation 4.4 shows, cell lost power output is the difference between the amount of power that a Cell is presently consuming and normally consumes. Cell lost data capacity is the IT analog of cell lost power and is defined similarly in Equation 4.5.

Lost downstream power output represents the amount of power output and data capacity a Cell and its sibling Cells have lost. The definition for this variable assumes the Cell-Channel network is in the parent/child configuration shown in Fig. 4.8.

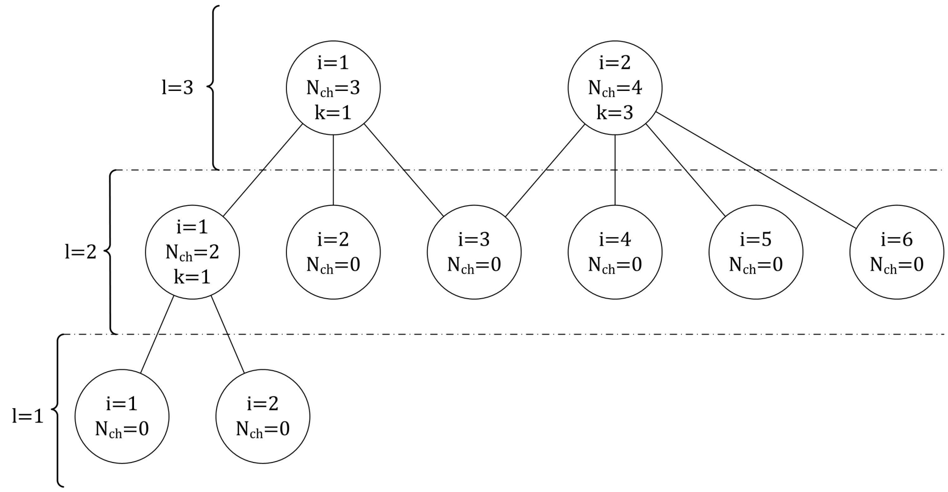

Figure 4.8: Cell-Channel Tree Diagram

The definition of lost downstream power P_{dslp} for Cell i at hierarchy level l is:

$$P_{dslp}^{l,i} \triangleq \begin{cases} P_{clp}^{l,i} + \displaystyle\sum_{j=K^{l,i}}^{N_{ch}^{l,i}+K^{l,i}} P_{dslp}^{l-1,j} & \text{for} \quad N_{ch}^{l,i} \geq 1 \\ P_{clp}^{l,i} & \text{for} \quad N_{ch}^{l,i} = 0 \end{cases} \tag{4.6}$$

In Equation 4.6, $N_{ch}^{l,i}$ denotes the number of children of Cell $\{l, i\}$ and $K^{l,i}$ denotes the lowest valued index of its children. This equation describes that the downstream lost power of a Cell with N_{ch} children is the sum of its own cell lost power output and its children's downstream lost power outputs. It also describes that if a Cell has no children, i.e. $N_{ch} = 0$, then its downstream lost power is simply equal to its cell lost power output. Fig. 4.8 is provided to further illustrate Equation 4.6. This figure depicts a Cell hierarchy with three levels, i.e. $l \in \{1, 2, 3\}$, where Cells 1 and 2 in level 3 have three and four children, respectively, i.e. $N_{ch}^{3,1} = 3$ and $N_{ch}^{3,2} = 4$. In turn, Cell 1 in level 2 has two children, i.e. $N_{ch}^{2,1} = 2$, which are indexed $\{1, 1\}$ and $\{1, 2\}$. This means the lowest valued index of the children of Cell $\{2, 1\}$ is 1, i.e. $K^{2,1} = 1$.

Lost downstream data capacity is defined similarly:

$$L_{dsld}^{l,i} \triangleq \begin{cases} L_{cld}^{l,i} + \displaystyle\sum_{j=K^{l,i}}^{N_{ch}^{l,i}+K^{l,i}} L_{dsld}^{l-1,j} & \text{for} \quad N_{ch}^{l,i} \geq 1 \\ L_{cld}^{l,i} & \text{for} \quad N_{ch}^{l,i} = 0 \end{cases} \tag{4.7}$$

We note here that the cell lost power or cell lost data capacity of a single Cell may be counted in the downstream lost power or downstream lost data capacity, respectively, of many Cells. Using these variables, we define cell lost combined capacity and downstream lost combined capacity as

$$C^i_{clc} \triangleq w_p P^i_{clp} + w_l L^i_{cld} \tag{4.8}$$

$$C^i_{dslc} \triangleq w_p P^i_{dslp} + w_l L^i_{dsld} \tag{4.9}$$

respectively. Again we employ the weighting variables w_p and w_l here, making C_{clc} and C_{dslc} unitless. Using the C_{clp} and C_{dslp} variables, repairs are performed according to the following two-stage procedure:

Stage 1:

1. Find all Cells that are completely damaged. These are the Cell for which $d^i_{bdl} \geq h^i_{bld}$.
2. Find all remaining Cells that have downstream combined lost capacity greater than zero, i.e. $C_{dslp} > 0$.
3. Find and repair the Cell that has the greatest downstream combined lost capacity, C_{dslp}.

Stage 2:

1. Find all remaining Cells that are partly damage. These are the Cells for which $d^i_{bdl} < h^i_{bld}$.
2. Find all remaining Cells that have cell lost combined capacity greater than zero, i.e. $C_{clc} > 0$.
3. Find and repair the Cell that has the greatest cell lost combined capacity, C_{clc}.

In the following section a discussion of the interdependencies that are modeled by UTIS are discussed.

4.7.2 UBC Infrastructure Interdependencies

Here we simply highlight the infrastructure interdependencies that exist between the electrical model and the IT model in the UBC Two-Infrastructure Simulator. There are two interdependencies: (1) IT Cells require electrical power to consume and transmit data; and (2) in the repair criteria, the output of both models contributes to the variables C_{dslc} and C_{clc}, which are used to determine which Cells are repaired.

In the following chapter, where we discuss test case simulations, some of the emergent properties of these two interdependencies are revealed and are further discussed. Before this, however, we present a performance metric for simulations carried out with UTIS simulator.

4.8 UBC Two-Infrastructure Simulation Performance Criteria

Simulations carried out using the UTIS produce a vector of system states in which the input and output of each Cell in the system can be looked at over each iteration. This data describes the overall 'health' of the system during its various stages of repair. In particular, at each n^{th} iteration we calculate the total lost power and lost IT capacity for all of the Cells in the system as:

$$P(n) = \sum_{i=1}^{N_{cells}} P^i_{clp}(n) \tag{4.10}$$

$$L(n) = \sum_{i=1}^{N_{cells}} L^i_{cld}(n) \tag{4.11}$$

In these equations, N_{cells} denotes the total number of cells and $P(n)$ and $L(n)$ denote the total lost power of the electrical model and total lost capacity of the IT model, respectively. Combining these two quantities in a weighted sum gives us the total lost capacity of the system denoted $C(n)$:

$$C(n) \triangleq w_p P(n) + w_l L(n) \tag{4.12}$$

Another useful measure would be lost service versus *time*, i.e. $C(t)$ instead of $C(n)$. To develop this measure, we define η as the units of damage which can be repaired per day and $r_c(n)$ as the cumulative repairs to the system at iteration n. Using these we estimate time, $\hat{t}$, as

$$\hat{t} = \frac{r_c(n)}{\eta}. \tag{4.13}$$

This assumption is somewhat crude because it does not take into consideration the fact that one Cell may take longer to repair than another and moving repair crews between Cells takes time. However, given our high-level modeling, this was assumed sufficient for comparing simulations.

Using our synthesized time variable, $\hat{t}$, the final step in quantifying the success of the repair procedure is to integrate the function $C(\hat{t})$ over the total duration of the simulation, T_{sim}:

$$\gamma = \int_0^{T_{sim}} C(\hat{t})d\hat{t} \tag{4.14}$$

where γ, is the total capacity-days of lost service. We define this measure for the individual infrastructures as well:

$$\alpha = \int_0^{T_{sim}} P(\hat{t})d\hat{t} \tag{4.15}$$

$$\beta = \int_0^{T_{sim}} L(\hat{t})d\hat{t} \tag{4.16}$$

where α represents the total lost energy of the electrical model and β represents the total lost IT capacity. Variables γ, α, and β, provide a simple means of comparison among different repair procedures that are being investigated.

Chapter 5

Case Studies with the UBC Two-Infrastructure Simulator

In this chapter we present simulations of the repair of the UBC electrical and information technology infrastructures following an earthquake disaster. We performed these simulations using two different repair approaches so they could be compared. In the first repair approach, 'Approach A', we provided the repair model with information from only the electrical infrastructure. In the second approach, 'Approach B', we provided the repair model with information from both infrastructures. These approaches are depicted in Fig. 5.1.

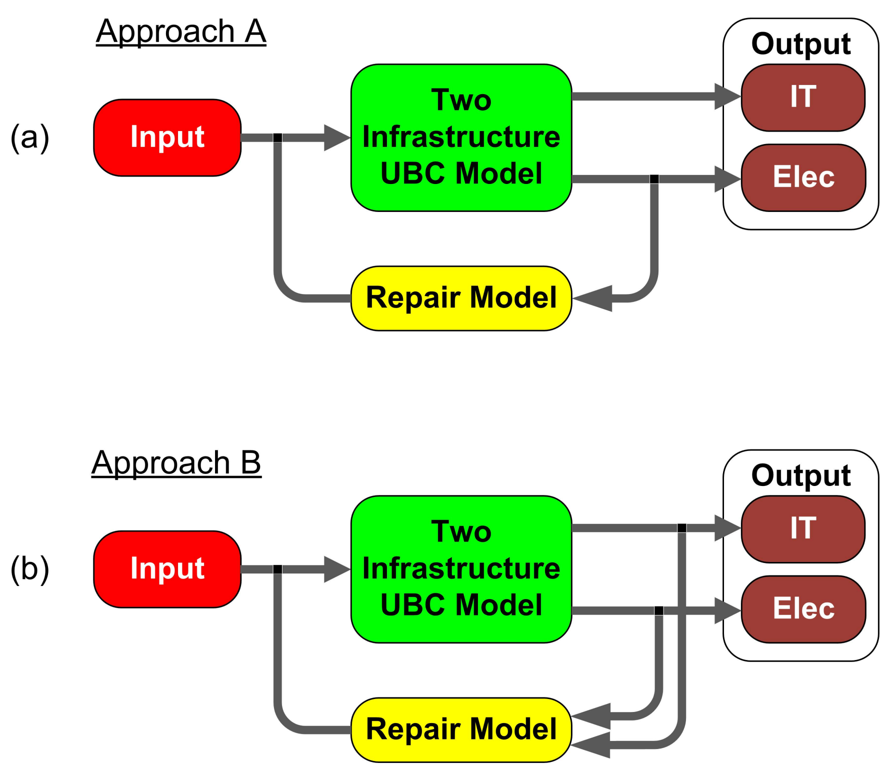

Figure 5.1: Simulation Approaches With Information from (a) One Infrastructure and (b) Two Infrastructures

5.1 Assumptions

We assumed the following conditions in the UBC Two-Infrastructure simulations:

System: We used models of the UBC electrical power distribution infrastructure and information technology infrastructure, as described in Chapter 4. We included 395 Cells in these models.

Building Damage: We assumed that the damage to the system was caused by a magnitude ten earthquake, as described in [27].

Global Damage Threshold: We varied the damage threshold, H, between the test cases. In Cases 1, 2 and 3 we assumed damage thresholds of 10, 20 and 30, respectively.

Branch Damage: We assumed there was no damage to the electrical branches. This was to simplify the repair criteria and because earthquake damage data was not available for the UBC electrical branches.

Repairs: We simulated Repair Approach A by setting the normal data capacity $L_{it_i}^{nom}$ and data consumed L_{it}^{i} to zero in the repair model. This effectively removes the feedback information flow from the IT model, as depicted in Fig. 5.1(a). Repair Approach B is implemented by using the calculated values of $L_{it_i}^{nom}$ and L_{it}^{i} in the repair model. This results in taking into account the IT information and providing an additional feedback path as shown in Fig. 5.1(b).

Our repair model assumed that only one Cell could be repaired at a time, and that when the repair of a Cell commenced it was fully completed. In addition, we assumed that 30 units of damage could be repaired per day, i.e. $\eta = 30$, regardless of the Cell repaired or the number of Cells repaired in a day.

Simulation Duration: We continued simulations until service to the system was fully restored. The amount of time this took depended on the amount of damage to the system and the sequence in which the repairs were made.

The distribution of the damage that was applied to the Cells is depicted in Fig. 5.2 relative to the level of the global damage threshold, H, for the three cases presented below. Each dot along the x-axis of this figure represents a Cell, and its position on the y-axis indicates its level of damage. The dots' positions on the x-axis in not significant; they are sorted by damage level to illustrate the number of Cells at different damage levels. We reference this figure in the following discussion.

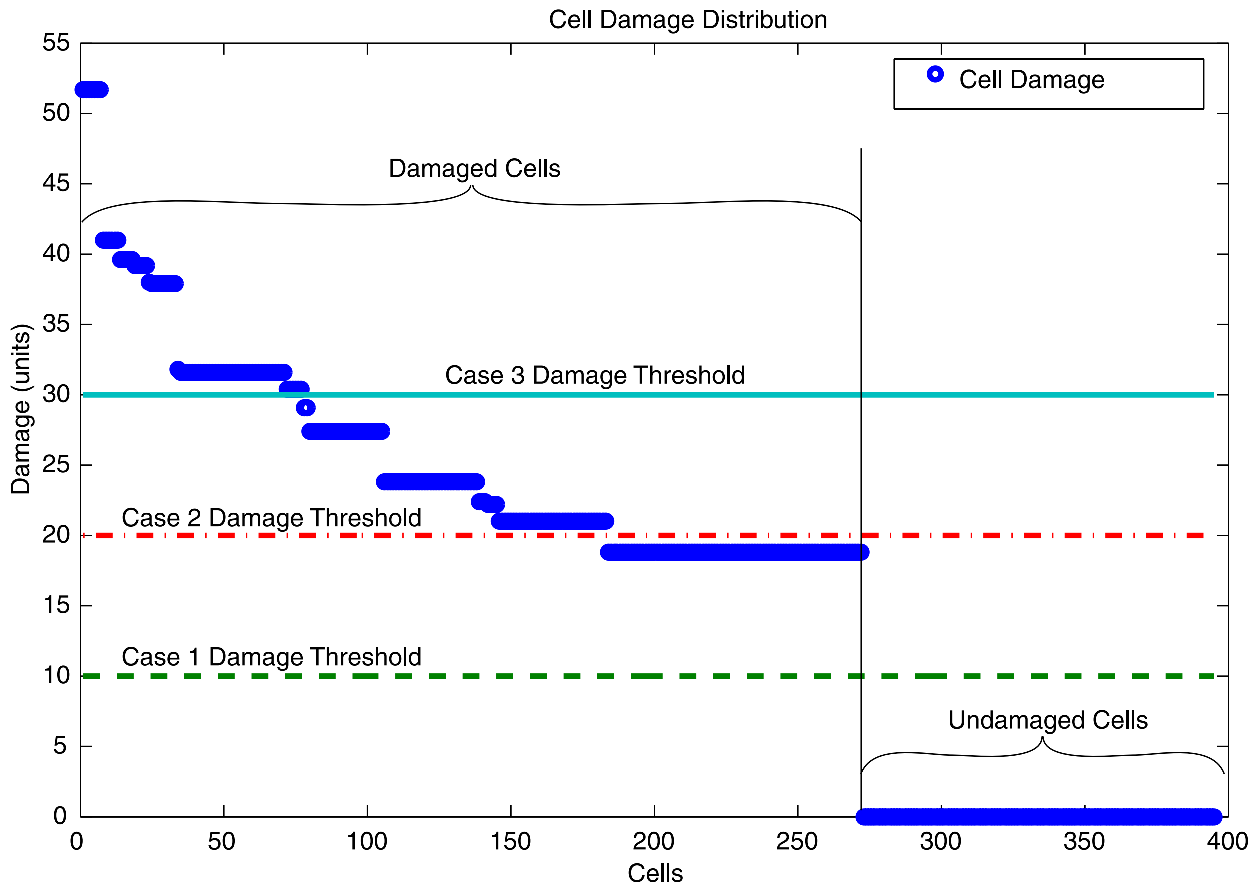

Figure 5.2: Plot of Test Simulation Cell Damages and Damage Thresholds

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5.2 Case 1

In Case 1 we assumed a damage threshold of 10. As illustrated in Fig. 5.2, this means that all of the damaged Cells were damaged in excess of their damage threshold. It also illustrates that 123 Cells had no damage at all, meaning that these Cells experienced normal output at the beginning of the simulation.

This simulation required 123 iterations to restore the system to full capacity, and in doing so repaired 3359 units of damage (equating to 112 days of repair) for both Approach A and Approach B. This means only 123 Cells were repaired, which at first seems erroneous given that 272 Cells were damaged at the beginning of the simulation. The reason for this is that many of the Cells in the simulation were Non-Representative Cells, whose consumed power (as Section 4.4 describes above) was not a function of their own damage, but a function of their Representative Cells' damage. The implication is that they did not need to be repaired because repairing them would not have affected their output. Due to the very small amount of capacity we associated with these Non-Representative Cells it was also rare for them to be chosen by the model for repair.

Fig. 5.3 shows a plot where each dot represents a Cell; its vertical position represents its damage and its horizontal position represents the point in time at which it was repaired. This figure also shows the global damage threshold for these simulations. This plot illustrates that every Cell repaired in this simulation was damaged to a level greater than the global damage threshold. The randomness of this figure also illustrates that the repair sequences in Approach A and Approach B had no correlation to the amount of damage a Cell had exhibited at the beginning of the simulation.

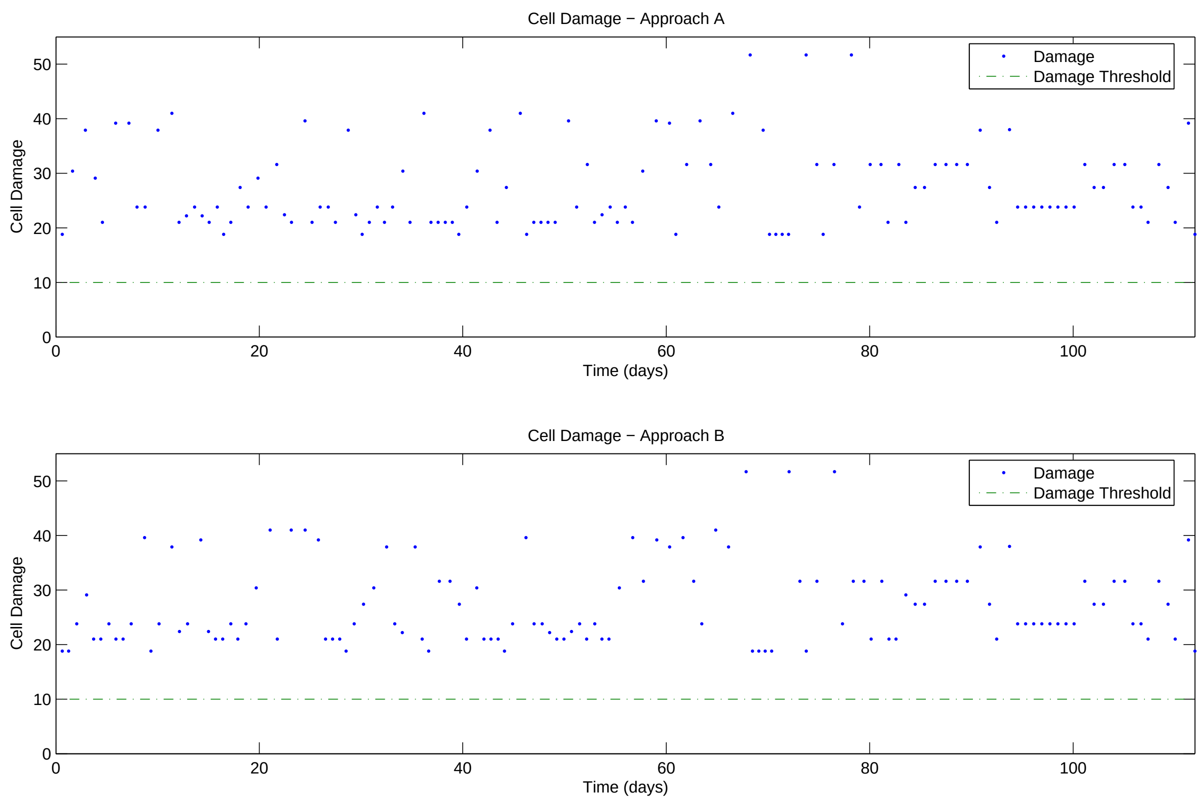

Figure 5.3: Case 1 Simulation Cell Damage and Damage Threshold Plot

The metric variables of this study, α, β and γ, for Approach A and Approach B are presented in Table 5.1 and provide a great deal of information about the simulation. In particular, the total lost capacity-days, γ, shows that Approach B has been more effective than Approach A in recovering the overall system by 34%. This indicates that incorporating data from both infrastructures, instead of only one, improved the recovery. The lost energy, α, and lost IT capacity, β, show that Approach B was less effective than Approach A at repairing the electrical model by 22%, but more effective at repairing the IT model by 51%, respectively. This large improvement in Approach B over Approach A in recovering the IT model explains why there was an improvement in the overall system recovery. Another interesting note is that the lost IT capacity was greater than lost electrical energy by 223% in Approach A but only by 28% in Approach B. This intuitively makes sense because the IT model is reliant on both itself and the electrical model, so when repairs were made using Approach A without regard for the IT model it had an exponential effect on the disparity between the recoveries of the two model.

	α	β	γ
Approach A	1572	5070	6642
Approach B	1918	2469	4387
Difference	-22%	51%	34%

Table 5.1: Case 1 Loss Totals

Fig. 5.4 depicts data from our simulations in three separate graphs, each with two plots. In each graph we have plotted the total lost service for the individual infrastructures and for the combined infrastructure for both Approach A and Approach B versus time. In addition, α, β and γ are listed in the legends of each respective graph. This figure gives us some insight into the results. The plot of P($\hat{t}$) shows that in the first iteration of both simulations there was a drastic decrease in the lost electrical power. This was a result of the main Substation transformers being restored at this simulation step, which allowed energy to flow to its undamaged child Cells. In the IT model, however, there was no change in lost IT capacity at this iteration because all the Level 1 IT Cells were damaged, meaning no data could flow to any Cells in the IT model.

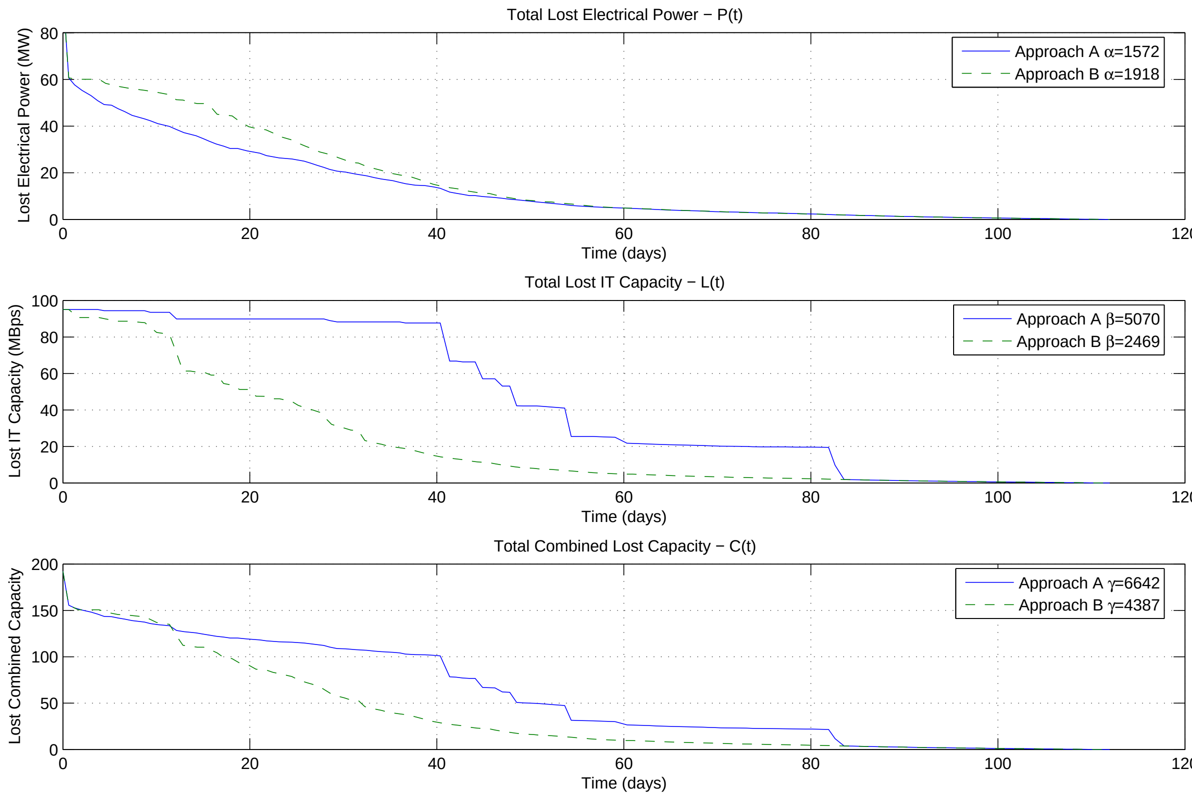

Figure 5.4: Case 1 Simulation Lost Capacity Results Plot

In Approach A, the first of the Level 1 IT Cells—Cell 428—was not repaired until the 5^{th} iteration and it was actually the least important of the three Level 1 Cells; the other two—Cells 493 and 486—were not repaired until the 44^{th} and 68^{th} iterations, respectively. At these points in the simulation there were sharp decreases in $L(\hat{t})$ due to their repair because by this time a number of IT Cells had been repaired but could not receive data due to these crucial Cells being inoperable. This is a very good illustration of how making repairs only based on the needs of a single infrastructure resulted in an inefficient procedure.

By contrast, in Approach B the IT model began to see a reduction in its lost service very quickly, because the two Level 1 IT Cells—Cells 493 and 486—were repaired in the 2^{nd} and 3^{rd} iterations, respectively. In the subsequent iterations the $L(\hat{t})$ transitions were much smoother because as the other IT Cells were repaired, data was allowed to immediately flow to them.

Fig. 5.5 presents plots of the changes in the lost services versus time—the derivatives $\frac{dP}{d\hat{t}}$, $\frac{dL}{d\hat{t}}$, and $\frac{dC}{d\hat{t}}$—providing us a different way of looking at the simulations. As it illustrates, Approach A exhibited number of large peaks in both $\frac{dL}{d\hat{t}}$ and $\frac{dC}{d\hat{t}}$, indicating the restoration of service to many Cells simultaneously. By contrast, the same Approach B plots have considerably flatter profiles, illustrating a more streamline repair procedure.

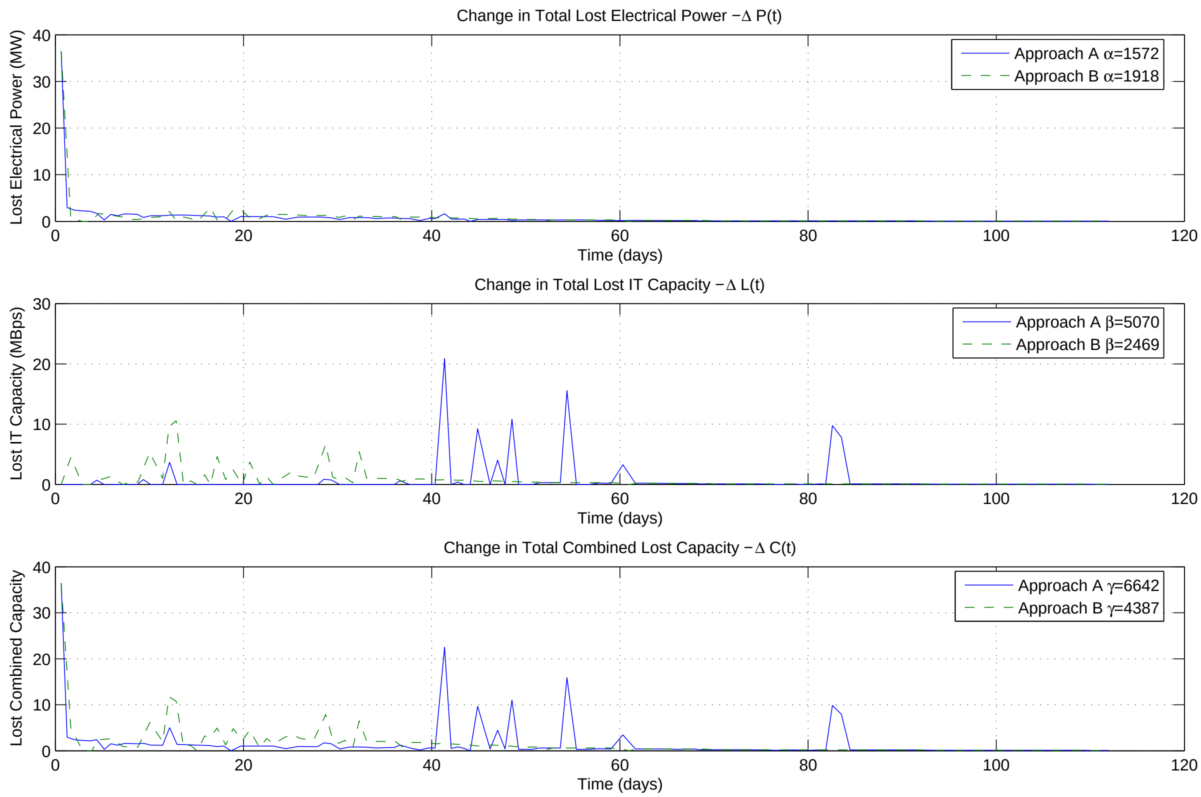

Figure 5.5: Case 1 Simulation Change in Lost Capacity Results Plot

Something interesting, and perhaps surprising, we note in these results is that prior to $\hat{t}= 12$ the lost combined capacity was less for Approach A than for Approach B. This illustrates that during this portion of the simulation, taking only the electrical infrastructure into account created a more efficient repair sequence. While unexpected, this does not de-validate Approach B because its complete result is still an improvement over Approach A. It illustrates that this approach improved the long term recovery by repairing critical Cells in the short term, which did not directly yield large amounts of restored service.

5.3 Case 2

Case 2 assumptions were the same as in the previous case, with the exception of the global damage threshold set to 20. In Fig. 5.2 one can see that this larger damage threshold caused a number of the damaged Cells, which were completely disabled in Case 1, to begin this simulation with their services only partially disabled. We should note that one of these Cells was the main Substation of the electrical infrastructure, meaning it was able to fully transmit power at the onset of the simulation.

The Case 2 simulations of Approach A and Approach B required 122 iterations and 3321 units of damage were repaired in each, which is fewer iterations than were required in Case 1. The reason is that fewer Non-Representative Cells were repaired. Fig. 5.6—similar to Fig. 5.3 from the previous section—shows plots of the Cell damages and their sequence of repair. This figure illustrates how the repair model restricted repair to the Cells whose damage was less than the damage threshold before repairing the Cells whose damage was greater than the damage threshold; this required 111 days. This contrasts the results of Case 1 where because all damaged Cells were damaged above the global damage threshold, the amount of damage to a Cell was not correlated to its place in the repair sequence.

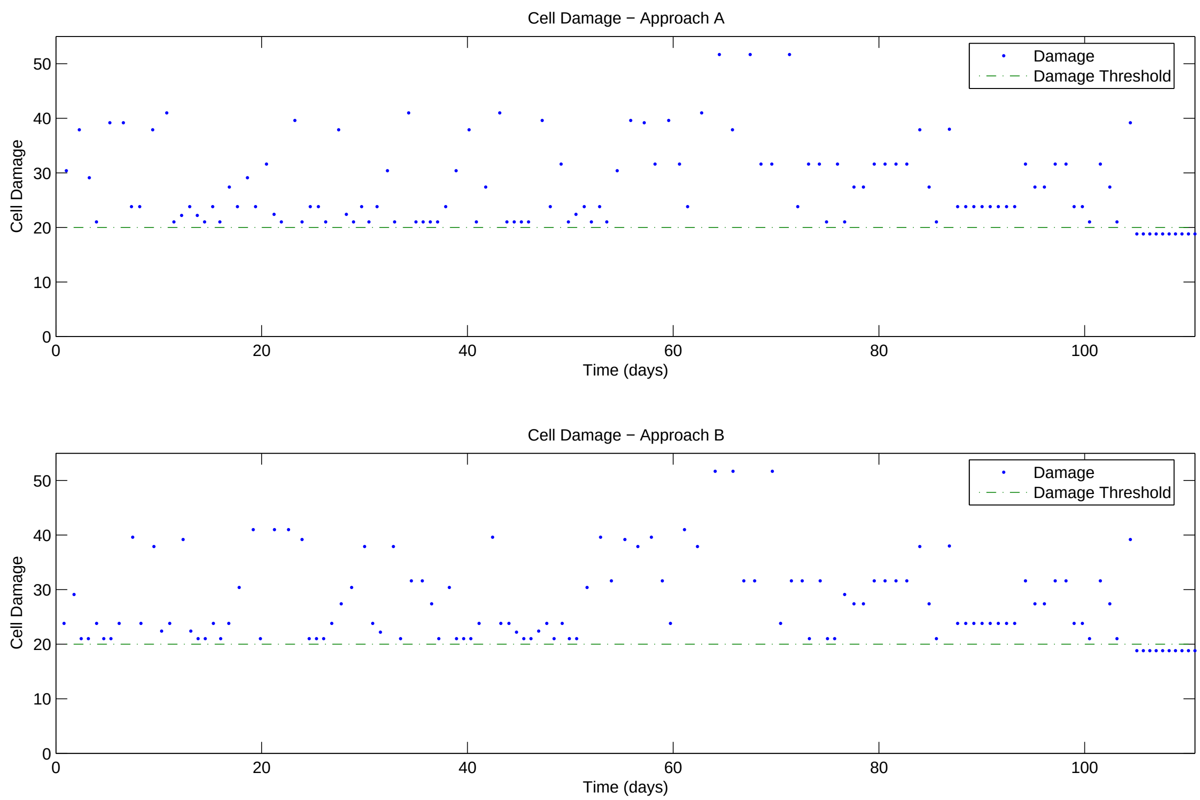

Figure 5.6: Case 2 Simulation Cell Damage and Damage Threshold Plot

	α	β	γ
Approach A	1355	4631	5987
Approach B	1652	2250	3901
Difference	-22%	51%	35%

Table 5.2: Case 2 Loss Totals

Table 5.2 again depicts the results from the Case 2 simulations and indicates a very similar overall result with a 35% decrease in combined lost capacity-days, a 22% increase in lost electrical energy and a 51% decrease in lost IT capacity. This similarity between the results for these cases is somewhat surprising, because the initial conditions were so different: In Case 1 the absolute values of α, β and γ were significantly higher than in Case 2, and in Case 1 the main substation was one of the Cells which initially had no service, whereas in Case 2 it had full service. This can be explained by the fact that in Case 2 only ten Cells had less damage than the damage threshold, and in Case 1 the main Substation was repaired in the first iteration of both approaches minimizing its effect on the results.

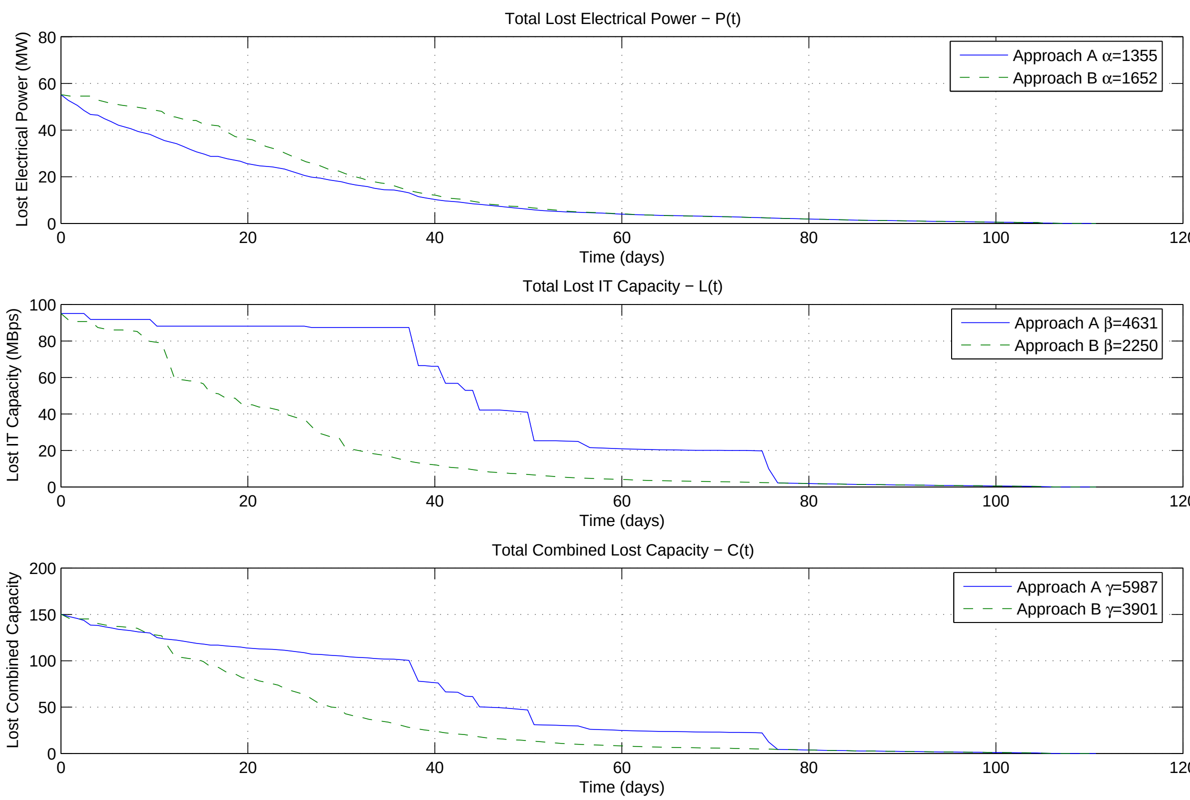

Figure 5.7: Case 2 Simulation Lost Capacity Results Plot

The plots in Fig. 5.7 again show lost electrical power, lost IT capacity, and lost combined capacity versus time. These plots have very similar shapes to the same set of plots from the previous case in Fig. 5.4. The main difference here is that the IT infrastructure was repaired more expeditiously, in both approaches, due to the fact that some key electrical Cells, including the main Substation, did not have to be repaired. This is very evident from the fact that the sharp drop in lost electrical power seen in the first iteration of the plot for Case 1 did not appear here. We can also see this by comparing $\frac{dP}{d\hat{t}}$ for this case, shown in Fig. 5.8, to the same variable in the previous case. The large spike in the Case 1 plot of $\frac{dP}{d\hat{t}}$, caused by the repair of the main Substation, did not exist in Case 2.

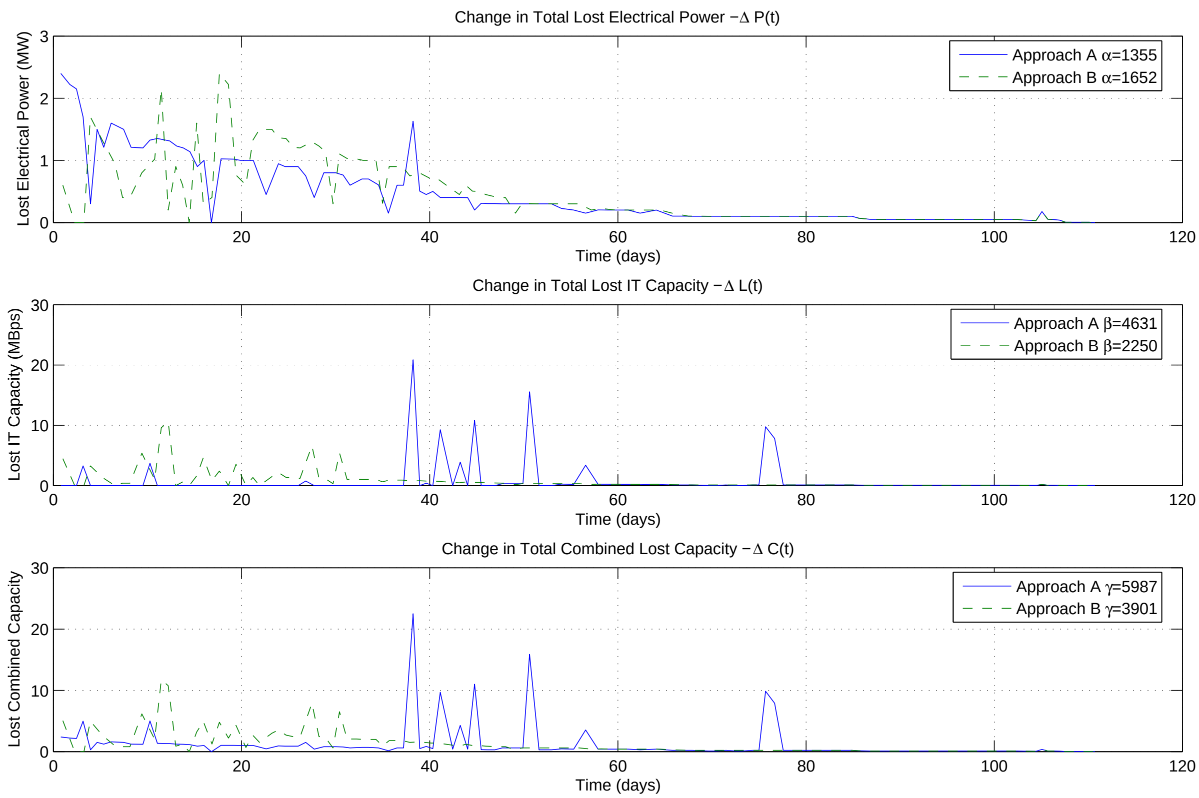

Figure 5.8: Case 2 Simulation Change in Lost Capacity Results Plot

Observing Figs. 5.6, 5.7 and 5.8, we also notice that after $\hat{t}$=77 days, the repair sequence in Approach A appears to be identical to the repair sequence in Approach B. The numeric simulation results, which can be found in [33], verify that this is true. The reason for this phenomenon is that no Cells' power or IT service were being restricted, thus there were no longer any interdependencies restricting service to any part of either model. At this point in the simulation, the total self lost service for every Cell in Approach B was simply double the output of the same Cell in Approach A causing their repair sequences to match each other in this domain of the simulation. This is observed to have also happened in Case 1 at $\hat{t} = 85$.

5.4 Case 3

Case 3 assumptions were the same as in the previous cases, with the exception of the global damage threshold, was set to 30. Fig. 5.2 illustrates that this larger damage threshold caused a significant percentage of the damaged Cells to begin the simulation with their services partially available, which would have affected the simulation results. In addition, one of the Cells from Level 1 of the IT hierarchy—Cell 428—was granted partial service by the increase in the damage threshold.

In this case, the simulations of Approach A and Approach B each required 130 iterations and simulated the repair of 3645 units of damage. A higher number of Cells were repaired in this case than either of the previous cases, which was again due to their differences in the number of Non-Representative Cell repairs made.

It would seem reasonable to hypothesize that the trend in the number of Non-Representative Cells repaired would be correlated to the damage threshold. This, however, was not the case because Non-Representative Cell repairs were lowest in Case 2 and highest in Case 3. The reason for this apparent randomness is that the simulator performed repairs in two stages. Stage 1 occurred when Cells existed with downstream combined lost service greater than zero and damage greater than the damage threshold. During this stage, Cells were repaired according highest downstream combined lost capacity, C_{dslc}. When all of these were repaired, Stage 2 began and Cells were repaired based on their cell combined lost capacity, C_{clc}. In each of the cases, the set of Cells repaired in Stage 1 was determined by the damage threshold, which was a function of the case. Subsequently, the set of Cells repaired in Stage 2 was both a function of damage threshold and the set of damaged Cells that remained from Stage 1. This means the effect of changing the damage threshold on the number of Non-Representative Cell repairs was two-fold and thus quite non-linear. Fig. 5.9, which contains plots of the damage to Cells in their order of repair, illustrates these repair stages; it shows that in this case Stage 2 began at $\hat{t}$=63 days, whereas Fig. 5.6 shows that in Case 2 it began at $\hat{t}$=104 days and Fig. 5.3 shows that in Case 1 there was no second stage of repair.

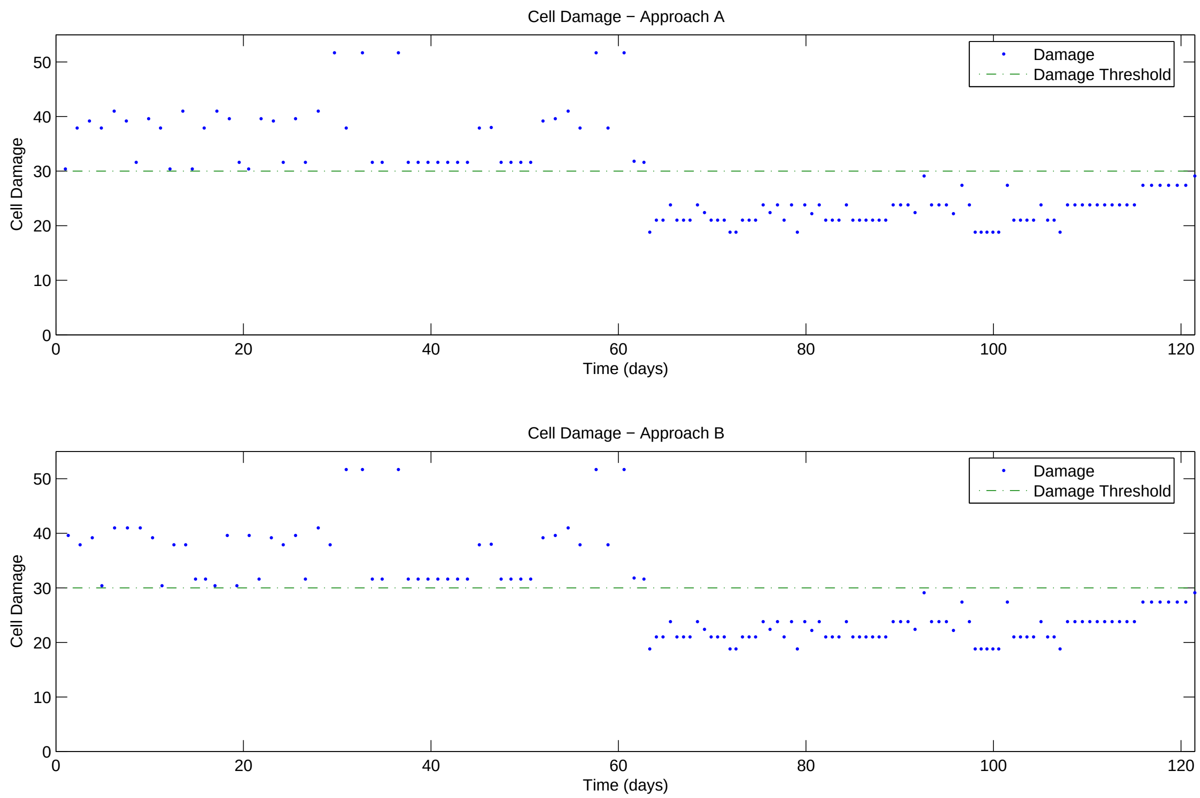

Figure 5.9: Case 3 Simulation Cell Damage and Damage Threshold Plot

	α	β	γ
Approach A	1082	2041	3123
Approach B	1093	1303	2395
Difference	-1%	36%	23%

Table 5.3: Case 3 Loss Totals

Table 5.3 shows the numerical results of this case and indicates that the difference between Approach A and Approach B was significantly lessened here as compared to Cases 1 and 2. In Case 3, the difference in γ was only 23%, whereas in Cases 1 and 2 it was 35% and 34%, respectively. The reason for this is related to the noted phenomena where at a certain point in time the repair sequences taken by the two repair approaches became identical. We see that this occurred very early in this simulation, at $\hat{t}$=31 days, which means that the window where Approach B had an advantage over Approach A in improving the overall repair procedure spanned only a small domain of the simulation. Fig. 5.10, which contains plots of P($\hat{t}$), L($\hat{t}$) and C($\hat{t}$), reveals this effect through the fact that the plots of the two approaches overlap after $\hat{t}$=31 days.

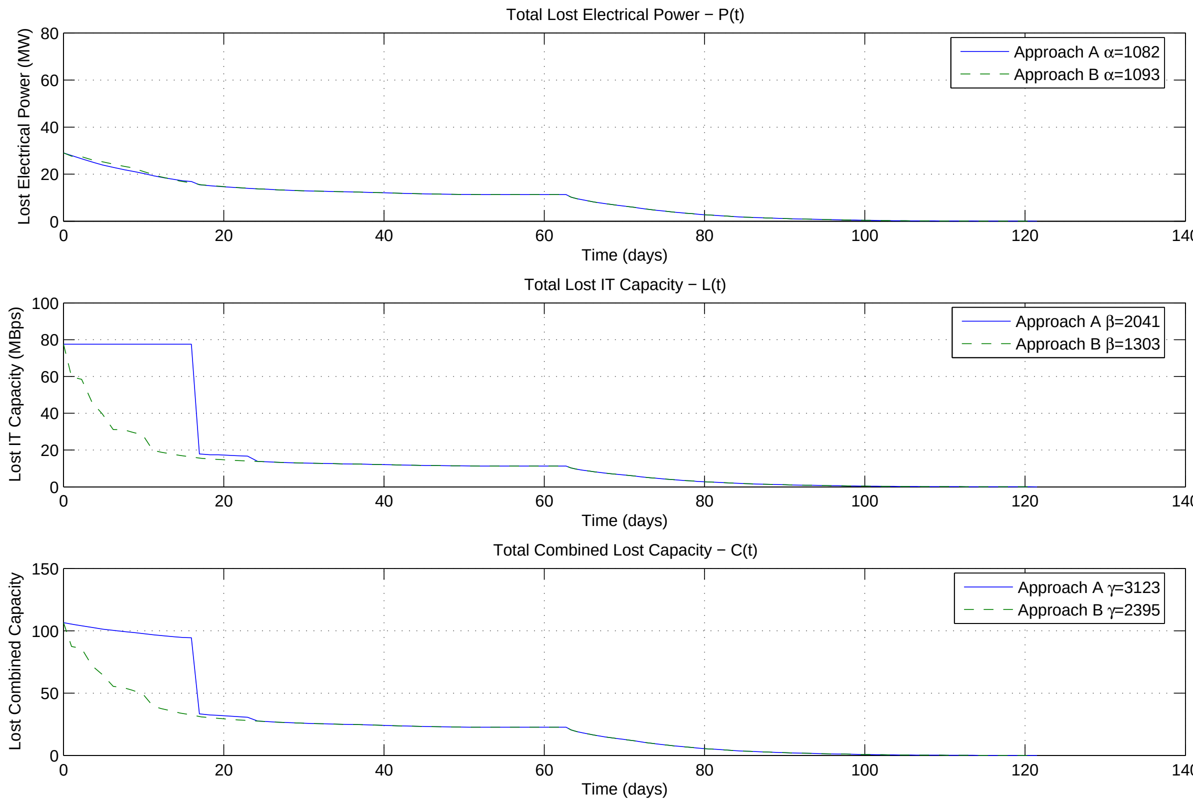

Figure 5.10: Case 3 Simulation Lost Capacity Results Plot

In further analyzing Fig. 5.10, another phenomenon is observed in the plot of L($\hat{t}$) for Approach A: Despite two of the Cells from Level 1 of the IT Hierarchy having been repaired from an inoperable level of damage, there was only one sharp decrease in L($\hat{t}$). This is because of the redundancy in the IT model; two of the three Level 1 IT Cells was enough to serve almost the entire network. So after the first Level 1 Cell repair was made the impact of the second Level 1 Cell repair was quite small. Another interesting phenomenon is the sudden change in the slope of P($\hat{t}$) in both simulations at $\hat{t}$= 63 days. Its presence indicates that the repair criteria used in Stage 1 was not optimal. This is because many of the Cells repaired in this stage may have had less lost capacity than others, despite having higher damage.

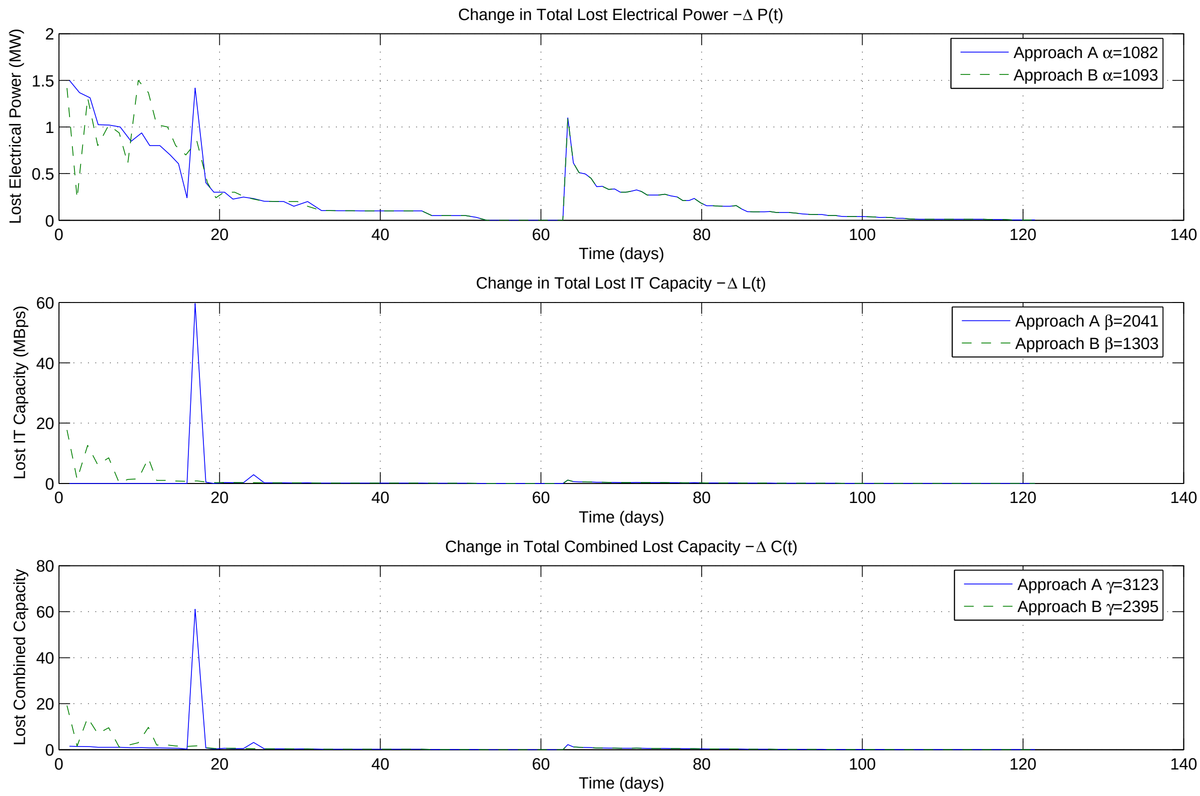

Figure 5.11: Case 3 Simulation Change in Lost Capacity Results Plot

The plots in Fig. 5.11, which again show the derivatives of P($\hat{t}$), L($\hat{t}$) and C($\hat{t}$), show that $\frac{dL}{d\hat{t}}$ and $\frac{dC}{d\hat{t}}$ each contain a spike at $\hat{t}$=17 days, where the first Level 1 IT Cell—Cell 493—was repaired and then a much smaller spike at $\hat{t}$=23 days where the next Level 1 Cell—Cell 486—was repaired. This again illustrates that the impact to the IT model of repairing Cell 486 was small. This figure also again illustrates that repair Approach A and Approach B became identical after $\hat{t}$=31 days, by their overlap past this point in time.

5.5 Summary of Case Results

The case studies presented here have demonstrated that a repair procedure, which incorporates information from multiple infrastructures can be more efficient than one using information from a single infrastructure. The conducted simulations have shown that by using additional data and a generic repair criteria, it was possible to improve a repair procedure from the perspective of the overall system.

In the three case studies presented, where all variables except the damage threshold were fixed, the effectiveness of including information from multiple infrastructures in the repair model was observed to decrease as the damaged threshold increased. The percent improvement seen in the combined lost capacity-days for Approach B over Approach A is presented for the three cases in Table 5.4 along with the number of Cells repaired that had damage greater than damage threshold. This table illustrates that the correlation between these variables seems to be very strong.

	Cells Repaired in Stage 1	Percent Improvement in γ
Case 1	123	35%
Case 2	111	34%
Case 3	51	23%

Table 5.4: Results Summary

In addition to these results, the three case studies revealed some of the limitations of the UTIS simulator. One of these was the effect that Non-Representative Cells had on the number of repairs made. We observed that because these Cells had damage and a small amount of capacity assigned to them, some of them were repaired unnecessarily by the repair model. This affected the number of iterations each simulation required in different cases, but did not cause a variance between the two repair approaches.

Something else we note is that at a certain point in each case, the repair procedures became identical. This was seen to be a function of the damage threshold because as damage threshold was decreased this effect appeared earlier in the simulations: at $\hat{t}$=85, 77 and 63 days for Cases 1, 2 and 3, respectively. This effect was particularly notable in Case 3 where it contributed significantly to the reduced efficiency of repair Approach B.

The most visible feature of the simulations, however, was the fact that Approach B was able to target Cells critical to the overall system for repair, while Approach A was not. This was consistent throughout the three cases and was the reason Approach B was able to recover the system more expeditiously than Approach A. This result helps to confirm the hypothesis of UBC I2Sim research: Infrastructure simulations can target critical infrastructure components for repair to reduce recovery time following of an emergency. Having confirmed this concludes our research into the interdependencies of electrical distribution system through simulations.

Chapter 6

Bulk System Model

The bulk power system is defined in [26] as an amalgamation of the generation and subtransmission systems. In this chapter we explore the feasibility of extending the concepts developed for the restoration of distribution systems to bulk systems. In aiming at this, we first review some of the typical differences between bulk system and distribution systems [26]:

1. Bulk system have fewer components than distribution systems, which are at greater distances from each other, meaning there are also have fewer Channels which are longer.
2. The technology used to operate Cells and Channels in the bulk system is more sophisticated than in the distribution system potentially making it more reliant on other infrastructure.
3. Physically, Cells and Channels in bulk system are more complex than those in distribution systems, possibly making them more susceptible to damage.
4. Bulk systems are typically connected in meshed networks, while distribution systems are often connected in radial networks. This may cause the interdependencies within bulk systems to be more complex than in distribution system.

These differences create challenges in operating and maintaining bulk systems that are not present in distribution systems. One such challenge is that bulk systems are not trivial to energize from a blackout condition (known as a 'Blackstart'). In contrast to distribution systems, there are restrictions on the sequence in which elements in the bulk system can be energized, and the consequence of not abiding to these restrictions is possible damage to infrastructure or simply an unstable procedure [25].

One of the implications of these restrictions is that the level of importance of bulk system elements during normal operation may be elevated during blackstart situations. In addition, blackstart situations are rare and can be adversely affected by other infrastructures, which may also be suffering an outage. This is where the value of simulator, similar to that developed and implemented in the previous chapters for distribution system restoration, lays for bulk systems.

Critical infrastructure points created by restrictions within the bulk infrastructure and the infrastructures it relies on (and which rely on it) can emerge during restoration. A simulator designed to model system restoration can be used to identify these points. Once identified, their robustness can then be studied and invested in appropriately.

In this chapter, we extend the simulation concepts developed in the previous chapter to aid in identifying critical points in a bulk electrical system following an outage. We selected a test system, the British Columbia Transmission Corporation (BCTC) bulk system, as an example and present our model in the following section. Following this, we discuss the limitations that bulk systems may face during Blackstart. We then develop a simulation method for this situation and present our analysis and the simulation results.

6.1 BCTC Electrical System Model

The BCTC bulk system model contains four major generating units producing a total of ∼8000 MW, three major load centres, each consuming approximately 2500 MW, 1700 MW and 1400 MW, and some additional small load centers, each consuming 600 MW or less. The total assumed load is 10.092 GW, and small generators are assumed to provide exclusively reactive power support. Additional power is assumed to be provided from other entities, which are represented by negative loads. The transmission voltage is 500 kV on all lines and 13.8 kV at all generators. The geographic dimensions of the system are approximately 1500 km north-to-south and 800 km east-to-west. A one-line representation of the BCTC system is shown below in Fig. 6.1, and a drawing of the PowerWorld model is shown in Fig. 6.2.

Figure of the British Columbia Transmission Corporation Bulk Power System. Removed for copyright purposes.

Figure 6.1: BCTC Bulk System Oneline Diagram [34]

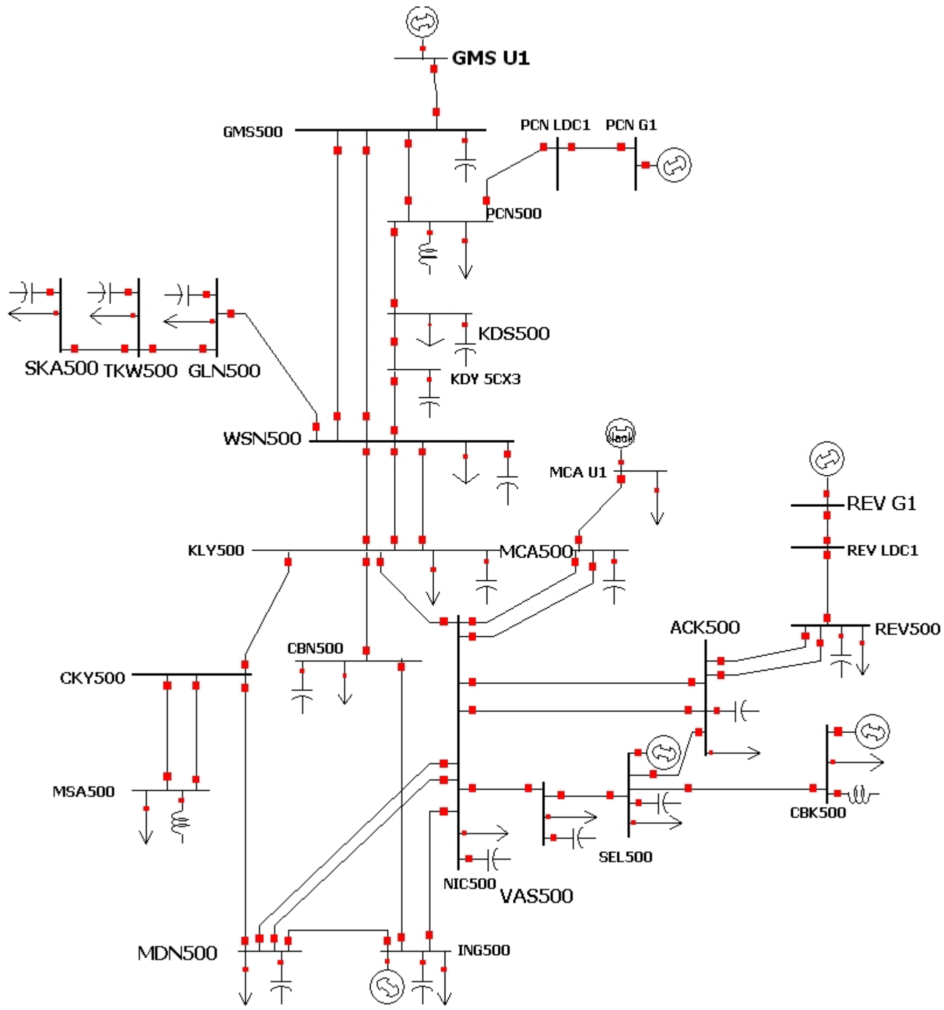

Figure 6.2: BCTC Bulk System PowerWorld Model

In the model shown in Fig. 6.2 for the BCTC bulk system, each bus represents a 500 kV transmission or generation substation.

6.2 Restoration Restrictions

To develop a plausible startup scenario for this system, the technical obstacles of this process must first be understood. Some of these are presented here:

Steady State Transmission Line Over Voltage: An effect caused by the capacitive charging of lightly loaded transmission lines. This effect must by remedied by either increasing real or reactive loading on the line, switching in shorter line segments or by decreasing the generator voltage [35], [36].

Transient transmission line over voltages: Lines will experience momentary over-voltages due to the traveling waves induced in the lines during switching. It must be assured that line voltages are below 1.2 pu before switching occurs, or lines could be damaged [36].

Harmonic over-voltages: Because power transformers normally operate just below their cores' saturation region, transient over-voltages in transformers can cause large harmonics to be induced. If these harmonics coincide with the natural frequency of the system, very large over-voltages can occur [35].

Frequency stability: If load is brought onto the system faster than generation is able to govern the system's frequency, an under-frequency condition can occur. This is preventable by increasing the mechanical inertia of the system by adding spinning reserves (i.e. synchronous condensers), which damp the frequency change of the system when large loads are brought online [23].

Cold load pickup: Loads could exceed their normal operating levels when common devices such as furnaces, which normally run sporadically and have been off for a period of time, come online simultaneously during restoration [37], [38].

Because of the geographic size of the test system and since the majority of its load is in the south-west while most of its generation is in the north and the east, the BCTC bulk system contains long transmission lines to bridge these regions. Before the major loads in the south-west are brought online, the lines are lightly loaded and are susceptible to steady state over-voltage. Furthermore, the fact that majority of the load is in only three places introduces another challenge: building a system with enough inertia to allow the loads to be switched online without destabilizing the system frequency.

6.3 Restoration Procedure

In extending the approach developed in the previous chapters, our first step was to develop a restoration sequence and evaluate where during this sequence another infrastructure is necessary. A restoration procedure, with consideration to the restrictions discussed in the previous section, is presented in Tables 6.1-6.3. This procedure contains five basic restoration actions: (1) energizing loads, (2) starting and connecting generators, (3) energizing transmission lines, (4) energizing shunt reactors and capacitors, and (5) adjusting generator setpoints.

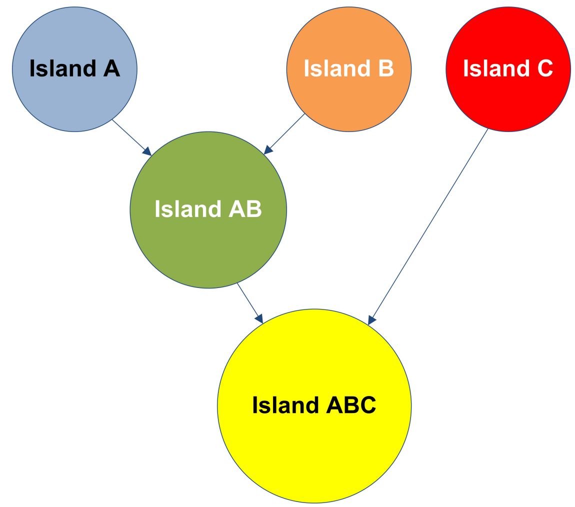

Figure 6.3: Bulk System Restoration Scheme

Step	Island A			Step	Island B			Step	Island C		
	Type	To	From		Type	To	From		Type	To	From
A1	Gen		GMSU1	B1	Gen		PCN G1	C1	Gen		MCAU1
A2	Line	GMS500	GMSU1	B2	Line	PCN G1	PCN LDC1	C2	Load		MCAU1
A3	Load		GMS500					C3	Line	MCA500	MCAU1
A4	Line	GMS500	WSN500					C4	Line	MCA500	NIC500
A5	Line	GMS500	WSN500					C5	Line	MCA500	NIC500
A6	Load		WSN500					C6	Load		NIC500
A7	Shunt		GMS500					C7	Line	ACK500	NIC500
A8	Line	GMS500	PCN500					C8	Line	REV500	ACK500
A9	Shunt		PCN500					C9	Line	REV500	ACK500
A10	Line	PCN500	KDS500					C10	Load		ACK500
A11	Load		KDS500					C11	Load		REV500

Table 6.1: Restoration Sequence Steps 1-11

As Tables 6.1–6.3 and Fig. 6.3 show, our system restoration begins with three separate islands (Island A, Island B and Island C), which are brought online simultaneously and eventually connected together to form a single system.

Step	Combined Island AB			Step	Island C		
	Type	To	From		Type	To	From
AB12	Line	PCN500	PCN LDC1	C12	Line	REV500	REV LDC1
AB13	Gen Adj.	200MW	PCN G1	C13	Shunt		Rev500
AB14	Line	KDS500	KDY 5CX3	C14	Line	REV G1	REV LDC1
AB15	Line	WSN500	KDY 5CX3	C15	Gen Adf.	350MW	REV
AB16	Line	WSN500	GLN500	C16	Gen		REV
AB17	Load		GLN500	C17	Line	ACK500	SEL500
AB18	Line	TKW500	GLN500	C18	Gen		SEL500
AB19	Load		TKW500	C19	Line	VAS500	SEL500
AB20	Line	SKA500	TKW500	C20	Line	NIC500	VAS500
AB21	Load		SKA500	C21	Load		VAS500
AB22	Line	WSN500	KLY500	C22	Gen Adf.	500MW	REV
AB23	Gen Adj.	350MW	PCNU1	C23	Line	ING500	NIC500
AB24	Load		KLY500	C24	Line	ING500	CBN500
AB25	Shunt		WSN500	C25	Load		CBN500
AB26	Line	WSN500	KLY500	C26	Line	CBK500	SEL500
AB27	Line	WSN500	KLY500	C27	Gen		CBK
				C28	Shunt		CBK500

Table 6.2: Restoration Sequence Steps 12-35

In addition to developing this procedure, it was necessary to model the potential impact another infrastructure could have on it. In a modern power system, actions are carried out remotely from one or more control centers through a Supervisory Control and Data Acquisition (SCADA) System. Similar actions can also be carried out manually at the local sites. An infrastructure which is necessary for this SCADA technology to operate is the communications infrastructure. With communications established, restoration actions can still be carried out relatively quickly if all other parts of the system are operating normally. Without communications, restoration actions can still be executed manually, but require more time. Table 6.4 lists some plausible timeframes for the actions carried out in the sequence presented above, assuming a SCADA system is both operational and non-operational.

Step	Combined Island 1-2-3		
	Type	To	From
ABC29	Line	NIC500	KLY500
ABC30	Shunt		ING500
ABC31	Line	CBN500	KLY500
ABC32	Shunt		MCA500
ABC33	Line	CKY500	KLY500
ABC34	Gen Adf.	900MW	REV
ABC35	Gen Adf.	680MW	PCN G1
ABC36	Line	MDN500	NIC500
ABC37	Line	MDN500	NIC500
ABC38	Line	ACK500	NIC500
ABC39	Shunt		ACK500
ABC40	Line	CKY500	MDN500
ABC41	Line	MDN500	ING500
ABC42	Gen		ING
ABC43	Load		MDN500
ABC44	Shunt		MDN500
ABC45	Gen Adf.	2028.MW	REV
ABC46	Gen Adf.	2800.MW	GMS
ABC47	Shunt		CBN500
ABC48	Shunt		KLY500
ABC49	Load		ING500
ABC50	Shunt		NIC500
ABC51	Line	CKY500	MSA500
ABC52	Line	CKY500	MSA500
ABC53	Shunt		MSA500
ABC54	Load		MSA500
ABC55	Shunt		CKY500
ABC56	Shunt		VAS500
ABC57	Shunt		SKA500
ABC58	Shunt		TKW500
ABC59	Shunt		GLN500
ABC60	Shunt		KDY 5CX3
ABC61	Shunt		KDS500
ABC62	Shunt		SEL500
ABC63	Load		SEL500

Table 6.3: Restoration Sequence Steps 29-63

Note that the times shown in Table 6.4 do not reflect specific figures of the BCTC system or its operating procedures.

Action	Time	
	Remote	Local
Energize Load	5 m	2 h
Energize Shunt	5 m	2 h
Energize Generator	30 m	2 h
Energize Line	10 m	2 h
Adjust Generator Setpoint	10 m	30 m

Table 6.4: Restoration Action Times

Using the information in Table 6.4, the restoration procedure described in Tables 6.1-6.3 can be augmented to simulate elements being restored without supervisory control. Specifically, simulations can be run which assume that communications are lost at a single substation in the system to determine which location has the greatest impact. To illustrate this idea, such simulations were run for the BCTC sample system, and are described in the following section.

6.4 Simulation Method

For the system configuration described in Section 6.3 and the energization procedure presented in Tables 6.1-6.3, a benchmark simulation was run. In this simulation we assumed that the SCADA was available to all elements. Each step of the restoration procedure was carried out, and its time was recorded. This simulation reflects a case where a blackout has occurred but no damaged was incurred by the bulk system's communications.

To measure the results of this procedure, lost energy as defined in Section 4.8 was used. This was defined as

$$\alpha \triangleq \int_0^{T_{sim}} P(t)dt \tag{6.1}$$

where P(t) is the lost power of the system at time T_{sim}. Table 6.5 contains the results of this 'base simulation', including both the time of each restoration step and $\alpha(t)$ for each step in the procedure.

Time (m)	Steps			Load	Time	Steps		Load	Time	Steps	Load
10	A1	B1	C1	886	185	AB9	C17	2662	375	ABC6	2921
40	A2	B2	C2	886	195	AB10		2662	385	ABC7	2921
45	A3		C3	887	200	AB11		2662	395	ABC8	2921
55	A4		C4	887	205	AB12		2662	405	ABC9	2921
65	A5		C5	887	210	AB13		2662	415	ABC10	2921
70	A6		C6	1146	215		C18	2662	420	ABC11	2921
75	A7			1146	220	AB14		2662	430	ABC12	2921
80	A8		C7	1146	225		C19	2921	440	ABC13	4630
85	A9		C8	1660	230	AB15		2921	470	ABC14	4630
90	A10			1660	235	AB16	C20	2921	475	ABC15	4630
95			C9	1660	240		C21	2921	480	ABC16	4630
100	A11			1660	245	AB17		2921	490	ABC17	4630
105	A12		C10	1660	250		C22	2921	500	ABC18	4630
110	A12		C11	1662	255	AB18		2921	505	ABC19	7189
120			C12	2452	260		C23	2921	510	ABC20	7189
125			C13	2452	270		C24	2921	515	ABC21	7189
130				2452	275		C25	2921	520	ABC22	7189
135			C14	2452	285		C26	2921	530	ABC23	7189
140				2452	315		C27	2921	540	ABC24	8589
145			C15	2452	320		C28	2921	545	ABC25	8589
150				2452	325		C29	2921	550	ABC26	8589
160				2452	335		ABC1	2921	555	ABC27	8589
165				2577	340		ABC2	2921	560	ABC28	8589
175			C16	2577	350		ABC3	2921	565	ABC29	8589
180				2577	355		ABC4	2921	570	ABC30	2662
				2662	365		ABC5	2921	575	ABC31	2662
$\alpha(575)$=30,309 MWh											

Table 6.5: Base Procedure

As Table 6.5 shows, the restoration time for this base procedure was 575 minutes and the lost power was 30,309 MWh. This criteria was repeated in 27 additional simulations where in each case we assumed a loss of SCADA communication at a single bus. The data produced by these simulations is shown in Table 6.6.

Bus		Restore	$\alpha(t)$	Increase (%)		Ranking	
Name	Number	Time (m)	(MWh)	Time	$\alpha(t)$	Time	$\alpha(t)$
None	Base	575	30309	0	0		
CKY500	501	1175	87928	104	190	11	4
MSA500	502	1055	90623	83	199	17	2
MDN500	503	1295	72198	125	138	8	7
ING500	1501	1295	73898	125	144	7	6
CBN500	1544	1055	57095	83	88	16	13
SKA500	3502	865	42871	50	41	24	24
TKW500	3503	985	47989	71	58	22	19
GMS U1	4021	745	34623	30	14	26	26
PCN G1	4091	1035	47933	80	58	18	20
GMS500	4501	1225	54304	113	79	9	15
PCN500	4509	985	44504	71	47	21	23
KDS500	4510	985	44504	71	47	20	22
WSN500	4511	1465	66416	155	119	3	10
GLN500	4514	985	47173	71	56	19	21
KDY 5CX3	4710	865	53887	50	78	23	16
PCN LDC1	4791	675	31863	17	5	27	27
REV G1	5041	1295	68779	125	127	6	9
MCA U1	5071	1055	56643	83	87	15	14
MCA500	5501	1055	53224	83	76	14	18
REV500	5504	1175	59519	104	96	10	12
ACK500	5510	1415	70946	146	134	4	8
NIC500	5511	1895	102657	230	239	1	1
KLY500	5512	1465	76537	155	153	2	5
VAS500	5515	1055	65013	83	115	13	11
REV LDC1	5741	815	41993	42	39	25	25
CBK500	6506	1055	53677	83	77	12	17
SEL500	6507	1295	88032	125	190	5	3

Table 6.6: Base Procedure

The simulation results shown in Table 6.6 include the amount of time each restoration required and the lost energy α in each case. In addition, this table shows the increase in both restoration time and lost energy over the benchmark case, and ranks each simulation restoration time and lost energy, i.e. the simulation that took the longest has a time ranking of 1.

To illustrate the correlation between restoration time and lost energy, Fig. 6.4 contains two plots showing total restoration time and lost energy for each simulation. In the first, total time and lost energy are plotted versus the lost time ranking for the bus which lost communications in each respective simulation. In the second, the same variables are plotted versus the lost energy ranking of the bus which lost communications in each respective simulation. These plots illustrate that restoration time decreased with lost energy demonstrating a correlation. However, the plots also show that there are some large inconsistencies in this trend indicating that the correlation is not strong.

We also plotted lost energy versus restoration time for each simulation, as we show in Fig. 6.5. This plot again illustrates that a weak correlation between the variables exists by the fact that the line which is traced within it trends linearly upward. It is clear that the line is not straight, however, indicating again that lost energy and restoration are not well-pronounced functions of one another.

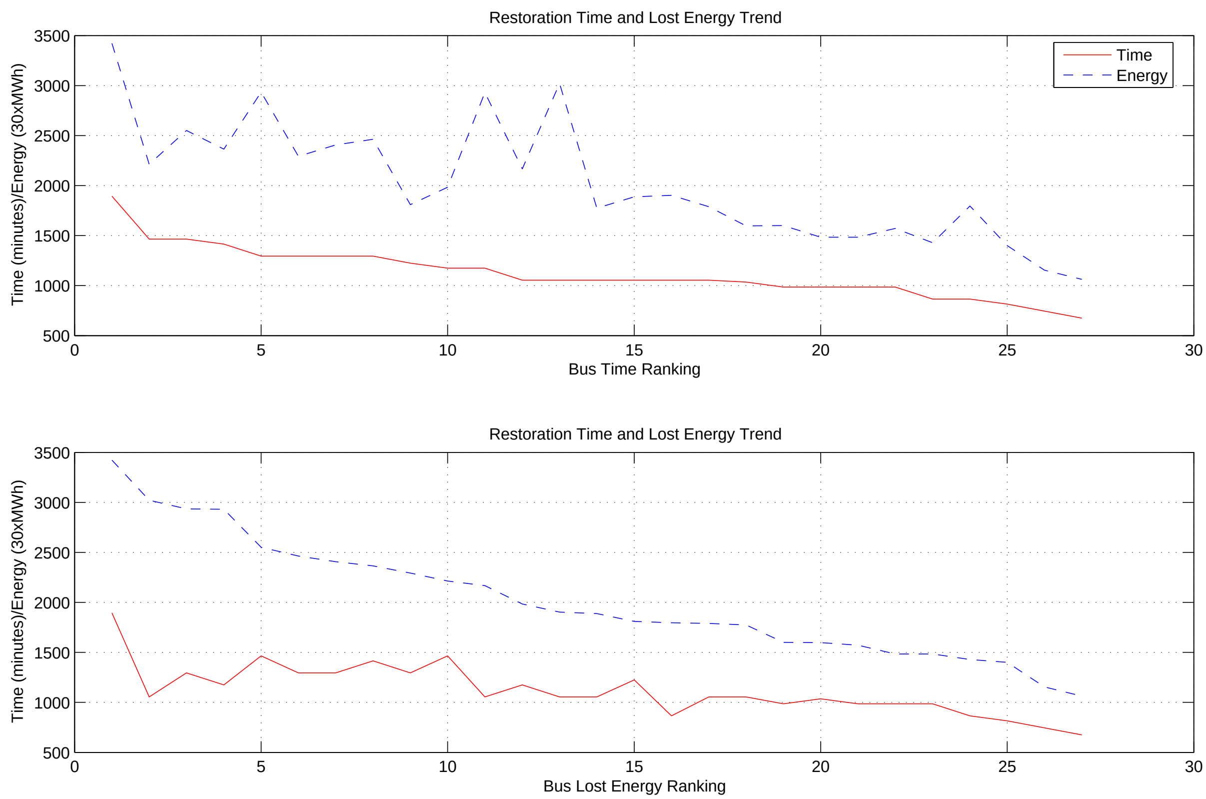

Figure 6.4: Bulk System Restoration Time versus (a) Bus Lost Time and (b) Lost Energy Rank Plots

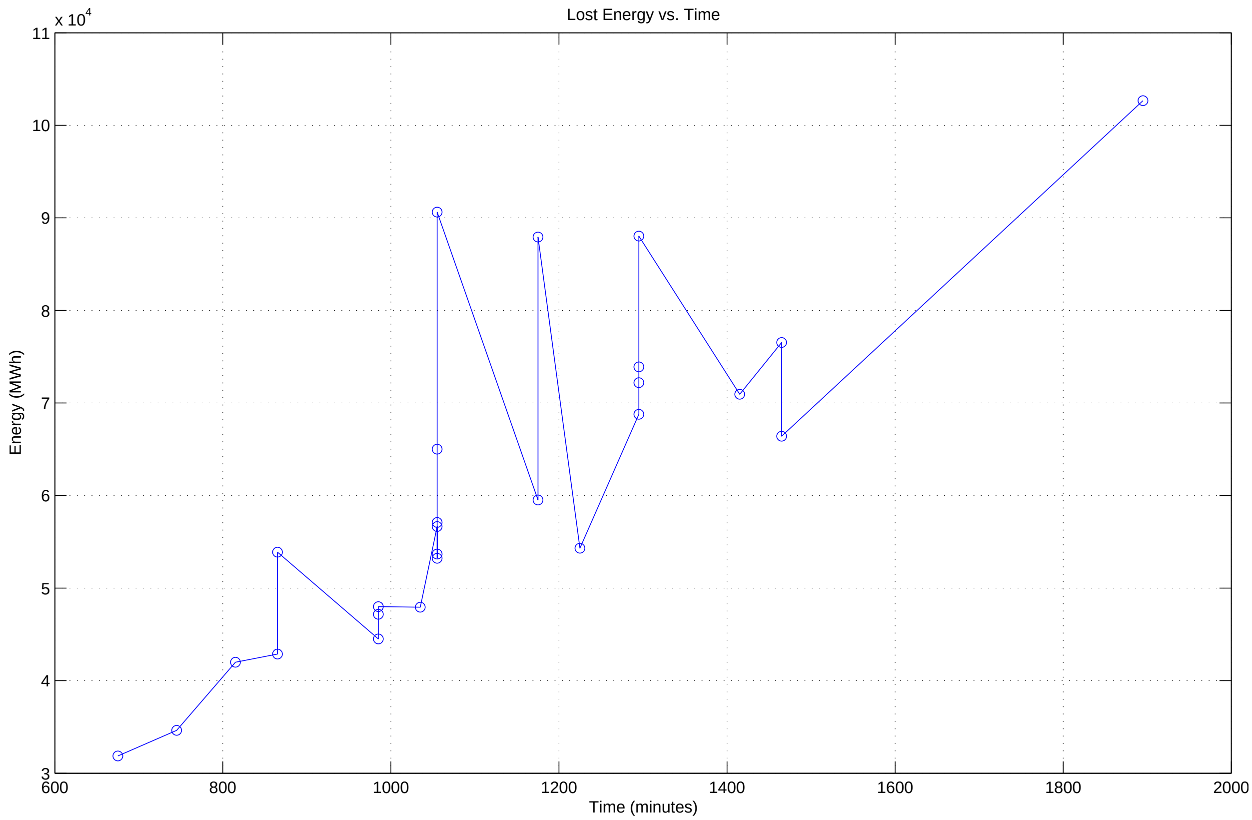

Figure 6.5: Bulk System Lost Energy versus Restoration Time Results Plot

We considered that another possible correlation in these simulation was between restoration time, or lost energy, and the number of component connections at each bus (i.e. line, load, generator or shunt). Table 6.7 shows the number of connections at each bus to illustrate this comparison. Fig. 6.6 shows two plots: The first plot is of lost energy versus number of bus connections, and the second plot is of restoration time versus number of bus connections.

Bus		Restore	$\alpha(t)$	Bus
Name	Number	Time (m)	(MWh)	Connections
None	Base	575	30309	-
PCN LDC1	4791	675	31863	2
REV G1	5041	1295	68779	2
REV LDC1	5741	815	41993	2
SKA500	3502	865	42871	3
GMS U1	4021	745	34623	3
PCN G1	4091	1035	47933	3
KDY 5CX3	4710	865	53887	3
MCA U1	5071	1055	56643	3
MSA500	502	1055	90623	4
CBN500	1544	1055	57095	4
TKW500	3503	985	47989	4
PCN500	4509	985	44504	4
KDS500	4510	985	44504	4
GLN500	4514	985	47173	4
MCA500	5501	1055	53224	4
VAS500	5515	1055	65013	4
CBK500	6506	1055	53677	4
CKY500	501	1175	87928	5
REV500	5504	1175	59519	5
MDN500	503	1295	72198	6
ING500	1501	1295	73898	6
GMS500	4501	1225	54304	6
SEL500	6507	1295	88032	6
ACK500	5510	1415	70946	7
KLY500	5512	1465	76537	8
WSN500	4511	1465	66416	9
NIC500	5511	1895	102657	11

Table 6.7: Table of Simulations Results and Number of Connections

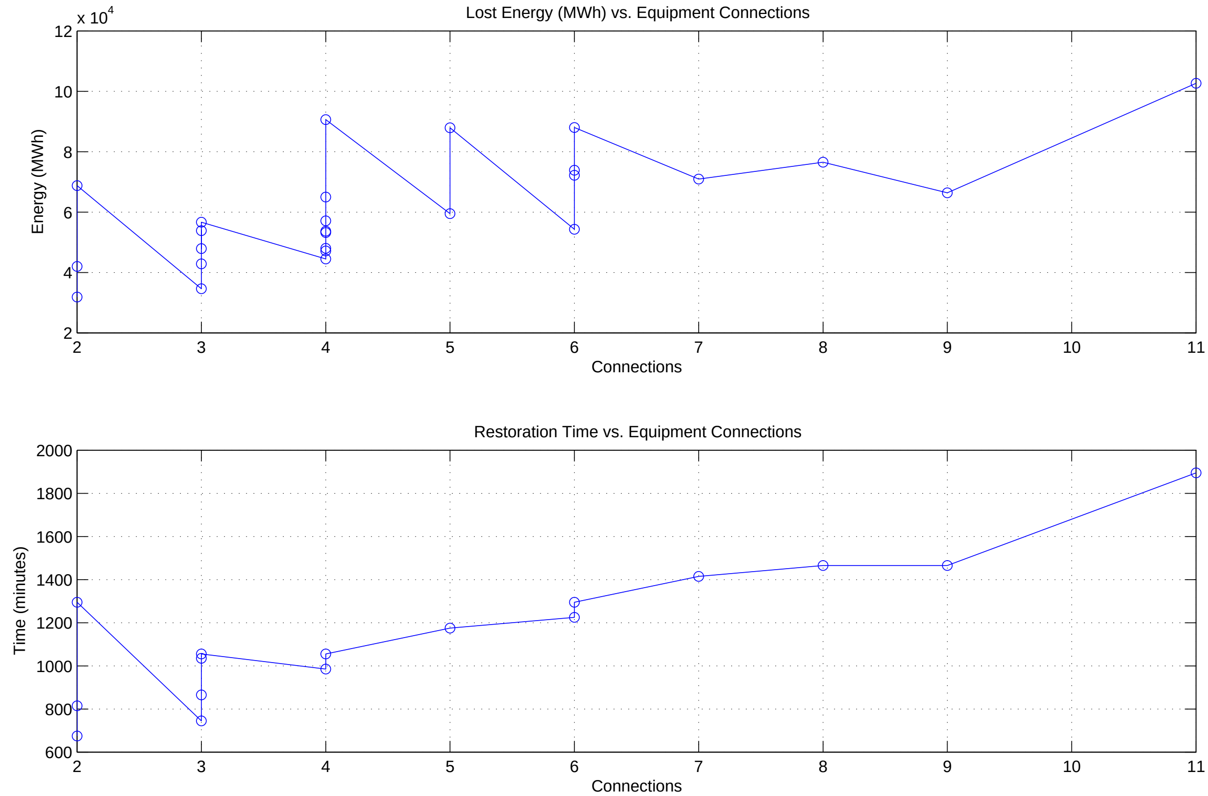

Figure 6.6: Bulk System Lost Energy versus Equipment Connections Plots

Fig. 6.6 illustrates that there is a reasonable correlation between restoration time and number of number bus connections. It also shows that the correlation between lost energy and number of bus connections is weak. This is consistent with our previous finding that the correlation between lost energy and restoration time is weak. While none of our results are absolutely conclusive in illustrating a correlation between the detriment caused by communications outages and another variable, they illustrate of the problem's complexity.

The point of this analysis is to illustrate that determining which elements will have a great impact on the system is not straightforward. The simulation performed here is simple, and clearly does not capture many of the details of restoring a system. However, it illustrates how iterative simulations can be used to determine the criticality of elements during a blackstart situation.

6.5 Application of Criticality Rankings

Having developed information indicating which equipment is most crucial to system restoration, our next step is to determine how to factor this into a maintenance plan. To do this a 'Risk Matrix' was employed, which is shown in its generic form in Figure 6.8.

PROBABILTY				
4	B	C	D	D
3	B	C	C	D
2	A	B	C	C
1	A	A	B	B
	1	2	3	4
	CONSEQUENCE			

Table 6.8: Generic Risk Matrix

This matrix is a tool that is used to determine the risks associated with prospective failures based on their consequence and probability. In this matrix, the 'A' boxes represent the portion of the matrix with the least amount of risk while the 'D' boxes represent the greatest risk.

In this study, probabilities are based on the expected outages of pieces of equipment per year in four ranges on a logarithmic scale. Consequence is assumed to be lost energy in GWh. The denominations assumed for the probability and consequence levels are illustrated in Fig. 6.9

OUTAGES PER YEAR				
y>1	B	C	D	D
.1≤y<1	B	C	C	D
.01≤y<.1	A	B	C	C
y<.01	A	A	B	B
	x<10	10≤x<50	50≤x<100	100≤x
	LOST ENERGY (GWh)			

Table 6.9: Assumed Risk Matrix

We used our simulation results to determine the consequence for each component. The probability, however, had to be determined through other methods. We applied random probabilities to the various assumed outages as shown below in Table 6.10.

Bus		Outage	Lost	Risk
Name	Number	Probability	Energy (MWh)	
PCN G1	4091	0.004	47933	A
GMS500	4501	0.007	54304	B
WSN500	4511	0.006	66416	B
MCA U1	5071	0.007	56643	B
MSA500	502	0.839	90623	C
MDN500	503	0.957	72198	C
ING500	1501	0.967	73898	C
CBN500	1544	0.324	57095	C
SKA500	3502	0.187	42871	C
TKW500	3503	0.542	47989	C
GMS U1	4021	0.301	34623	C
PCN500	4509	0.386	44504	C
KDS500	4510	0.218	44504	C
GLN500	4514	0.126	47173	C
KDY 5CX3	4710	0.496	53887	C
PCN LDC1	4791	0.858	31863	C
REV G1	5041	0.735	68779	C
MCA500	5501	0.406	53224	C
REV500	5504	0.610	59519	C
ACK500	5510	0.025	70946	C
KLY500	5512	0.209	76537	C
VAS500	5515	0.160	65013	C
REV LDC1	5741	0.419	41993	C
CBK500	6506	0.075	53677	C
SEL500	6507	0.026	88032	C
NIC500	5511	0.027	102657	C
CKY500	501	10.020	87928	D

Table 6.10: Communication Outage Probability and Outage Risk

Table 6.10 is sorted according to ascending risk, and illustrates that the majority of outages have a 'C' level of risk. It shows that CKY500 has the highest level of risk a moderate consequence and an extremely high outage probability (>10 per year) while PCN G1 has the lowest level of risk as a result of its low probability of outage combined with its very low outage consequence. Interestingly, the bus with the highest consequence, NIC500, with a potential of 102,657 GWh of lost energy only yielded a risk of 'C', which is because of its moderately low probability of ∼1 outage every three years.

This information is useful in evaluating the amount of resources which should be expended on different parts of the system. While we would expect that most power authorities do similar risk analysis for the normal operation, this differs in that it reviews system restoration, which is a rare but important event.

Chapter 7

Conclusion

7.1 Contribution

The main contributions of this thesis are the methodology for incorporating an electrical power distribution system into the I2Sim simulator using PowerWorld, an the off-the-shelf powerflow modeling tool, and a 395 Cell model of the UBC electrical distribution system with the functionality to model damage and decisions to electrical Cells and Channels. In this research we have demonstrated the usefulness of such a model with damage-assessment in a two-infrastructure system for the purpose of developing an efficient restoration procedure. The UBC Two-Infrastructure Simulator results showed that using information from multiple infrastructures in a repair procedure decreased lost service by $\sim$30%. This research also illustrates that a crucial part of the overall system modeling process is the criteria used to map the effect of one infrastructure to another. This had a palpable effect on the results of our simulations.

The secondary contribution of this work is a methodology for analyzing the outages in communication system components during the blackstart of a bulk power system. To this end, we developed a method for incorporating the consequence of lost communication elements into blackstart energization studies. Using a model of the British Columbia Transmission Corporation bulk system, we simulated this method and its results detailed the increase in restoration time and energy lost when its communications elements were removed from service during the restoration procedure. These results indicate that correlations exists between the number of communications points removed from service and restoration time. We also illustrated a method for incorporating these simulation results into a risk analysis. This analysis allowed us to determine the importance of elements from the communication infrastructure during the re-energization of the bulk system following the simulated blackout.

7.2 Future Research

An important part of future research in this area will be to integrate our UBC electrical distribution model into the I2Sim simulator and perform test simulations with them. Another aspect of research may be to adapt the distribution modeling methodology for use with distributed generation such as emergency diesel generators or battery power supplies. These components can be an important aspect of emergency response and recovery.

To extend the research carried out here for electrical bulk system interdependencies, future work can be done to develop a more specific case study with BCTC, which would use our method to determine the correlation between system recovery and communications, or other, infrastructures.

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