Understanding Marine Transport Resilience to the Cascadia Subduction Zone Earthquake Through Recovery Modelling in South-Coastal British Columbia

by

Anika Bell
B. Eng., University of Victoria, 2017

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Civil Engineering

University of Victoria

Supervisory Committee

Understanding Marine Transport Resilience to the Cascadia Subduction Zone Earthquake Through Recovery Modelling in South-Coastal British Columbia

By

Anika Bell
B. Eng., University of Victoria, 2017

Supervisory Committee

Dr. David Bristow (Department of Civil Engineering)
Supervisor

Dr. Madeleine McPherson (Department of Civil Engineering)
Departmental Member

Abstract

Marine transportation systems provide a vital lifeline to coastal communities. Coastal British Columbia (BC) is dependent on marine transportation for goods distribution, public transportation, and tourism. This marine transportation dependence can challenge the region's capability to withstand large disruptions. This work seeks to gain a detailed understanding of the southern British Columbia marine transportation system, with regards to food and public transportation to Vancouver Island. This includes the public ferry corporation, BC Ferries, and the private cargo trailer transporter, Seaspan Ferries Corporation. To do this, a model is presented that graphically simulates the system response and recovery timelines following disruption. The model is created using the python-based Graph Model for Operational Resilience (GMOR) platform. The model includes the interdependent relationships of systems and provides results with respect to cascade failure. The disruption scenario used in this case-study is the region's projected M9.0 Cascadia subduction zone earthquake.

The step-by-step recovery timeline produced by the model is intended to provide stakeholders with a concrete example of how recovery could unfold for their operations. The results indicate that berth infrastructure recovery is the limiting factor for terminal recovery, in most cases. For the public, these results show that it would be prudent for Nanaimo households to ensure they have five days' worth of food, water, and medicine in their earthquake preparedness supplies, and seven days' worth for Victoria households. This work builds on the existing GMOR platform to provide re-usable dependency templates for marine transportation infrastructure. Future work includes sensitivity analyses of risk treatments and stakeholder review. Finally, this model may be applied to other disruption scenarios or incorporated with other models to cover a larger disruption recovery scope.

Table of Contents

List of Tables

List of Figures

List of Equations

Glossary

BC: British Columbia

CDF: Cumulative distribution function – a statistics distribution function of the probability that a real-valued random variable X will have a value less than or equal to x, when evaluated at x.

Dependency map: a visual network showing the relationship of downstream entities upon which an operation depends.

DS1: Damage State 1: the no damage state within the GMOR marine transportation recovery model. There are also damage states 2-5 (DS2, DS3, DS4, and DS5) for slight, moderate, extensive, and complete damage.

fc_dist: Abbreviation for fragility curve distribution

fc_params: Abbreviation for fragility curve parameters

FFF: Ferry Fuel Facility Classification from Hazus

GHG: Greenhouse Gas

GIS: Geographic information system

GMOR: Graph Model for Operational Resilience – a python-based modelling platform for determining disaster recovery timelines

GSC: Geological Survey of Canada

Hazus: Hazus – MH 2.1 Earthquake Model Technical Manual (Federal Emergency Management Agency, 2013)

The island: Vancouver Island

LNG: Liquified Natural Gas

MCTS: Marine Communications and Traffic Service

$P[Liquefaction_{SC}]$: Probability of liquefaction for a given susceptibility category for calculating ground failure with the Hazus methodology

PGA: Peak ground acceleration – horizontal acceleration experienced by a particle on the ground during an earthquake

PGD: Permanent ground deformation during earthquakes

PGV: Peak ground velocity during earthquakes

P_{ml}: Proportion of the map unit susceptible to liquefaction for calculating ground failure with the Hazus methodology

SFC: Seaspan Ferries Corporation

SIREN: Shipping Resilience: Strategic Planning for Coastal Community Resilience to Marine Transportation Disruption

SQLite: A database management system established in a C library

VHF Radio: Very High Frequency Radio

Acknowledgements

I would like to thank my supervisor, Dr. David Bristow of the University of Victoria Civil Engineering Department, for his guidance and instruction throughout this degree. Dr. Bristow was an invaluable resource to me both during the research and writing of this thesis, but also beforehand, in the stages leading up to this project.

I would like to thank Alison Goshulak for her work on the GMOR modelling platform, particularly the do_apply_failures function. Special thank you to the SIREN project team, and the stakeholders who attended SIREN workshops and made themselves available for meetings and phone calls. I would also like to thank MEOPAR for providing funding and resources for this project.

Finally, thank you to the CISL group, E Hut members, and my family for providing support, encouragement, and entertainment throughout this degree.

1 Introduction

Marine transportation systems provide a vital lifeline to coastal communities around the world. Due to its archipelago geography, coastal British Columbia (BC), Canada, is especially dependent on marine transportation for goods distribution, public transportation, and tourism. The islands and remote coastal communities rely on regular use of marine transportation networks most of all. With 90% of the food for its nearly 800,000 inhabitants coming from off-island sources, Vancouver Island is particularly vulnerable to marine transportation disruption, having only a three-day supply of fresh foods in the stores (Upland Agricultural Consulting, 2016). In addition to coastal communities' importation of food and goods, many of these communities also generate significant portions of their economic revenue from the tourism industry, with BC Ferries transporting over 20 million passengers throughout coastal BC annually (British Columbia Ferry Services Inc. & B.C. Ferry Authority, 2018). The marine transport dependence within BC is essential to withstanding large disruptions.

A large earthquake is one of the disruption threats to marine transportation infrastructure. The coastal region of BC is a seismically active area with a high relative hazard rating and regularly occurring minor earthquakes (magnitude 1-3) (Natural Resources Canada, 2015, 2018). A visual representation of Vancouver Island's shaking probability is shown in Figure 1, below (Seemann, Onur, & Cloutier-Fisher, 2011). This figure indicates that there is a 26-50% chance of structurally damaging shaking in Victoria within 50 years from 2011. The geographical region of this likelihood expands to include both Victoria and Nanaimo when looking out to the year 2111.

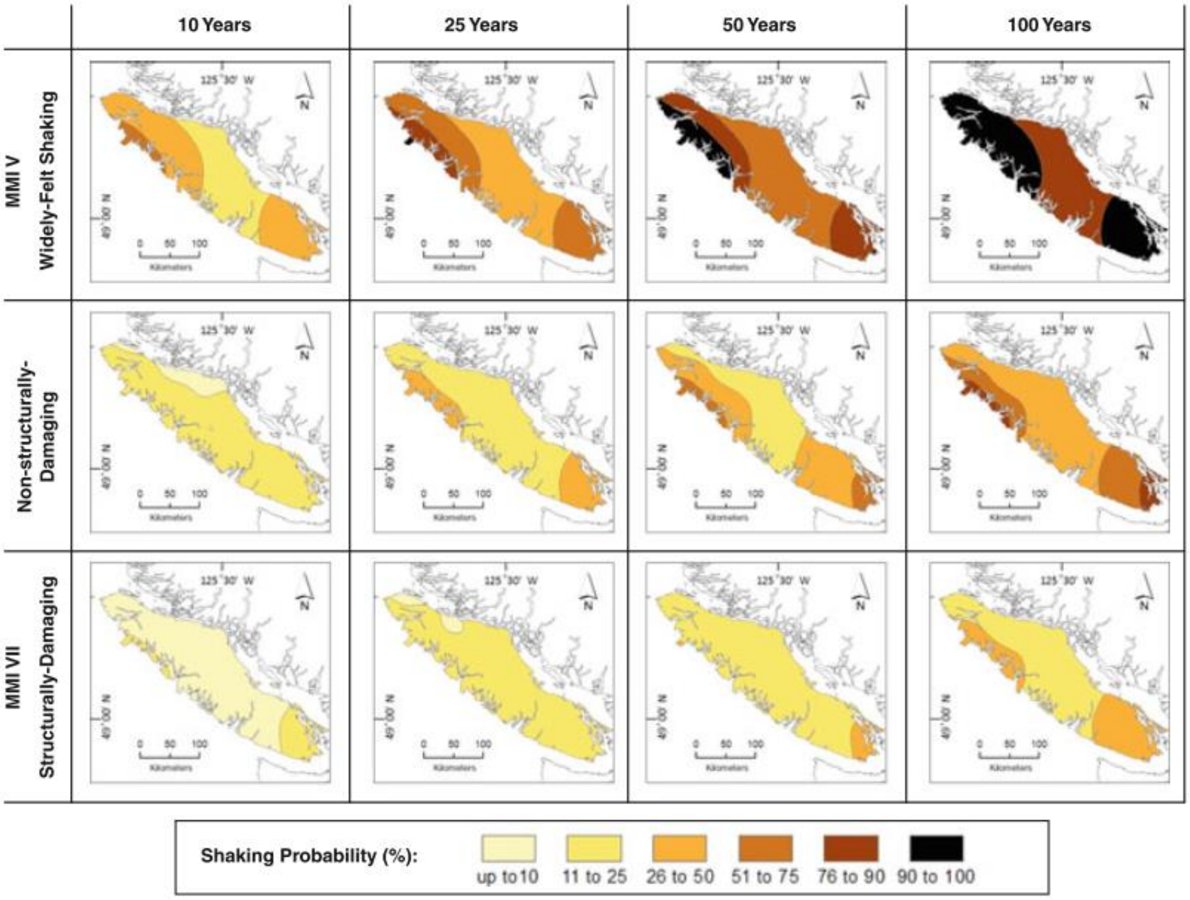


Figure 1: Aggregate (crustal, sub-crustal and subduction earthquake) shaking probability matrix for Vancouver Island. This matrix illustrates the earthquake shaking probabilities at three shaking intensity levels ("Widely Felt", onset of "Non-structurally Damaging" and onset of "structurally Damaging" shaking over four timeframes (10, 25, 50 and 100 years)). Probabilities assume homogeneous firm ground conditions (Seemann et al., 2011)

This work seeks to gain a detailed understanding of the southern British Columbia marine transportation system, with regards to food and public transportation to Vancouver Island. To do this, a model is presented that graphically simulates the system response and recovery timelines following disruption from a potential Cascadia subduction zone earthquake. The model is created using the python-based Graph Model for Operational Resilience (GMOR) platform along with operations and disaster response information collected from stakeholder engagement workshops. The following subsections of this introduction discuss the research questions, research goals, scope, modelling platform, and author's contributions to this research.

1.1 Research Questions

There are three primary research questions that this work aims to address:

1. What are the dependencies of BC Ferries and Seaspan Ferries operations with respect to connecting Vancouver Island to Metro Vancouver?
2. How would a major disaster likely affect marine transportation routes between Vancouver Island and Metro Vancouver?
3. What does the recovery timeline look like for service to Vancouver Island communities?

These questions are discussed in more detail in the three subsequent sections.

1.1.1 What are the dependencies of BC Ferries and Seaspan Ferries operations with respect to connecting Vancouver Island to Metro Vancouver?

Network modelling of BC Ferries and Seaspan Ferries operations is used to gain a detailed understanding of the internal processes and external entities upon which these organizations rely. Acquiring dependency information and producing a visual dependency network (dependency map) of the ferry corporations under normal operations is fundamental to understanding the requirements of these corporations' post-disruption. A complete understanding of the organizations' dependencies enables the model to accept individual damage and restoration functions for each of the nodes. The combined interaction of the damage and restoration functions for each node produce an overall restoration time for the nodes and the marine transport system.

1.1.2 How would a major disaster likely affect marine transportation routes between Vancouver Island and Metro Vancouver?

One of the goals of this research is to identify the components of greatest importance within the marine transportation routes. The work identifies the sources of greatest vulnerability and greatest delay to the resumption of regional system function, considering the vulnerability of interdependent infrastructure. The model uses geospatial data to overlay earthquake ground motions and component damage functions to provide a snapshot of the damage and failures from an earthquake.

1.1.3 What does the recovery timeline look like for service to Vancouver Island communities?

This research question aims to address how the system's capability, post-disruption, compares to the community needs. Given that failure occurs from the earthquake event, what does this mean for the population of Vancouver Island? Which terminals and operators could be used for ingress and egress of populations and resources?

1.2 Research Goals

Taking a broader perspective from the details of the research questions, the goals of this project are to communicate the dependencies of the regional marine transportation system, calculate the recovery timelines of this system for the given disaster scenario, and explore the system-wide failure states at the time of that disaster. The resolution of the model is to show systems at the terminal, route, and berth specific level.

The research goals for the transport model, specifically, are as follows:

1. Generate a generic template for dependency maps of marine transport systems and ports.
2. Produce a geospatially explicit regional marine transportation dependency model that includes the system interdependencies within the system boundary.
3. Use Monte Carlo simulation to determine the expected effects on routes and terminals over time following the selected disruption.

1.3 Scope

The scope of this thesis is resilience of marine transportation for Vancouver Island. More specifically, this thesis examines the operations of BC Ferries and Seaspan Ferries—the two primary suppliers of trucked food and goods for Vancouver Island. In general, the entities included in the dependency mapping and in the model are those that are likely to be affected by a large earthquake. However, some dependencies that are particularly relevant to daily operations are also included in the model and dependency maps. The earthquake scenario that this work examines is the magnitude 9.0 (M9.0) Cascadia subduction zone megathrust—defined on the Modified Mercalli intensity scale—discussed and introduced further in section 3.8.1 Earthquake Scenario. This thesis uses the Hazus – MH 2.1 Earthquake Model Technical Manual (Federal Emergency Management Agency, 2013) methodology of earthquake damage and restoration estimation. This version of the technical manual, from here on referred to as Hazus, was developed by the U.S. Department of Homeland Security and the Federal Emergency Management Agency in 2013.

The process diagram for this project is displayed in Figure 2. The inputs to the novel marine transport model are the ground motions of the earthquake in the form of peak ground acceleration (PGA) from the Geological Survey of Canada (GSC), the fragility curves and restoration activity times from Hazus (Federal Emergency Management Agency, 2013), and the qualitative and spatial descriptions of the systems that are developed in this thesis. The modelling platform, Graph Model for Operational Resilience (GMOR), is used to determine the probability of failure of the infrastructure components, and finally the recovery time estimates are produced as the results.

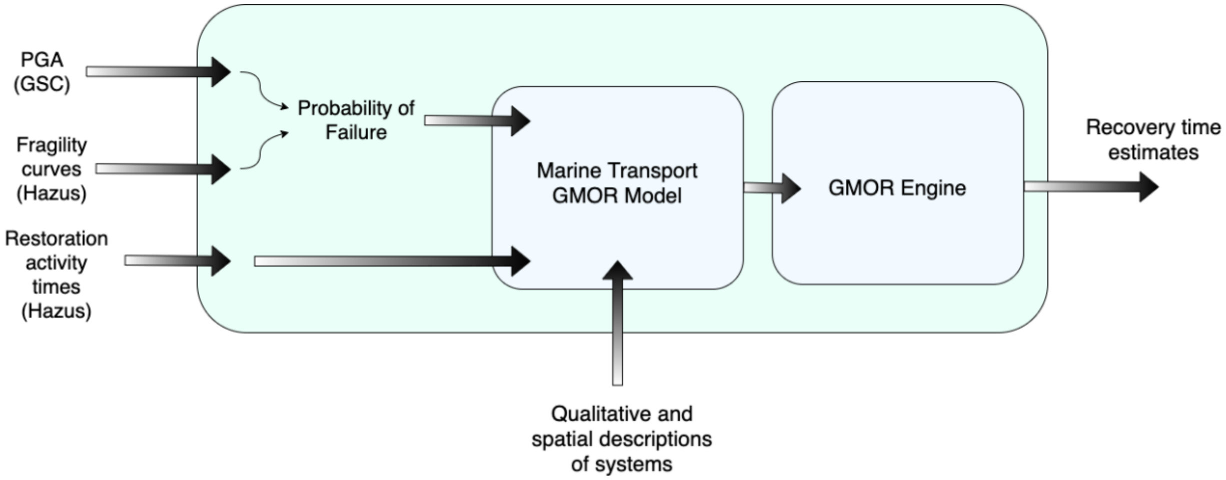


Figure 2: Project process diagram

1.4 Modeling Platform

Researchers Bristow and Hay developed a method to estimate outcomes after a shock or a stress to a multi-infrastructure system. The method enables dependencies, scenarios, losses, and risk treatments to be graphically understood by the user and, furthermore, provides recovery timing and operational loss information (Bristow & Hay, 2016). This project uses an updated version of the method—called the Graph Model for Operational Resilience (GMOR) from the Cities and Infrastructure Systems Lab at the University of Victoria[1]—to perform the modelling. GMOR is also still in its development stage; therefore, it is continuously being updated with new features to facilitate the modelling work being performed. The work from this thesis has helped to contribute new features to the GMOR platform.

1.5 Author's Contributions

The core of this thesis is composed of a novel model and case study that will be submitted as a peer-reviewed manuscript. Below the author list, preliminary title and author contributions are clarified:

Bell, A., Bristow, D. Analysis of the Marine Transport System Resilience to the Cascadia Subduction Zone Earthquake through Recovery Modelling in South-Coastal British Columbia.

- A.B. developed the model, wrote a custom model merge script, performed the analysis, and wrote the manuscript.
- D.B. supervised contributing to the methodology (the apply failures method), results, and revisions.

---

[1] UVic Cities and Infrastructure Systems Lab: https://cisl.uvic.ca/

2 Background

There are a variety of companies that provide essential marine transportation services to BC communities; however, the two primary operators for providing food to Vancouver Island are BC Ferries and Seaspan Ferries. These two companies differ in their mandates but share in the responsibility of transporting trucked foods and goods to Vancouver Island. Upon understanding the operations of these entities, GMOR is used create the model and run the simulations for this research. The background information of this thesis is comprised of four components: BC Ferries, Seaspan Ferries, a compare and contrast of the two, and GMOR. The BC Ferries and Seaspan Ferries background information provides the necessary background for the dependency map and modelling composition of this thesis. Meanwhile, the GMOR background information contains the necessary details to understand how the modelling platform is used to perform the analysis for this thesis.

2.1 BC Ferries Background

BC Ferries (BCF) is a public ferry and goods transportation service for coastal communities in British Columbia. BCF services 47 ports in locations including Vancouver Island, Metro Vancouver, the Gulf Islands, the Sunshine Coast, and Haida Gwaii (BC Ferries, 2018b).

BC Ferries is the primary means of marine public transit in British Columbia. It is also a major provider of transportation for commercial goods and food. Overall, 2018 saw BC Ferries carry 22 million passengers and 8.7 million vehicles on its routes throughout coastal BC (British Columbia Ferry Services Inc. & B.C. Ferry Authority, 2018). Due to its logistical importance and its, in some cases, aging infrastructure, BC Ferries has been identified as a resilience concern after a large earthquake (Smart, 2017). The research in this thesis is limited to the BC Ferries service between Metro Vancouver and Vancouver Island. As shown in Figure 3, there are three routes between these destinations: Tsawwassen-Swartz Bay (TW – SB), Tsawwassen-Duke Point (TW – DP), and Horseshoe Bay-Departure Bay (HB – DepB).

Figure 3: BC Ferries Vancouver Island-Metro Vancouver Routes (BC Ferries, 2019)

The operations for each of these five terminals are largely identical. The primary difference between terminal operations is the vessels used for each route. There are three types of vessel classes that run on these routes: The Coastal class, the Spirit class, and the Queen class. These vessel types are divided somewhat evenly amongst the three routes—although the two Spirit class vessels run exclusively along the Tsawwassen-Swartz Bay route. Further details about these vessels are provided in Table 1. BC Ferries operates with reduced service during the winter to allow for vessel retrofits and repairs, and then runs at full capacity during the summer months.

Table 1: BC Ferries vessel details for Metro Vancouver – Vancouver Island Routes (BC Ferries, 2018a)

Vessel Name	Route	Build Year	Build Location	Car Capacity	Passenger & Crew Capacity
Coastal Celebration	TW – SB	2007	Germany	310	1,604
Coastal Inspiration	TW – DP	2008	Germany	310	1,604
Coastal Renaissance	HB – DepB & TW – SB	2007	Germany	310	1,604
Queen of Alberni	TW – DP	1976	Vancouver	280	1,200
Queen of Coquitlam	HB – DepB & DepB – Langdale	1976	Vancouver	316	1,494
Queen of Cowichan	HB – DepB	1976	Victoria	312	1,494
Queen of New Westminster	TW – SB	1964	Victoria	245	1,332
Queen of Oak Bay	HB – DepB	1981	Victoria	308	1,494
Spirit of British Columbia	TW - SB	1993	Victoria	358	2,100
Spirit of Vancouver Island	TW SB	1994	Victoria	358	2,100

The two Spirit class vessels—Spirit of British Columbia and Spirit of Vancouver Island—have recently been retrofitted be to dual fuel. These vessels are now capable of running on either ultra-low sulfur diesel or natural gas (British Columbia Ferry Services Inc. & B.C. Ferry Authority, 2018). The new addition of being able to run on natural gas provides considerable cost and GHG emissions savings. However, the Coastal and Queen class vessels do not possess dual fuel capabilities and remain with the capacity to only run off of diesel at the present date.

Although not a function in and of itself, electricity is a critical dependency that enables many essential functions of the terminal to perform. These functions include lighting, ramps, ticket sales, and internet connection. Electricity can be provided at the terminal via two means: grid electricity and back-up generator electricity.

2.2 Seaspan Ferries Background

Seaspan Ferries Corporation (SFC) provides goods transportation and commercial ferry service to coastal BC communities (Seaspan, 2019). Seaspan and BC Ferries are the two primary suppliers of trucked food and goods for Vancouver Island. Media reports have listed Seaspan as responsible for 60% of the commercial goods transportation to the island (Smart, 2017). An interview with Seaspan also reported Seaspan responsible for 60% of cargo carried to the island via marine transport, with BC Ferries responsible for the remaining 40%.

SFC performs on average 7-9 round trips each weekday between the island and the mainland; the vessels also run, with reduced service, on the weekends (Seaspan Ferries Corporation, 2019). The ferries service both Swartz Bay and Duke Point Seaspan terminals from Tilbury Island and Surrey Seaspan terminals on the Fraser River (Seaspan Ferries Corporation, 2019). There are three regularly scheduled routes[2]: Tilbury-Duke Point, Surrey-Duke Point, and Tilbury-Swartz Bay. These routes and terminals are shown in Figure 4. The crossing times are between three and four hours—depending on the vessel used—for the Tilbury Island routes and five hours for the Surrey route. Cargo to Vancouver Island includes automobiles and trailers of food, goods and fuel; returning to the lower mainland, the vessels are typically loaded with lumber, paper, pulp, and related products (Islam, 2019). Unlike BC Ferries, Seaspan Ferries exclusively offers cargo transportation service rather than passenger and cargo. The deliveries to the Swartz Bay terminal supply goods to the south end of the island; meanwhile, the Duke Point terminal deliveries supply goods to the remainder of the island. For further details on the Seaspan Ferries operations, the following subsections discuss the vessel specifications, departure checklist, and arrival process for the organization.

---

[2] Seaspan Ferry Schedules available online: https://www.seaspan.com/seaspan-ferries-schedule

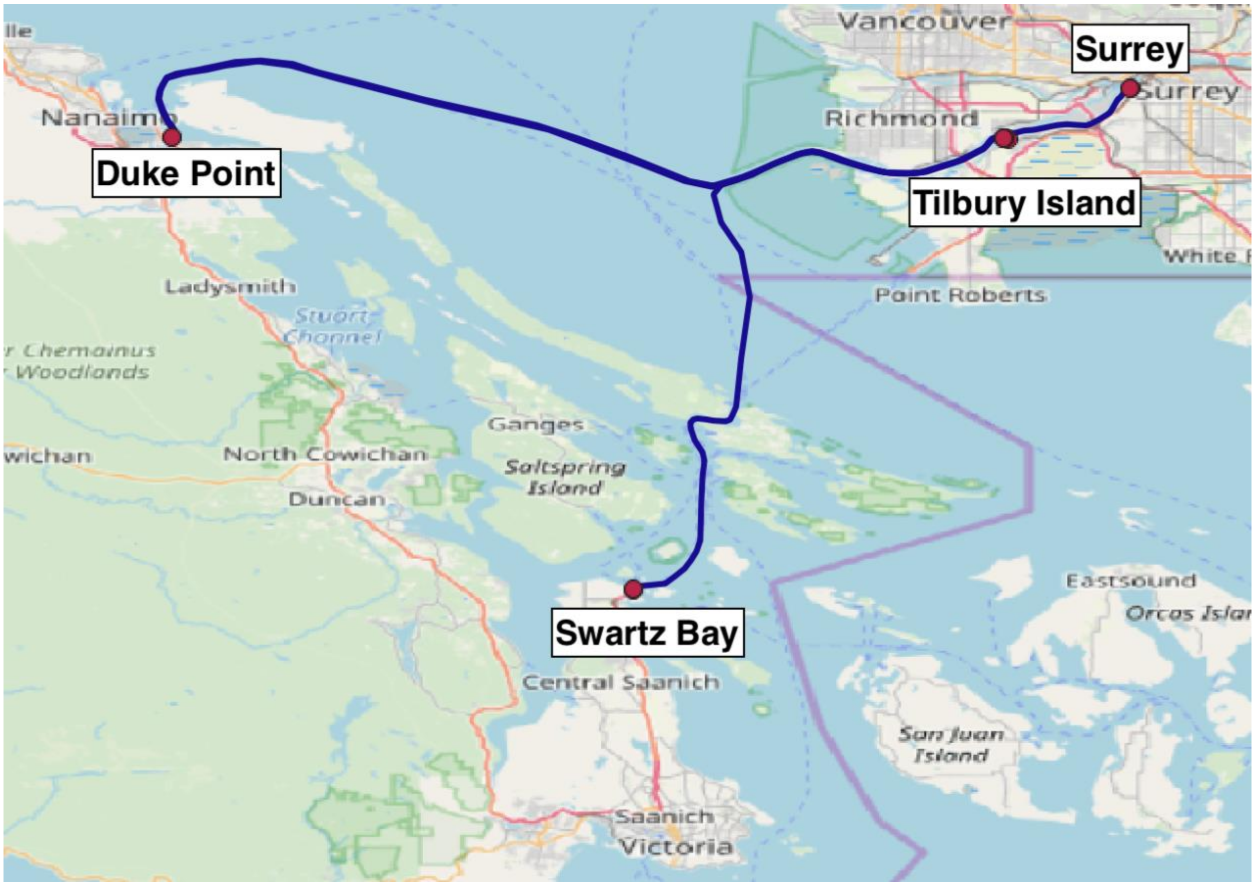


Figure 4: Seaspan Ferries Corporation routes

2.2.1 Vessels: Seaspan

Seaspan Ferries has two vessels capable of running on LNG fuel. The first of these vessels, the Seaspan Swift, was acquired in 2016, and the second, the Seaspan Reliant, was acquired in 2017 (Seaspan Ferries Corporation, 2016, 2017). These vessels are dual fuel, meaning they are able to run on either LNG or diesel fuel. In order to reduce the environmental impact and GHG emissions of Seaspan's services, these vessels prioritize LNG use over diesel.

Each vessel has the capacity to carry up to 59 trailers with a maximum trailer length of 53 feet. Trailers are driven on the ferry by a shunt truck with the regular truck cabs removed to conserve space on the vessel. Seaspan also offers a tow-on/tow-off service, for an additional charge, where trailers can be dropped in the Seaspan yard and Seaspan will perform the tow-on/tow-off task. For normal service, land transport companies are responsible for loading and unloading their cargo. Booking requests can be made up to an hour before departure; however, tow-on/tow off trips and dangerous goods (e.g., dangerous chemicals, propane, etc.) require a minimum of 24 hours' notice. Booking can be performed via the online system, email, telephone, or fax. The booking system allows Seaspan to have a fairly detailed idea of which type of cargo they are transporting. Additionally, Seaspan Ferries has the responsibility to notify Transport Canada of any dangerous goods 24 hours prior to shipment. (Islam, 2019)

All seven Seaspan Ferries vessels are self-propelled; however, some of the older vessels still require a tug at times, particularly in a flood tide. Vessels are typically allocated an hour and 45 minutes for unloading and loading[3]. The roll-on/roll-off loading and unloading is performed using a hydraulic ramp at the loading berth. This ramp is not designed and constructed to the same standards as the ramps at the BC Ferries terminals. Therefore, although a Seaspan Ferries vessel would be capable of using the ramps at a BC Ferries terminal, BC Ferries vessels are not able to use the ramps at Seaspan Ferries terminals. When berthed, vessels connect to shore-side electricity. (Islam, 2019)

The crew on a Seaspan Ferries vessel is approximately 7-9 people, which typically includes two engineers, one cook, two mates (navigating officers), three deck hands, and the captain (ship master). Because these are short sea shipping trips (rather than deep sea/international trips), pilots and pilot boats are not required. (Islam, 2019)

2.2.2 Departure Checklist: Seaspan

The following list represents the Seaspan Ferries departure checklist, which is performed prior to each port departure (Islam, 2019):

---

[3] Seaspan Ferries Schedule April 29-May 19 2019: https://www.seaspan.com/wp-content/uploads/2019-April-29-May-19-V4.pdf

1. Restock and refuel: the restocking and refueling of the vessels takes place once every seven days. This is when they ensure they have enough food for the crew and fuel for the ship to perform one week's worth of duties.
2. Reporting of dangerous goods: the dangerous goods that will be onboard the vessel must be reserved and reported to Transport Canada 24 hours in advance of the sailing. Additionally, prior to the sailing, the ship master must be provided with a list of the contents and location of the dangerous good on the vessel. The Harbour Master, responsible for enforcing safety and security regulations of a particular port, must also be provided with the dangerous goods contents on the sailing.
3. Safety check: the security check is conducted before every single departure. It is critical to ensure there is the required personal flotation devices, lifeboats, and security equipment before every trip.
4. Change of berth: there are two kinds of berths: the loading berth and the berthing berth. Vessels spend the night in the berthing berth but have to be moved to the loading berth for the loading process.
5. Hydraulic Ramp: the ramp of the loading berth is essential to the loading and unloading process of the vessels. The ramp is also used to lock the vessel in place at the loading berth.
6. Loading: the combined process of unloading and loading a vessel is completed within an hour and 45 minutes at the Duke Point and Swartz Bay terminals.
7. Navigational equipment checks: the navigation equipment onboard the vessel is checked for functionality before departure. The equipment checked includes magnetic compass, gyrocompass, radar, radio, GPS, navigation lights, deck lights, normal steering, and emergency steering. The check is performed in the bridge.
8. Passage Plan: although the route itself for the ferries is fixed, the shipping channel is wide. The passage plan defines which shipping lane to take on the route. The passage plan is created by the captain. This is the passage the ferry will take for this voyage unless there are unexpected events, such as stormy weather.

9. Report to Marine Communications and Traffic Service (MCTS): this must be done 15 minutes prior to departure. The Canadian Coast Guard MCTS is responsible for monitoring current shipping traffic conditions (Canadian Coast Guard, 2019). Post departure, the vessel is responsible for reporting to MCTS three more times. A VHF radio is used to do this. Reporting to MCTS will provide the vessel with information on the other marine traffic that the vessel may encounter within the next hour.
10. Report to Ship Master: the type of onboard cargo, the passage plan, etc. is all reviewed with the ship master (captain of the vessel) as the final step before departure.
11. Depart from port.

2.2.3 Arrival Process: Seaspan

Upon arriving at a port there is a series of five steps that ship crew must follow (Islam, 2019):

1. Report to the ship master
2. Connect the ship to the ramp
3. Moor the ship
4. Unload the ship
5. Step five consists of one of two options:
    a. Load the ship for the return trip
    b. Move vessel from the loading berth to the berthing berth for the overnight stay.

2.3 BC Ferries and Seaspan Ferries: Compare and Contrast

BC Ferries and Seaspan Ferries fulfill different needs for the communities of Vancouver Island, with BCF serving the public directly, and SFC providing services that benefit the public indirectly. Despite these differences—and the differences in the types of information that was collected from these stakeholders—the two operators do have many things in common. First, it can be assumed that, with the exception of the different docks for loading and overnight berthing, and the acknowledgement that BC Ferries carries passengers and a significantly larger crew, the departure checklist and arrival process of Seaspan Ferries is representative for that of BC Ferries. A difference between the two operators is the time they require for unloading and loading between sailings. Because the BC Ferries vessels have the truck cabs remain with their trailers for the sailing, the vessels are able to be unloaded and loaded within 20 minutes. In contrast, Seaspan vessels are loaded via shunt truck with the truck cabs removed from the trailers. This results in a much slower process with an overall unloading and loading time of 1 hour and 45 minutes. Because this turn-around time is so much less for BC Ferries and the vessels perform continuous sailings throughout the day, it is probable that some of the departure checklist is only performed once, at the beginning of each day. Ultimately, however, the similarities within the two entities' basic operations—such as their dependence on berths, ramps, vessels, radio, and crew, along with their availability of back-up power—outweigh their differences.

2.4 GMOR Background

The model designed in this thesis uses GMOR to determine nodal and system recovery times of a marine transportation network, post large earthquake. Using sensitivity analysis, the efficacy of risk treatments can be tested. The subsequent sections aim to deliver a basic overview of GMOR to provide an understanding of how the marine transportation model makes use of this platform. Refer to Figure 2, previously shown in section 1.3 Scope, for an example of a GMOR project process diagram.

2.4.1 How GMOR Works

In GMOR, spatially explicit entities are created (such as a berth or a road section) that have the capacity to fail and be recovered. The relevance of these dependencies is established through a dependency network, also referred to as a dependency map in this thesis. The dependency network establishes primary entities, upon which a system depends, and then uses the Boolean operators AND, OR, and NOT to list the entities that those primary entities depend on; this constitutes a single layer dependency map. Dependency layers can be added until the dependency map has fully exhausted its intended scope. GMOR uses this dependency network to develop the failure and recovery ordering.

2.4.1.1 A Basic GMOR Model

A GMOR model is designed with four entity types: functions, resources, times, and events. The functions are the primary entity types used in the model. A basic, minimum entity, GMOR model may have only one of each of these entity types, as shown in Figure 5. All entities that have no external dependencies are set to be dependent on themselves. This is indicated by the circular arrows on the “Failure of Function” and “Repair Resource” entities in Figure 5.

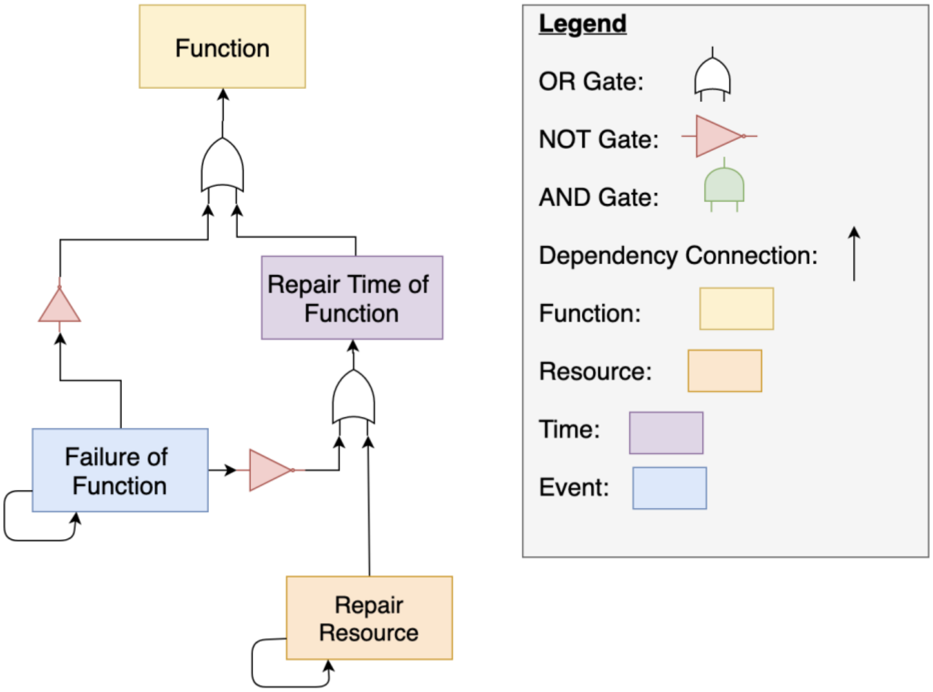


Figure 5: Basic GMOR model

Examples of function type entities include terminals, berths, road segments, vessels, and personnel. The resource, time, and event entities are used in the case where an entity may fail, and the function needs to use specific recovery dependencies. In its simplest form, specification of an entity in GMOR includes the name, type, and dependencies of the entity (Bristow, 2019). The spatial information (e.g., the location of the entity from accompanying geographic information system (GIS) shapefiles) is also usually included.

In GMOR, failure of an entity is determined by the entity having a binary output value of either 0 or 1. A value of 1 indicates that the entity is functioning properly or that the event has occurred. Contrastingly, a value of 0 indicates that the entity function has failed or that the event has not occurred. If an entity function has failed, the entity must wait for all its dependencies to be in the recovered state before the entity can initiate its own recovery.

2.4.1.2 More Complex GMOR Models

More complex GMOR models may have entities that share repair resources. In this case, the order of resource allocation and the effort of the resource required by the repair time entity becomes important. Repair resources will become available as they complete the tasks with higher priority and there is enough of the resource available for the required effort.

It is possible that not all function entities will have a failure possibility. Some entities exist in the model to represent an overarching component of a network, or some entities exist in the model to show that a component may be important even if there is no failure and recovery data for it at the moment or it is not expected to fail. The example in Figure 6, below, demonstrates this. The land access function for the Tsawwassen BC Ferries Terminal depends on three sub-functions: a clear causeway, the highway approach, and parking areas. In the case that the highway approach fails, it will require a resource to enable recovery. In this case, the resource is road construction workers. The clear causeway and parking area function in this model will not fail. The land access entity, though it does not have the capacity to fail independently, will fail if the highway approach function fails.

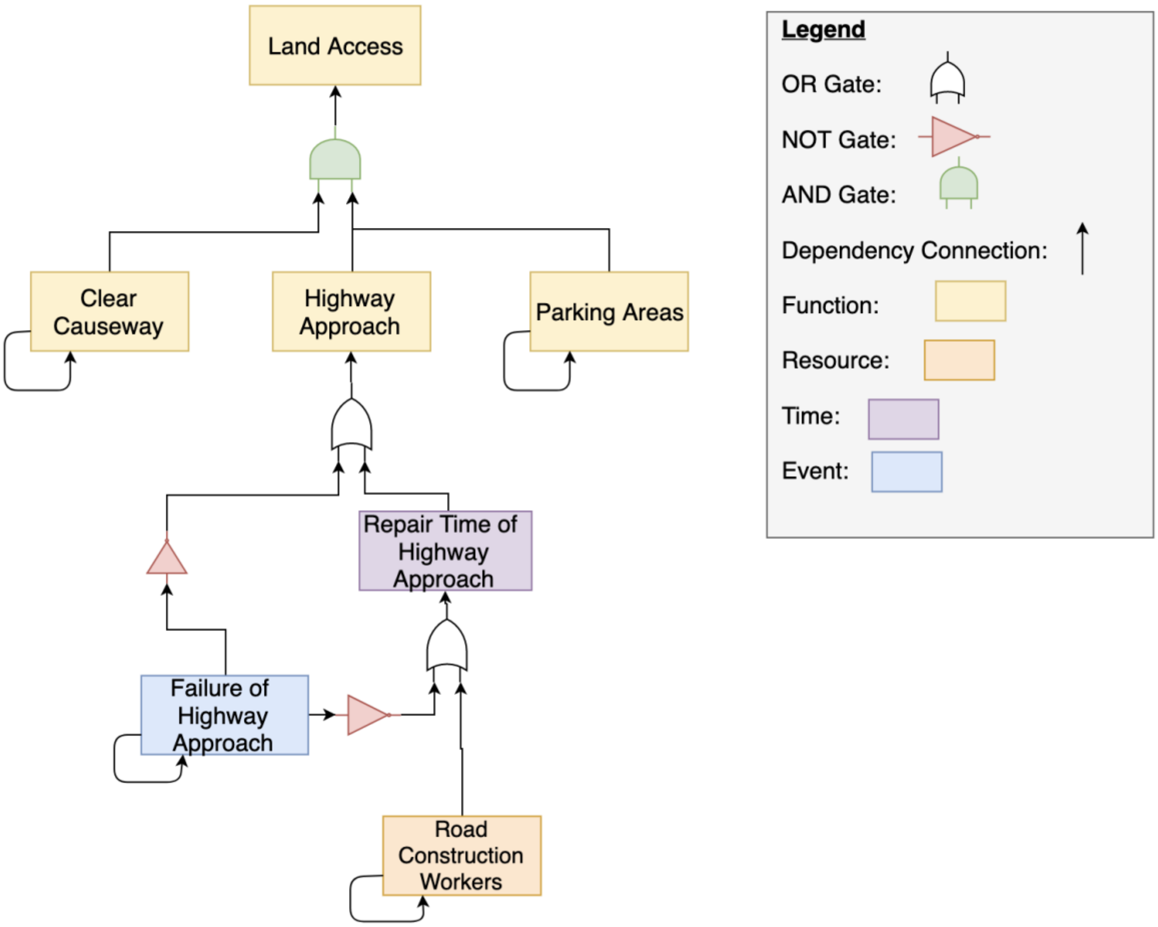


Figure 6: Example of land access dependencies for a BC Ferries terminal.

2.4.2 Mutually Exclusive Damage States in GMOR

A new feature within GMOR is the mutually exclusive damage states capability (Deelstra, 2019). Mutually exclusive damage states represent the various degrees to which an entity may be damaged. The number of damage states may vary by model, but they will include a “no damage” state, a “completely damaged” state, and various states in between—which, in this case, include slight, moderate, and extensive damage. The states are mutually exclusive because there can only be one damage state that occurs for an entity at one time. This feature enables the user to adopt the Hazus – MH 2.1 Earthquake Model Technical Manual (Federal Emergency Management Agency, 2013) method of determining damage states and repair times. Further description of how this thesis’s marine transportation model uses damage and restoration functions is provided in sections 3.3 Damage Functions and States and 3.5 Restoration Functions, respectively.

2.4.3 Using GMOR

GMOR is a package written in the Python language. The package exposes several functions to the modeller for building a model, for defining a scenario by which to analyze the model, for running the Monte Carlo simulations of the scenario, and for producing the results of the output. These functions along with the files that a modeller works with in the GMOR workflow are shown in Figure 7. These steps create a set of intermediary files (Figure 8).

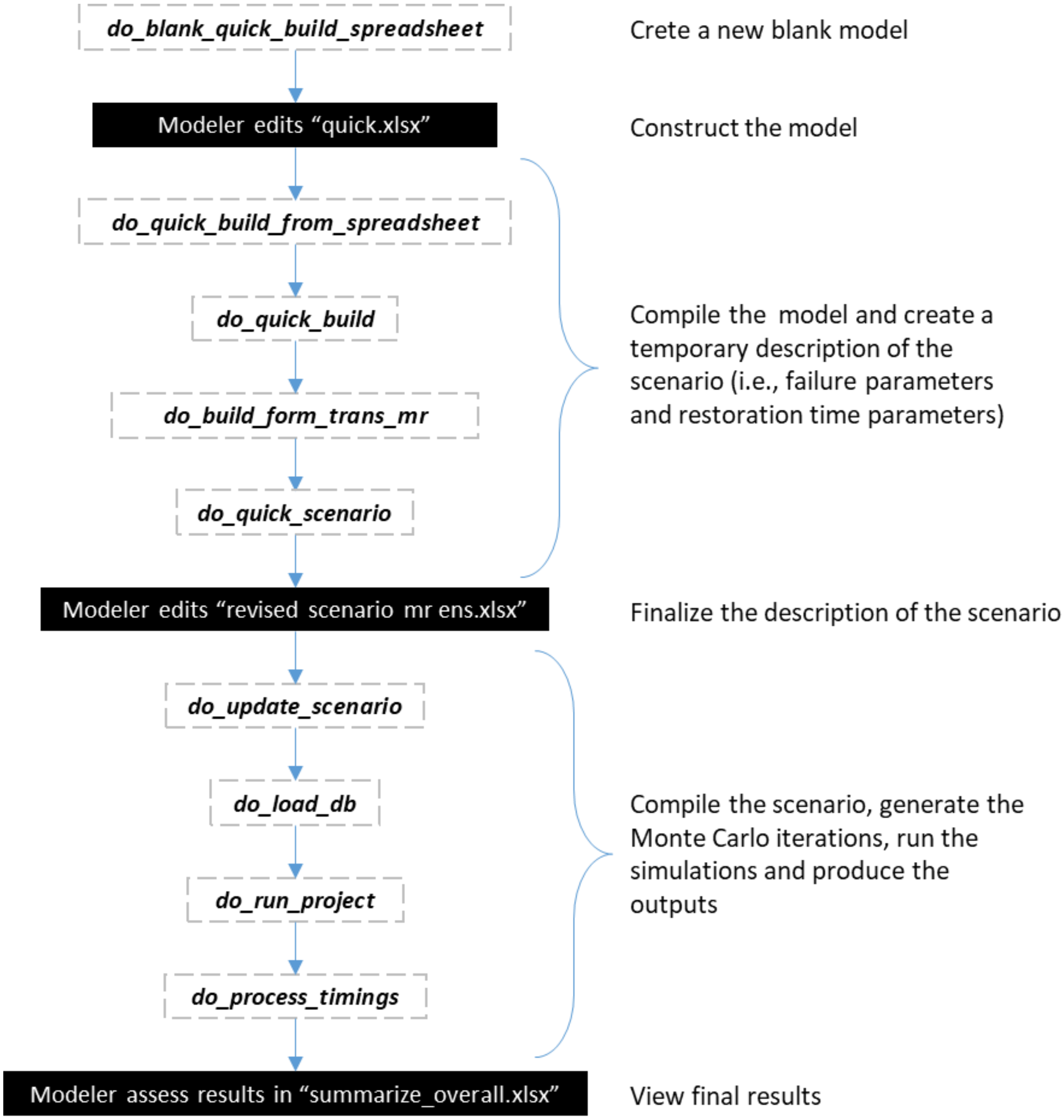


Figure 7: GMOR workflow to build and analyze a model. Boxes with dashed borders are GMOR functions. Solid coloured boxes are manual steps made by the modeller.

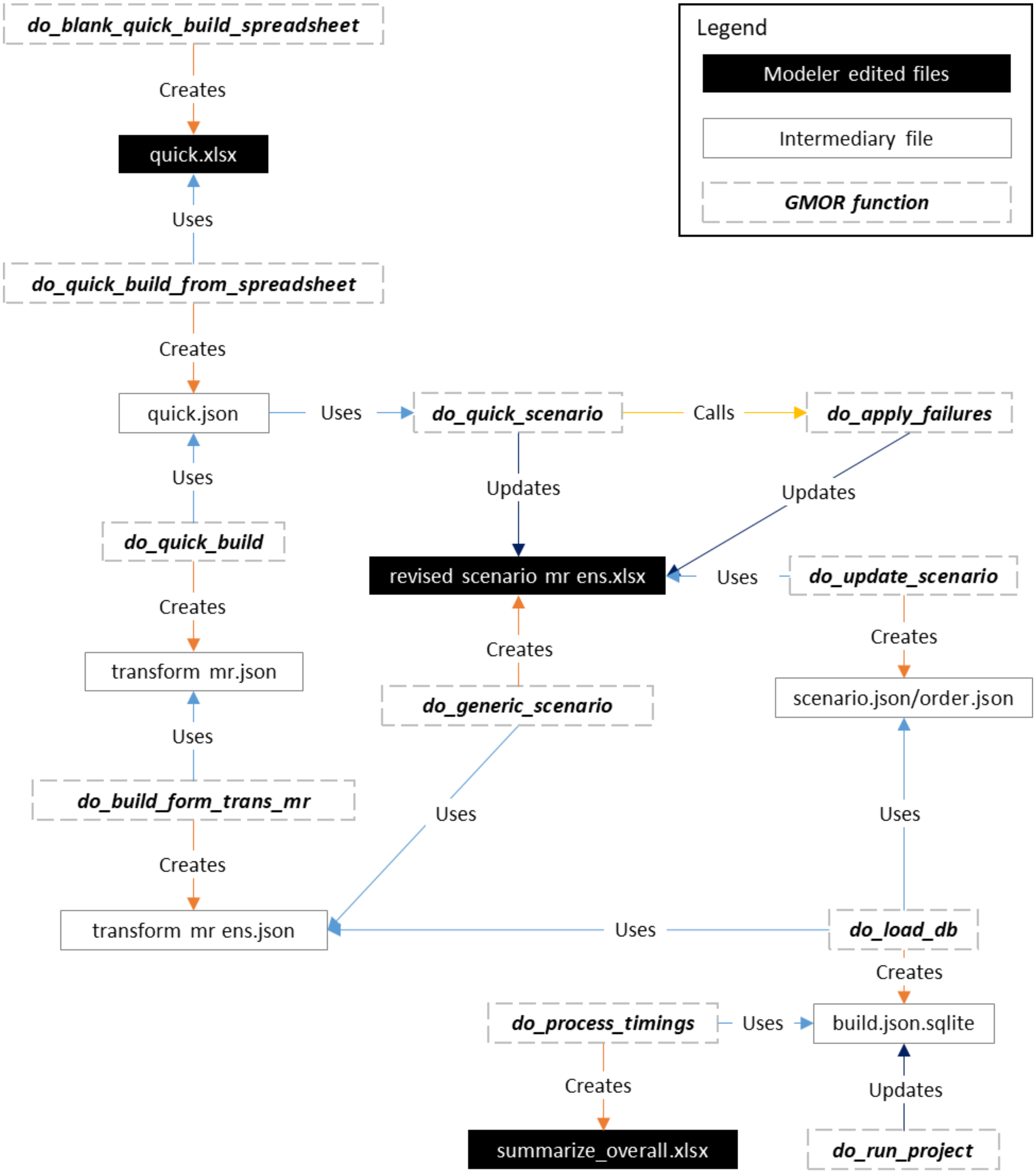


Figure 8: GMOR functions and files used in the workflow.

A new function in do_quick_scenario called do_apply_failures, developed in parallel to this work in order to support the case study described herein, allows GMOR to generate the probabilities of failure. This is completed by overlaying the spatial hazard severity information with the location of model entities. The function uses this overlay to determine the severity of the hazard at the given location. The severity is then used to calculate the probability of failure of the model entity based on a fragility curve function for each model entity that defines their vulnerability to different hazard severities.

The apply failures GMOR function was created in GMOR by Dr. David Bristow and Alison Goshulak. The methodology behind this code (“apply_failures.py”) is described below. Equation 1 through Equation 6, below, represent the pseudo-code of Bristow and Goshulak’s apply_failures code. These equations use the cumulative distribution functions (CDF) of the damage state (DS) fragility curves. Equation 1, Equation 3, and Equation 5 represent the probability that a particular damage state will occur. Meanwhile, the conditional probability—also referred to in the model as the probability of occurrence—is the probability that a particular damage state will occur given that the previous damage states—the damage states of lesser damage—have not occurred. The conditional probabilities of damage state 1 (DS1), damage state 2-4 (DSi), and damage state 5 (DSMax) are described in Equation 2, Equation 4, and Equation 6, respectively below.

Equation 1: DS1 probability if PGA is not too small

$$1 - CDF_{DS2}, \quad else: 1$$

Equation 2: DS1 conditional probability if PGA is not too small

$$1 - CDF_{DS2}, \quad else: 1$$

Equation 3: DSi probability if PGA is not too small

$$CDF_{DSi} - CDF_{DSi+1}, \quad else: 0$$

Equation 4: DSi conditional probability if PGA is not too small

$$\frac{CDF_{DSi} - CDF_{DSi+1}}{1 - \sum_{k=1}^{i-1} CDF_{DSk} - CDF_{DSk+1}}, \quad else: 0$$

Equation 5: DSMax probability if PGA is not too small

$$CDF_{DSMax}, \quad else: 0$$

Equation 6: DSMax conditional probability if PGA is not too small

$$\frac{CDF_{DSMax}}{1 - \sum_{k=1}^{Max-1} CDF_{DSk}}, \quad else: 0$$

3 Methodology

Understanding how a complex marine transport system may be impacted by a large earthquake is challenged by the number of components and operations that make the functioning of this system possible. As such, the model described herein that aims to reduce the uncertainty around this issue focusses on the parts of the system deemed vulnerable and critical to the functioning of the system. This section describes these various pieces in eight primary subsections. First, the development of the BC Ferries and Seaspan Ferries components of the model are discussed. Next, the damage functions, damage states, restoration functions, and model size management are discussed. The final sections describe the testing of the model and the details of the case study application of the model.

3.1 BC Ferries Model

BC Ferries is the first of two operators considered in the marine transportation model network. For BC Ferries, the "BC Ferries Operations" entity depends on the five terminals being operable: "Tsawwassen Operations", "Swartz Bay Operations", "Horseshoe Bay Operations", "Duke Point Operations", and "Departure Bay Operations". Because the operations for each of these five terminals are largely identical, to create the model, they have been duplicated and then modified for each specific location—modifications involve changing the geospatial tie to be entity location specific and including the proper route and vessel entities for that terminal. A visual depiction of the BC Ferries Tsawwassen terminal operations dependency map is shown in Appendix A: BC Ferries Tsawwassen Operations GMOR Model Diagram to provide a detailed example. The entities that have been designed in the model to have the capacity for mutually exclusive damage state failure and recovery are listed below:

- Potable water;
- Local electrical connections;
- Regional electrical transmission;
- Radio;
- Back-up fuel;
- Highway approach; and

- Clear marine route.

The terminal entities included within the scope of this analysis—for both BC Ferries and Seaspan Ferries—are outlined in Table 2. BCF and SFC execute 5 primary functions from their terminals: transportation, passenger/cargo counting, communication, lighting, and personal relief in washrooms. The dependencies listed in the left-hand column of Table 2, exist to support these functions—the particular function that a dependency supports is indicated with an x in the corresponding row-column intersection.

Table 2: BC Ferries and Seaspan dependencies by functions. The x symbols represent the intersection between a function and the dependency it fulfills for the ferry service's operation. The dependencies listed in the left-hand column exist to support the functions listed along the top of the table.

Functions **Dependencies**	**Transportation**	**Passenger/Cargo Counting**	**Communication**	**Lighting**	**Personal Relief**
Vessels	x				
Electricity		x		x	x
Radio			x		
Ramps	x				
Internet connection		x	x		
Telephone			x		
Access	x				x
Water					x
Food					x
Toilets					x
Fuel	x			x	
Navigational Aids	x				
Navigation Technology	x				
Routes	x				
Crew	x	x			
Paper		x			
Safety Equipment	x				

Many of the dependencies listed in Table 2 also have sub-dependencies. For example, electricity can be achieved through two possible avenues within the model: grid electricity and back-up power. Sub-dependencies of grid electricity include local electrical connections and regional electrical transmission—with a possible need for electricians and power line technicians, in case of failure. Power generation could also be included in future work if a case of interest arises where there is a risk that generating stations will be damaged. Sub-dependencies of back-up power include back-up fuel storage and a functioning generator. Another example of sub-dependencies related to Table 2 are the dependencies of the routes. One of the sub-dependencies within routes is having a clear marine route, should this fail, debris removal, bathymetry, and dredging may be required.

Although the Tsawwassen-Swartz Bay route requires at least two vessels running the route in order to provide a sailing from each location every two hours (winter operations), the number of vessels required in the model for the terminal to return to operational status is one. This is because the interest at this stage is determining when the minimum possible level of service (dubbed here skeletal operations) is disrupted. Therefore, the model is currently designed to reflect skeletal operations. This criterion has been set for all routes. Further differences between normal BCF operations and skeletal operations are presented in Table 3.

Table 3: Differences between skeletal operations and normal operations for BC Ferries terminals

Topic	Skeletal Operations	Normal Operations (full performance)
Number of Vessels	One vessel running per route.	Two to four vessels running per route.
Number of Berths	A minimum of one berth is operable.	All berths available for use.
Terminal Services	Reduced electricity available to power terminal buildings resulting in possible closure of accessory buildings (e.g. Tsawwassen Quay).	All terminal buildings and services offered (food, shopping, etc.).
Terminal Space and Water Heating	Unavailable space and water heating in terminal buildings.	Space and hot water provided in terminal buildings.

Pedestrian Access	Pedestrian overhead boarding walkway access unavailable. Pedestrians board on vehicle ramps with bicycles.	Pedestrian overhead boarding walkway access available.
Ticket Sales	Cash only and paper-based ticketing. In emergency evacuation circumstances, BC Ferries may resort to only counting vehicles and passengers, for safety purposes, and wave charges.	Cash, debit, and credit accepted as payment methods. Human and virtual ticket kiosks available.
Communication	VHF Radio and walkie-talkie are the only means of communication available for terminal operators.	Radio, internet, and telephone are all available for communications purposes.
On-Board Services	No unnecessary on-board services provided. Cancelled services may include food services, gift shop services, and on-board naturalist services, among others. Washrooms, water, and passenger and vehicle boarding are considered on required services.	Full array of on-board services available including food services, gift shop services, and on-board naturalist services, among others.

Space and water heating are assumed to be provided by natural gas. This has been left out of the model because this not considered to be an essential service for skeletal operations. If the model reaches a point where it differentiates between full and skeletal operation dependencies, this set of dependencies should then be included in the model.

3.1.1 BC Ferries Vessel Crew and Fuel

The model is set-up so that the crews all must come from Metro Vancouver. This is to compensate for the fact that it is unknown where the crew comes from for each specific vessel. If both Metro Vancouver and Vancouver Island are provided as options for the crew to come from, the options would either be an AND gate or an OR gate. Neither the AND gate or the OR gate is appropriate in this situation because although the crew either comes from the island side or the mainland side it is only one of these sides that the people are actually on. Using an AND gate would over-define the number of entities necessary; meanwhile, using an OR gate would potentially under-define the recovered entities required. Likewise, although refueling happens on both the Vancouver Island and the Metro Vancouver terminals, refueling is modelled to occur on the mainland only. For future versions of the model, certain vessels could be declared to have home-harbours on Vancouver Island rather than all on the mainland. This would be a more accurate representation of true operations.

3.1.2 BC Ferries Terminal Electricity

In the case that grid electricity fails at a terminal it will require one or both of two resources to become recovered: electricians and power line technicians. The former will be required if the local electrical connection(s) fail; the latter will be required if the regional electrical transmission fails.

The back-up power not only depends on a functioning generator, but also a robust fuel tank with fuel supplies. Should refueling be necessary, a fuel delivery truck and land access are required. Diesel fuel is the fuel for the back-up power generators at the terminals.

3.2 Seaspan Ferries Model

The Seaspan Ferries terminal operations models are developed to represent the relevant dependencies of the terminals’ five core functions: transportation, cargo counting, communication, lighting, personal relief. Like the BC Ferries operations model, these core functions have many sub-dependencies including, but not limited to, clear marine route, vessels, berths, crew, grid electricity, back-up power, internet, radio, land access, and potable water. The SFC terminal entities that have been designed in the model to have the capacity for mutually exclusive damage state failure and recovery are the same as those for BCF terminals. As an example, a visual of the Seaspan Ferries Duke Point terminal operations dependency map, as laid out in the model, is shown in Appendix B: Seaspan Ferries Duke Point Operations GMOR Model Diagram. For Seaspan Ferries, the “Seaspan Ferries Operations” entity depends on the four terminals being operable: “Seaspan Duke Point Operations”, “Seaspan Swartz Bay Operations”, “Seaspan Tilbury Island Operations”, and “Seaspan Surrey Operations”.

3.3 Damage Functions and States

In order to determine the post disaster damage states, the model requires damage functions for the entities. These are available in the Hazus technical manual (Federal Emergency Management Agency, 2013). Hazus provides specification of lognormal damage functions in terms of medians and standard deviations (beta) for four damage states with respect to peak ground acceleration (PGA) and permanent ground deformation (PGD). The four damage states that Hazus describes are slight damage, moderate damage, extensive damage, and complete damage (Federal Emergency Management Agency, 2013). The GMOR marine transportation model lists these damage states as damage state 2 to 5, respectively, while damage state 1 is the no damage case.

Hazus provides an extensive array of damage functions for all types of infrastructure including ferry facilities, port facilities, roadways, electric power facilities, and water and wastewater treatment facilities, among others. The utility facility classes used in this model are listed below:

- AM or FM radio stations or transmitters (utility communication system classification)
- Distribution circuits (electric power system classification)
- Ferry fuel facility (ferry system classification) – threshold for failure is extremely high
- Piers and dock facilities (ferry system classification)
- Major roads (highway system classification) – roadway fragility curves are defined in terms of PGD, not PGA (Federal Emergency Management Agency, 2013)
- Potable water system classification default

The description of how the Hazus methodology defines infrastructure damage states is provided in Appendix D: Damage State Descriptions from Hazus. Additionally, there are two damage functions used in the model for which Hazus data is not available. These are the engineering damage inspection of pier and dock facilities and the clearing of marine routes. The damage functions for these entities are supplied by the modeller. For more details on the damage functions used in the case study of this thesis, see section 3.8.4 Damage Functions for Case Study.

3.4 Calculating the Probability of Damage States

The probability of each damage state is generated by overlaying the PGA and PGD maps with the spatially linked model entities, which contain the damage function parameters provided by Hazus. GMOR uses the combination of these inputs (ground motion, location, and damage function) to generate the damage states. Because the damages states are determined through probabilistic rather than deterministic data, the results of which damage state occurs for each of the entities are different for each iteration.

3.5 Restoration Functions

Restoration functions are probability distributions of the time to recover from the possible damage states. For the entities in this model the functions from the Hazus technical manual are used (Federal Emergency Management Agency, 2013). The restoration functions are normally distributed, and the standard deviation and mean is provided for four different damage states: slight, moderate, extensive, and moderate. There is also the possibility of no damage to an entity, which is defined as damage state 1 in the model and requires no recovery time. Hazus provides restoration functions for all of the infrastructure types that it provides damage functions for; a list of these infrastructure types is provided previously in section 3.3 Damage Functions and States. Like the damage functions, the restoration functions for the engineering damage inspection of pier and dock facilities and the clearing of marine routes are supplied by the modeller. For more details on the restoration functions used in the case study of this thesis, see section 3.8.5 Restoration Functions for Case Study.

3.6 Managing Model Size

The final model contains 638 entities, each containing one or more dependency relationships. Due to the size of the model it has been necessary at times to divide the specification of the model into multiple text files by sub-categories (such as by each individual terminal). A script was written to merge all of the sub-category model files together into one before running the model. This merge script is provided in Appendix E: Merge Script for GMOR Transform and Scenario Files. An updated version of GMOR has since been released that uses Excel workbooks to support building large models. Although the merge script was critical for the development of this model, it is thus no longer necessary. In the future the script may be adapted to support merging Excel workbooks as despite the improvement they bring, it may still be helpful to divide a model of this size into multiple workbooks. Additionally, this script may be adapted to allow for the merging of models developed by specialists of different infrastructure sectors for even larger studies.

3.7 Testing

Many intermediate issues arose during the creation of this model. In order to determine if the model is running properly, a set of Excel formulas and conditional formatting rules have been created to analyse the model output. Readers may want to refer back to Figure 7 and Figure 8 throughout this description of validation tests. Upon running the model and processing the timings, GMOR generates an Excel spreadsheet (summarize_overall.xlsx) that provides the name of all the entities that change states through the simulation period along with their respective object IDs (locations), scenario IDs (iteration run), and recovery times (in days). However, this table alone is not enough to understand if the 2,000 entities within it are recovering as the modeller expects. Therefore, a set of formulas has been created. First, the timing, order, and efforts sheets from the Excel scenario file (revised scenario mr ens.xlsx) are copied into sheets of the Excel output analysis spreadsheet along with the entities' initial system state list obtained from the SQLite output database (build.json.sqlite). The goal of the formulas is to understand which damage state each entity failed with, what the corresponding recovery time of that entity is supposed to be, and whether or not the recovery occurred at the appropriate time, given the possible recovery dependencies and the damage state. Each of these formulas and conditional formatting rules were copied into each new output spreadsheet, with each version of the model, to analyse the results.

3.7.1 Testing Formulas

This section provides more details on the formulas used to test the simulation output. To view a detailed breakdown of each formula within the worksheets, the reader is referred to Appendix F: Formula Descriptions for Model Testing. This appendix contains the description of the Excel worksheet used to determine which damage state occurs for each model entity at the beginning of each iteration simulation and the Excel worksheet created to test whether the recovery time the model outputs for an entity is the same recovery time expected by the modeller. A brief summary of the types of formulas used to create these testing functions are listed in Table 4. This testing is conducted when the simulation is run with stochastic damage states, but deterministic recovery times.

Table 4: Simplified summary of testing formulas for stochastic damage and deterministic recovery simulations

Purpose	Formula	Example Output
Display entity damage state	Uses the INDEX and MATCH functions to search for the initial system state of the entity and display the corresponding damage state.	DS1
Determine entity type	Uses the IF, ISERROR, and SEARCH functions to determine if the entity name contains particular text (e.g., “Ticket Agents”, “BUP Fuel”, etc.) that corresponds to entities that are dependent on land access.	TRUE
Display the number of days to repair the entity	Uses the IF, AND, and NOT functions to display the difference between entity recovery time and Land Access recovery time if either the entity is a berth or ramp requiring recent inspection or is an entity dependent on land access and the damage state is not “DS1”. Otherwise the original GMOR generated recovery time is displayed.	3
Determine the repair time value for the corresponding entity damage state	Uses the INDEX and MATCH functions to search for the repair time value (in days) corresponding to the entity name and damage state.	3

Identify if the correct number of days to repair has occurred (excluding sub-dependencies)	Uses the IF and ROUND functions to display "Yes" if the simulation repair time matches the assigned repair time when rounded to 3 decimal places. Otherwise displays "No".	Yes

3.7.2 Damage State 1 Recovery Resource Issue

One challenge that occurred during testing was the damage state 1 (DS1) recovery. The testing of the model uncovered that the recovery resources and recovery dependencies need to be removed from the recovery requirements of DS1 entities (except for those of "Recently Inspected" entities). This is because, unlike the damaged entities (DS2-5), entities that have not experienced damage do not require inputs to become recovered. This is important because although the DS1 recovery time has already been set to zero, the entities also wait for their recovery resources and dependencies to become available, before reverting to a recovered state. However, when the recovery resources and dependencies were initially removed from the DS1 entities, no change occurred in the model output. It was as if the dependencies remained. This identified a problem within the model or GMOR platform. As a result of this testing GMOR was updated to support this case. The entities that fail via DS1—also known as experienced no damage—now recover on day 0, as expected.

3.7.3 Land Access Recovery Dependency Issue

At the same time that the DS1 recovery resource issues were discovered, it was also discovered that the land access dependencies were being ignored for many damage state entities. The interesting part of this was that the land access dependency was being ignored for the ramp and berth entity recoveries, but not for certain other dependencies. Collaboration with Dr. Bristow helped to determine that the spatial join component of the dependency links was dropping dependency relationships of entities that didn't directly geographically overlap. The geographical overlap did not occur because the land access entities were spatially linked to the GIS points representing the terminals while the ramps and berths were spatially linked to each GIS point representing the specific berths at each terminal.

The solution here was to create GIS polygons for each of the terminal's land access entities rather than using the terminal GIS points. The polygons were drawn to encompass the terminal GIS points as well as each of the berth locations and the highway approach route GIS lines. With the polygons overlapping with the necessary dependencies, the spatial joins no longer drop the land access dependencies.

3.7.4 Applying Failures Issue

The next issue arose with the step of applying the correct failure probabilities for the case study to the model (using the do_apply_failures method described in section 2.4.3). The do_apply_failures command performs as expected for most entities; however, there are certain entities that result in a DS5 probability of occurrence value of infinity. The infinity value produces an error in GMOR. These entities are the BUP Fuel entities (Ferry Fuel Facility classification from Hazus) and the roadway entities (Highway Approach and Victoria Nanaimo Road Connection, both of which are Highway System classification from Hazus). The probability of occurrence values for these entities are listed in Table 5. The infinity value occurs because the denominator of Equation 6 for DS5 becomes $1 - 1 = 0$.

Table 5: Initial probability of occurrence of BUP fuel and roadway entities for the case study earthquake scenario

Damage State	Probability of occurrence from GMOR (pre issue resolution)
DS1	1
DS2	0
DS3	0
DS4	0
DS5	infinity

Upon review of the Hazus data it was discovered that these facility classes both have unexpected values for their PGA damage function medians and standard deviations. For all damage state functions, the Ferry Fuel Facility class (FFF) has a PGA median of 10.1 and a PGA standard deviation of 0.1 and the Hazus Major Roads Highway System classification has a PGA median of 10.0 and a PGA standard deviation of 0.1. Not only are these medians extremely high for PGA values, which are typically between 0 and 2, but it is also unexpected that they would be the same for all damage state functions.

For the roadway entities, the Hazus values for the PGD mean do increase by damage state, as expected. Therefore, the unexpected PGA values will likely be able to be overlooked, once PGD values are available, because the Hazus technical manual states that it is PGD values rather than PGA values that are to be used for the road segment damage state functions (Federal Emergency Management Agency, 2013). However, this is not the case for the FFF class. The FFF class is not accompanied with the statement that PGD should be used instead of PGA, nor do the PGD median values for the FFF class increase with damage state. However, in the case of building damage with respect to ground failure, the Hazus technical manual simplifies the damage functions so that there are only two states: a no damage state and an extensive/complete damage state (Federal Emergency Management Agency, 2013). Upon reviewing the Hazus manual, it is assumed that this is the methodology to be used for the FFF class for both PGA and PGD, and all other facility classifications that have identical parameters for all damage state functions. In the case of FFF, because a PGA value of 10.1 is significantly larger than the greatest PGA experienced on eastern Vancouver Island in the Cascadia megathrust scenario (the case study used in this thesis, described in section 3.8.1 Earthquake Scenario), for the purposes of this model, it is assumed that there will be no damage to BUP Fuel entities.

This was solved in the model through changing the formulas of the fragility curve distributions and fragility curve parameters for the do_apply_failures function. The fragility curve distribution formula was changed from being constant for all DS1 entities and lognormal for all DS2-5 entities to being constant for all BUP Fuel and Recently Inspected entities as well as constant for all DS1 entities and lognormal for all remaining entities. The fragility curve parameters formula originally prescribed a value of 1 if the entity is a DS1, or single row array containing the standard deviation value, distribution location (0.0), and mean. The fragility curve parameters (fc_params) formula now contains the following rules:

- For BUP Fuel entities, fc_params for DS1 is set to 1 and the remaining damage states are set to 0;
- For Recently Inspected entities, fc_params for DS1 is set to 1 and the remaining damage states are set to 0;
    - DS1 is used because within GMOR the probability of more damage must be smaller than the probability of less damage; however, this is still considered a failure in the case of whether or not entities have been recently inspected. This is reflected in the restoration times for these entities.
- For all other entities, fc_params for DS1 is set to 1 and the remaining damage states are set to or single row array containing the standard deviation value, distribution location (0.0), and mean.

These rules solve the issue of the DS5 probability of occurrence value being infinity in the model because Equation 1 through Equation 6 will be bypassed in the model and the values will become the constant values set by the user. The specific descriptions of each formula used to solve this issue for the do_apply_failures function are provided in Appendix G: Formula Descriptions for Apply Failures.

3.8 Applying the Model to Understand the Possible Effects of a Cascadia Subduction Zone Earthquake

As presented in the introduction, the chance of an earthquake causing damage can be compiled into an ensemble probability. Any actual earthquake, however, will cause a specific set of damages, and there is one possible earthquake whose potential to cause damage is of particular concern in the province of British Columbia. This section describes that earthquake and how the model is used to assess the potential effect of that earthquake on the marine transport system in BC. The following subsections first describe the specifics of this case study scenario, followed by the details on how the case study effects the model set-up, finally followed by specific applications of the damage functions and restoration functions to the case study simulation iterations.

3.8.1 Earthquake Scenario

The earthquake scenario used for these simulations is the M9.0 Cascadia subduction zone earthquake (Geological Survey of Canada, 2019). This is the earthquake that is frequently referred to by west coast residents and media as “the big one” (Dangerfield, 2018; Murray, 2019; Schulz, 2015).

This model uses the Hazus – MH 2.1 Earthquake Model Technical Manual (Federal Emergency Management Agency, 2013) methodology of earthquake damage and restoration determination. Hazus describes the two important components for determining earthquake damage as ground motion and ground failure (Federal Emergency Management Agency, 2013). Ground motion is discussed in terms of peak horizontal ground acceleration (PGA), spectral acceleration (in periods of both 0.3 and 1.0 second), and peak ground velocity (PGV). Of these, PGA is the variable within the damage functions. Ground failure may be a form of liquefaction, landsliding, or surface fault rupture and is quantified in terms of permanent ground deformation (PGD) (Federal Emergency Management Agency, 2013). The PGA and effort to determine the PGD are discussed in the subsequent sections.

A map of the PGA values for the Cascadia megathrust rupture of the subduction interface and locked zone is shown in Figure 9. Specifically, these are the mean ground shaking intensity values from three different ground motion models (Geological Survey of Canada, 2019). The units of PGA are a fraction with respect to the acceleration due to gravity, g ($g = 9.81\ m/s^2$).

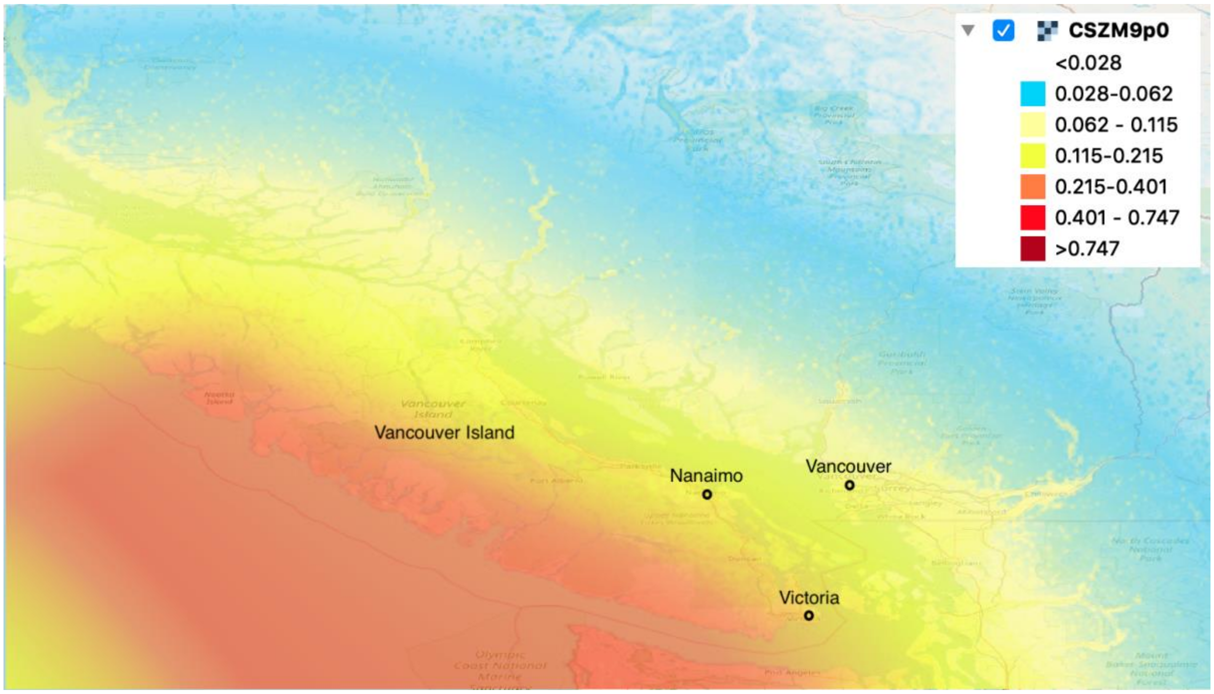


Figure 9: PGA visualization for M9.0 Cascadia megathrust. The units of PGA are a fraction with respect to the acceleration due to gravity, g (g = 9.81 m/s^2).

PGD for this earthquake scenario are unfortunately not available, therefore, an effort was made to determine the PGD using the Hazus methodology. Liquefaction, landsliding, and surface fault rupture are the three types of ground failure quantified by PGD in the Hazus methodology (Federal Emergency Management Agency, 2013). The inputs required by the Hazus methodology to determine the PGD from these ground failures are listed below.

Liquefaction Input Requirements (Federal Emergency Management Agency, 2013)

- A geological map with the age, depositional environment, and material characteristics of the geological units. This will be used in conjunction with the Hazus technical manual's Table 4.10 to create a liquefaction susceptibility map.
- Map containing the groundwater depth for the area with a default depth of 5 feet.
- Earthquake Moment Magnitude (M): in this scenario the moment magnitude is 9.0.

Landsliding Input Requirements (Federal Emergency Management Agency, 2013)

- A geological map, a topographical map, and ground water conditions map. These will be used in conjunction with Hazus technical manual's Table 4.15 to produce a landslide susceptibility map.
- Earthquake Moment Magnitude (M): in this scenario the moment magnitude is 9.0.

Surface Fault Rupture (Federal Emergency Management Agency, 2013)

- Surface trace location of a segment of an active fault that is theorized to rupture during the earthquake scenario – none have been provided by the Geological Survey of Canada for this earthquake scenario.

Given these inputs, the outputs for liquefaction and landsliding are an aerial depiction map of estimated PGDs—important to note when evaluating fragility curves is that PGD is measured in inches in the Hazus documentation. No maps are generated for the surface fault rupture, rather, site-specific demands are determined. However, the active fault for the Cascadia subduction zone earthquake is located offshore the west coast of Vancouver Island; therefore, the surface fault rupture component of PGD can be ignored for this scenario.

Due to complications with the available literature and the available data regarding soil deposits and groundwater levels, determining the PGD was not possible at this time. Instead, the importance of roads for the marine transportation resilience of Vancouver Island is addressed qualitatively through the discussion rather than quantitatively. The issues with determining the PGD values are outlined in Appendix H: Attempt to Determine Permanent Ground Deformation.

3.8.2 Scope of Failures Included in Case Study

The set of failures included in the case study is slightly smaller than the set of possible failures included in the model. Table 6, below, lists the entities that have been designed with the capacity for direct damage within the model. Only six have failure and recovery parameters associated with them in this case study, the reasons for which the final three are excluded are listed in the table.

Table 6: Boundary of failures included in case study, with explanations.

Entity Type	Possibility of Failing in Case Study?	Reason for Excluding Failure from Case Study
Berths	Yes	Included
Ramps	Yes	Included
Local electrical connections	Yes	Included
Regional electrical connections	Yes	Included
Potable water	Yes	Included
Radio	Yes	Included
Highway approach	No	Damage functions are defined by PGD, not PGA.
Victoria Nanaimo road connection	No	Damage functions are defined by PGD, not PGA.
BUP fuel	No	Hazus damage functions do not permit this entity (ferry fuel facilities) to fail.
Clear marine route	No	There is a lack of data on how this earthquake scenario would affect the marine routes.

The failure of berth and ramp entities is separated into two components: structural integrity and recently inspected. The Hazus data is used in the structural integrity component of the berth and ramp failure. The recent inspection of berth and ramp entities is set to fail every time due to the unknown nature of whether this marine infrastructure will be safe to use post large earthquake.

The distribution of grid electricity is accounted for in this model and case study; however, the generation of power is not. Similarly, the constant functioning of back-up power within the case study will require sufficient fuel to be present. The possibility of the facility running out of fuel is out of this scope for two reasons. First, if need be, the vessels can be hooked-up to the berth ramps to provide the ramps power. Second, damage to the road accessibility of the terminals is unknown, but it is assumed that fuel allocation within the region will be prioritized to essential transportation services such as these terminals. The results of grid electricity failure will help to determine a minimum amount of back-up power fuel the ferry terminals should store in preparation for the earthquake.

The potable water function is a general system classification default from Hazus, and therefore is not broken down into components. The radio failure entity is for AM or FM radio station or transmitters and the damage and restoration functions are identical to those of the electric power system distribution circuits (Federal Emergency Management Agency, 2013). Finally, not included in the model or the case study is the possibility of disruptive damage to vessels as there is a high probability that a minimum of vessels will remain intact following the event.

3.8.3 Case Study Dependency Details

The novel GMOR model constructed through synthesis of available data on BCF and SFC is very detailed, containing 638 entities. The scale of the model can make it difficult to follow. Therefore, summaries of the dependencies of terminals and communities are provided below.

A simplified ferry terminal dependency map is shown in Figure 10. This figure illustrates only the simplified dependency relationships that contain function entities with the potential for failure in the model. In this figure, all land access/road entities and electricity entities have been excluded because these do not fail in this iteration of the model. As discussed earlier, the land access/road entities do not fail because of the lack of sufficient PGD data, and the electricity entities do not fail due to the presence of back-up power—the failure and recovery of the grid electricity of each terminal is displayed in the results though. This leaves berth, ramp, potable water, and radio components as the critical dependencies for terminals to display a recovered status. It is important to note that, to achieve this recovered status, at least one berth/ramp of both the terminal itself and one per terminal for each of its connection routes must be recovered.

The recovery resources shown in Figure 10 are unique to each location. This results in some dependencies sharing recovery resources. For example, Swartz Bay and Duke Point both contain a BCF and SFC terminal each. Therefore, unlike a location like Tsawwassen, which only contains a BCF terminal, the Swartz Bay BCF and SFC terminals depend on the same Swartz Bay designated recovery resources and the Duke Point BCF and SFC terminals depend on the same Duke Point designated recovery resources. In the cases where recovery resources are shared, the BCF terminals are given priority to recover first, over the SFC terminals. This is done because BC Ferries vessels have the capacity to transport both cargo and people, while Seaspan Ferries Corporation only transports cargo. These parameters can be adjusted in the model, if desired for future sensitivity analyses.

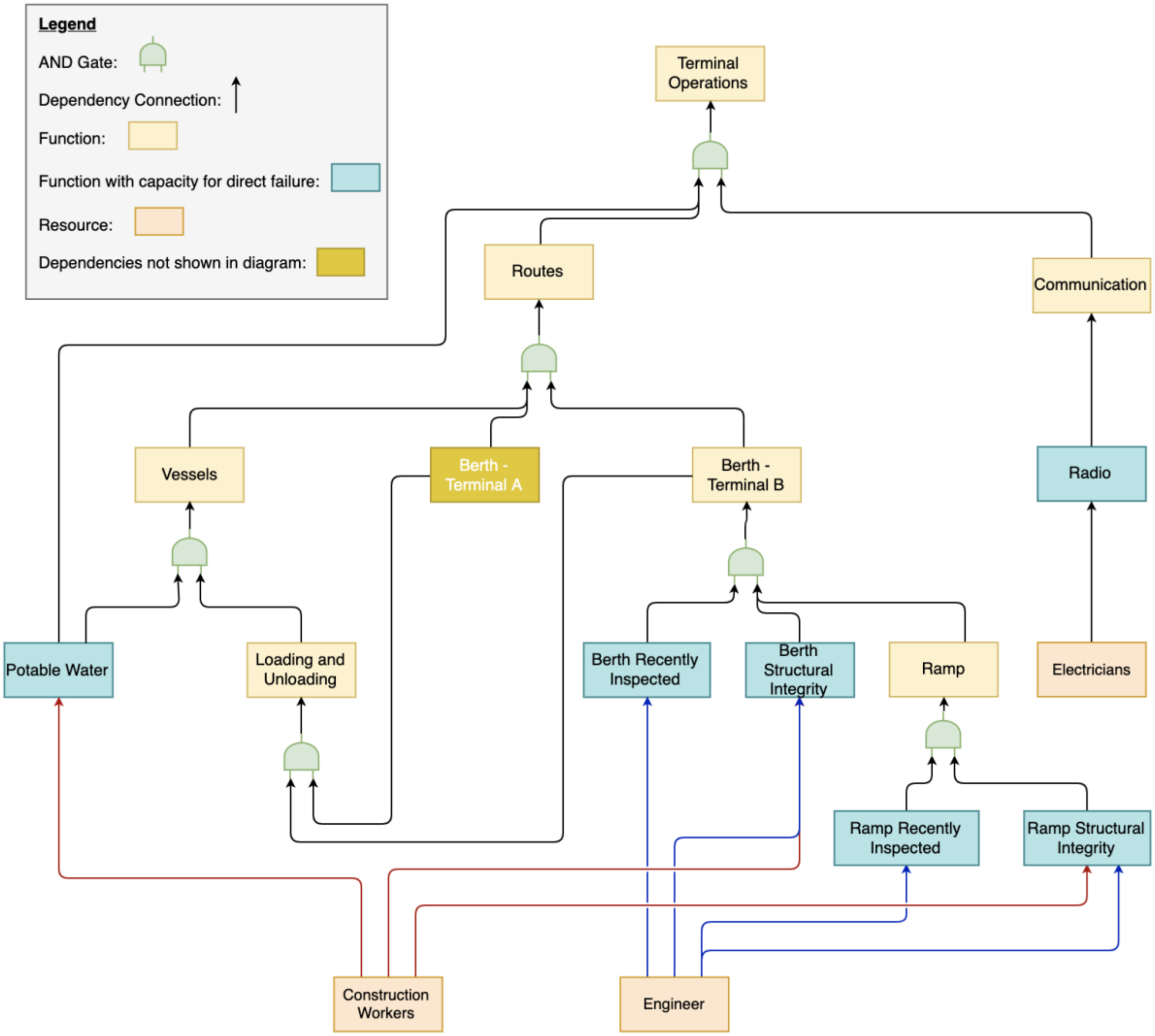


Figure 10: Simplified ferry terminal dependency map. Dependency connections with different colours are used for clarity purposes only.

The model is based largely on the recovery of BC Ferries and Seaspan Ferries terminals. In order to understand recovery on a community level, special entities have been created. The dependencies of these entities are described in Figure 11. Figure 11 shows the community service dependencies for Victoria, specifically; however, this diagram also represents the layout of how the Nanaimo dependencies are created as well. An explicit dependency diagram of both Victoria and Nanaimo's community service dependencies is provided in Appendix I: Community Service Recovery Dependency Diagram. Ultimately, the community service entities depend on the recovery of the ferry terminals. In order for “community service”, for a particular community, to be recovered, there must be at least one BCF terminal and one SFC terminal recovered in that community, or road connection must be intact to a community with those recovered terminals. Because road connection does not fail in this iteration of the model, if there is community service to either Victoria or Nanaimo, there will be community service recovery to the other. This is discussed further in the results. Passenger ferry service and access represents BCF operations, while freight ferry service and access represent SFC operations. “Access” is defined by there either being ferry service to the community itself, or there is road connection to a community with this type of ferry service. “Ferry service” is defined as having at least one of this type of ferry terminal—either BCF or SFC—recovered in a specific community.

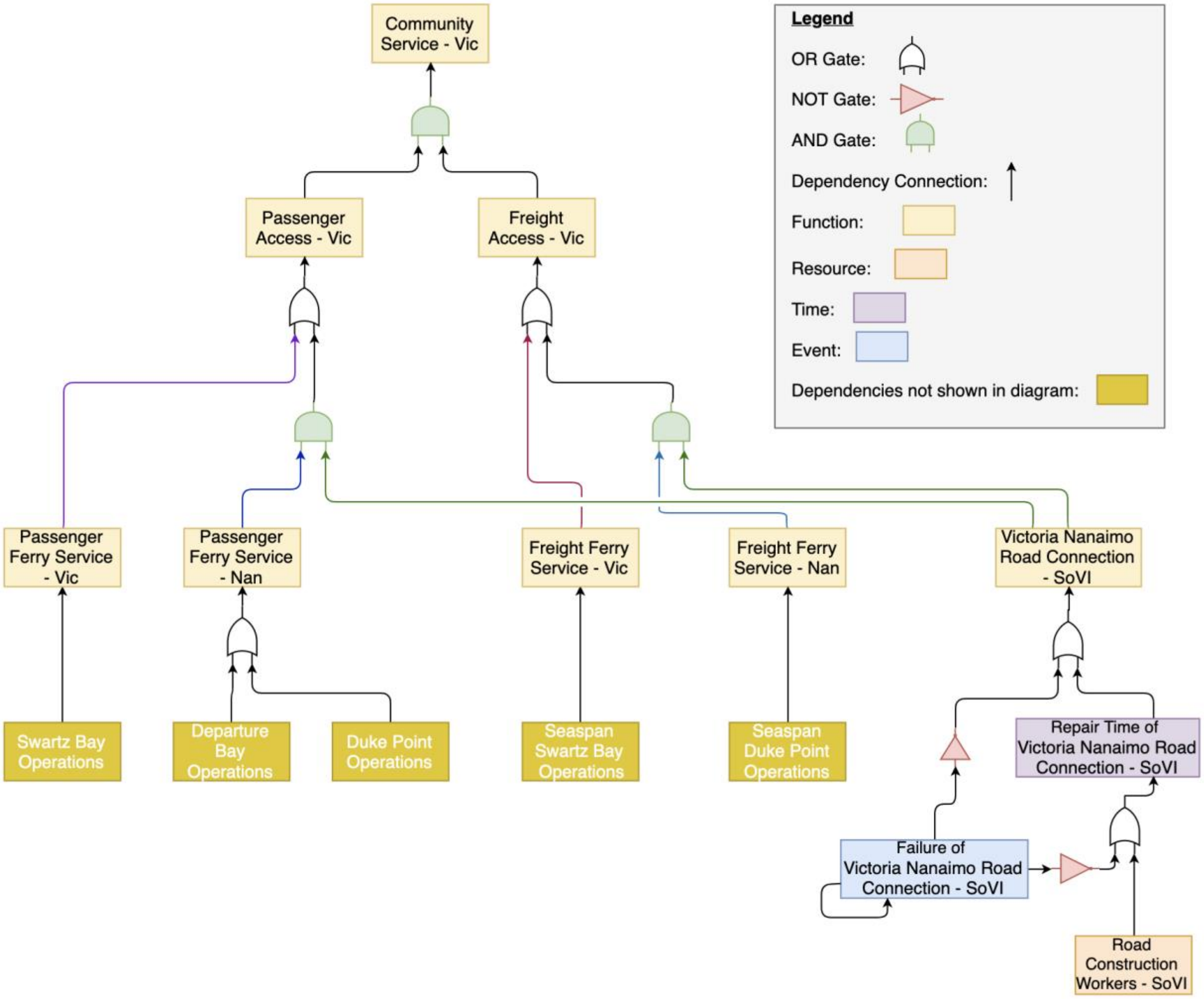


Figure 11: Community service dependency diagram for Victoria. Dependency connections with different colours are used for clarity purposes only.

3.8.4 Damage Functions for Case Study

The two damage functions that require case study specific inputs are the engineering damage inspection of berths and ramps and the clearing of marine routes. These are the two entities used in the case study in which Hazus data is not available. For the purposes of this case study, the assumption has been made that engineering inspection of all berths and ramps will be required post disruption event. The clear marine route entities are assumed to not fail in this iteration of the model. The damage functions for all the utility facility classes used in this model are provided in Appendix J: Damage Functions.

3.8.5 Restoration Functions for Case Study

The GMOR marine transportation model developed herein uses five damage states; this includes a "no damage" state (aka: damage state 1). All recovery times for damage state 1 have been set to zero, except for the "recently inspected" entities of the terminal berths and ramps. This is because the entities will not need any time to be repaired if they are undamaged (damage state 1), but, regardless of their damage state, the inspection will still need to take place. The inspection determines which damage state the ramps and berth are in and if they are safe to use.

Like their damage functions, the inspection of berths and ramps and the clearing of marine routes also require case study specific restoration functions. For this case study iteration, the mean has been set to 0.25 days and the standard deviation has been set to 0.2 for the engineering inspection of the berths and ramps. Meanwhile, the restoration function of clear marine routes is irrelevant due to the no-fail criteria in this case study. The impact of these assumptions on the results can be determined through sensitivity analysis in future iterations of the case study. The restoration functions for all the utility facility classes used in this model are provided in Appendix K: Restoration Functions.

4 Results and Discussion

The model provides the estimated recovery time of each of the nodes in the network model. The stochastic nature of the model results, due to the damage functions and the restoration functions, require the model to be run numerous times to determine a mean recovery time for the system. The Monte Carlo method is therefore used to obtain representative results of the mean recovery times.

4.1 Damage Probabilities

The damage probability curves for the entities in the model with the capacity for direct damage, are shown in Figure 12 and Figure 13, below. The data to produce these curves was obtained from Hazus (Federal Emergency Management Agency, 2013). The PGA values for the entity locations in this model are between 0.128 and 0.304. Figure 12 shows the probability of damage for berth and ramp entities within the model. The relevant range is shown with the red dashed rectangle. This figure shows that the probability of extensive damage is low, and damage between slight and none is relatively higher.

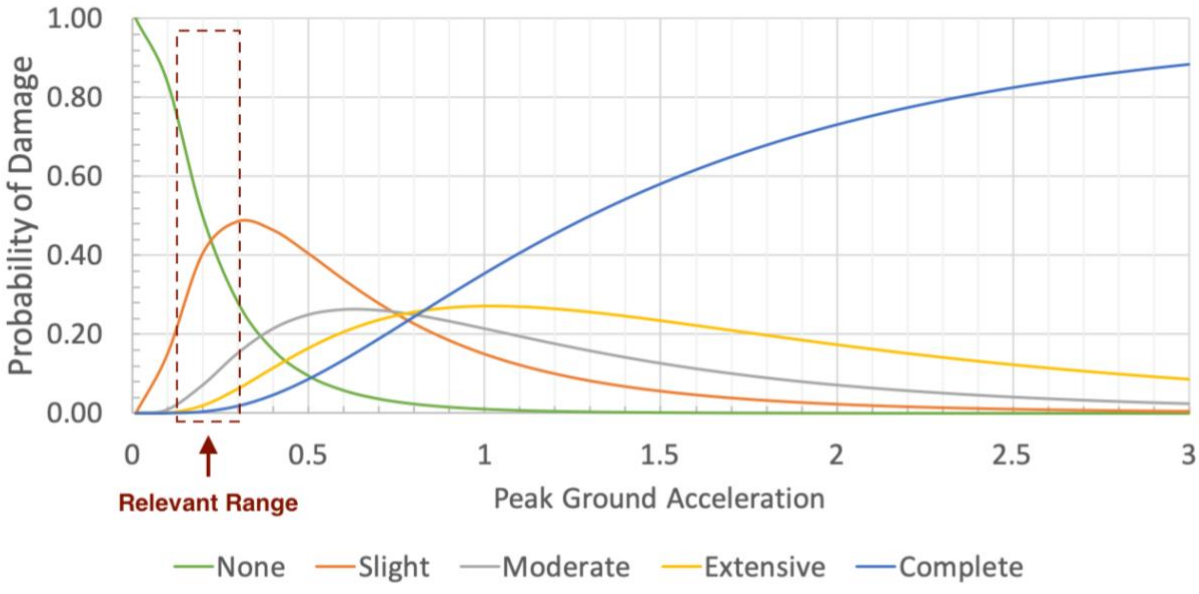


Figure 12: Probability of damage for berth and ramp structural integrity

Figure 13 shows default probability of damage for electricity, water, and radio entities from Hazus (Federal Emergency Management Agency, 2013)—external entities upon which marine transportation depends. Again, the relevant range is shown with the red dashed rectangle. In this figure, the most probable damage state is no damage, for the entire relevant range, followed by slight and moderate. The probability of extensive damage is low.

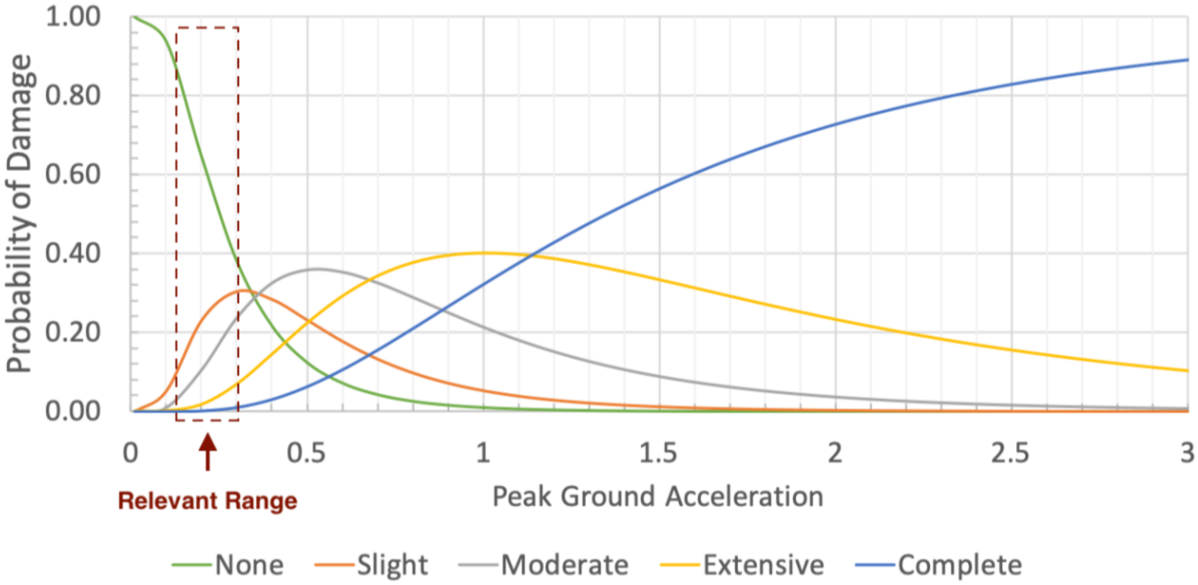


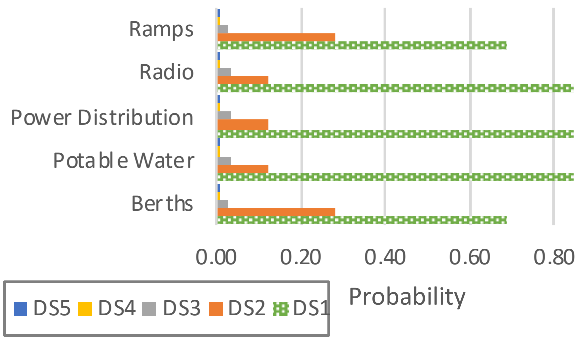
Figure 13: Probability of damage for electricity, water, and radio

Due to lack of data for determining permanent ground deformations, damage to roadways are not included explicitly in this iteration of the model results.

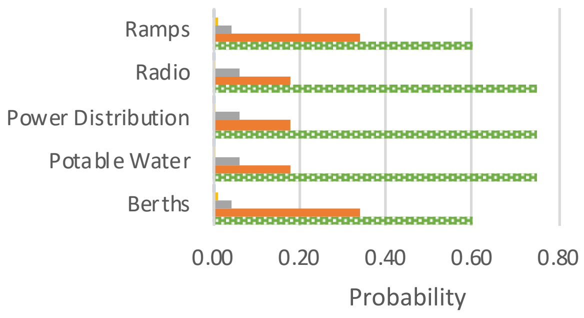
The peak ground acceleration ranges for each specific location within the model are listed, in ascending order, in Table 7, below. The strongest shaking among the model entities occurs along the Malahat drive from Victoria to Nanaimo. More generally, the locations on mainland BC experience less shaking than locations on Vancouver Island. These trends reveal themselves in the probabilities of component failures at terminals (Figure 14). The items of the top four graphs in the figure have higher probabilities of experiencing no damage (DS1) and are all on the mainland. The figure also shows how experiencing no damage or slight damage (DS2) are the most likely outcomes, meaning large catastrophic failures, though possible, are unlikely.

Table 7: Peak ground acceleration range by location, for entities within the model.

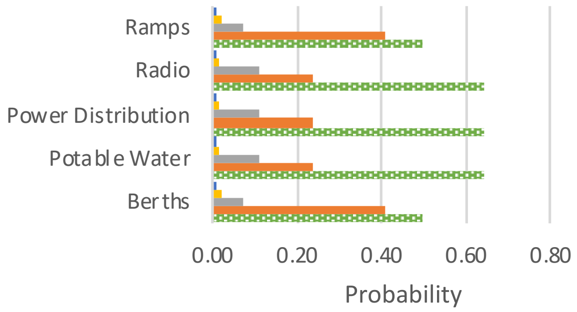
Location	**PGA Range**
Horseshoe Bay (BCF)	0.128 – 0.143
Surrey (SFC)	0.167 – 0.169
Tilbury Island (SFC)	0.179 – 0.180
Tsawwassen (BCF)	0.195 – 0.202
Marine Routes (BCF and SFC)	0.205 – 0.220
Duke Point (BCF and SFC) **Departure Bay (BCF)**	0.231 – 0.242
Swartz Bay (BCF and SFC)	0.244 – 0.266
Victoria Nanaimo Highway Connection (Malahat Drive)	0.304



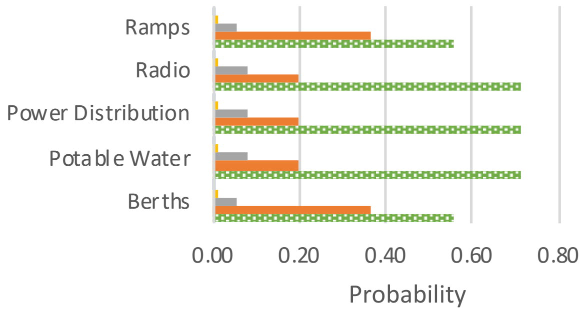
(a) Horseshoe Bay (BCF)



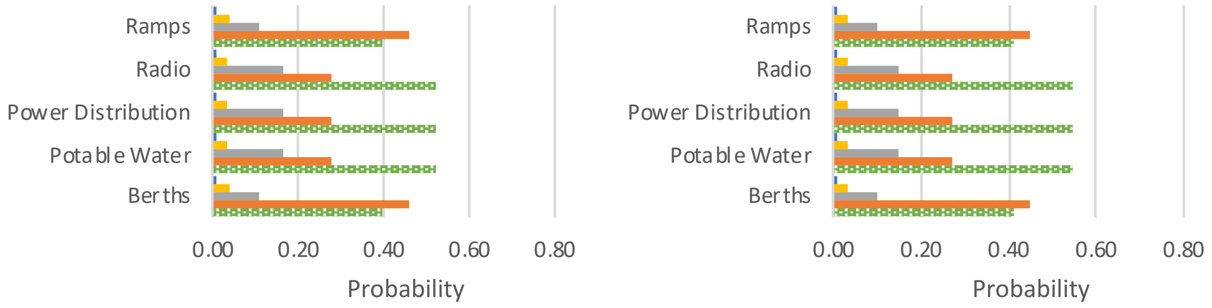
(b) Surrey (SFC)



(c) Tsawwassen (BCF)

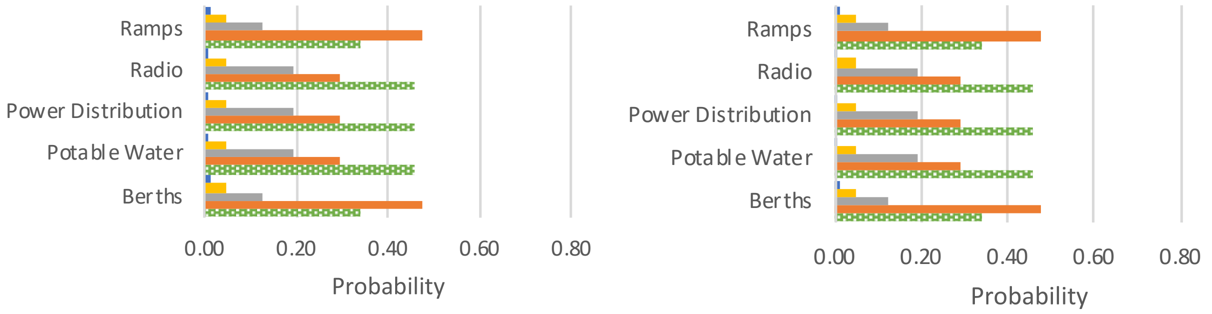


(d) Tilbury Island (SFC)



(e) Departure Bay (BFC)

(f) Duke Point (SFC)



(g) Swartz Bay (BCF)

(h) Swartz Bay (SFC)

Figure 14: Damage state probabilities at terminals. Terminals in (a)-(d) located on the mainland. Terminals in (e)-(h) located on Vancouver Island. Duke Point (BCF) terminal is not included as it is similar to Departure Bay (BCF). DS1 = no damage, DS2=slight, DS3=moderate, DS4=extensive, DS5=complete

4.2 Checking for Convergence

The marine transportation model simulation was first run with 500 iterations of stochastic damage state determination and deterministic recovery. Next, a simulation with both stochastic damage states and stochastic recovery was run with 500 iterations. The convergence of the average recovery time of the Vancouver Island marine transportation operations and 95% confidence interval are shown in Figure 15 and Figure 16, respectively. This convergence occurs at 76.1 days with a 7.4-day 95% confidence interval. This agrees with the result of the simulation when 500 iterations were run with stochastic damage but deterministic recovery, which had a Vancouver Island marine transportation operations average recovery time of 68.7 days with a 5.8-day 95% confidence interval. The 95% confidence interval of the stochastic recovery simulation overlaps with the mean of the deterministic recovery simulation.

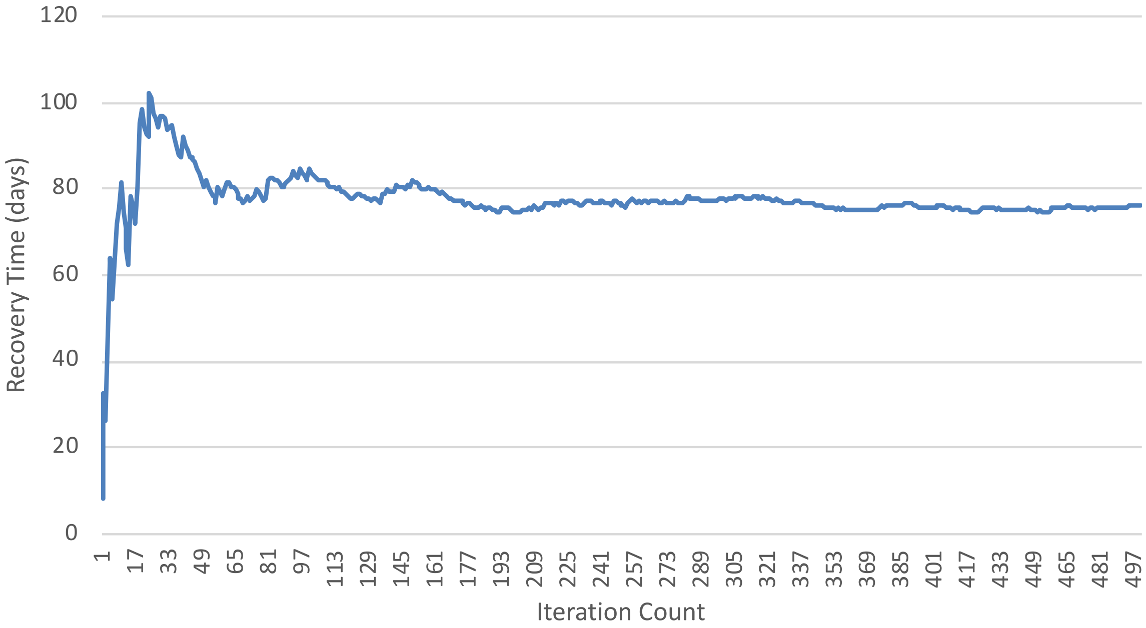


Figure 15: Running average of Vancouver Island marine transportation operations recovery time. Convergence occurs at 76.1 days.

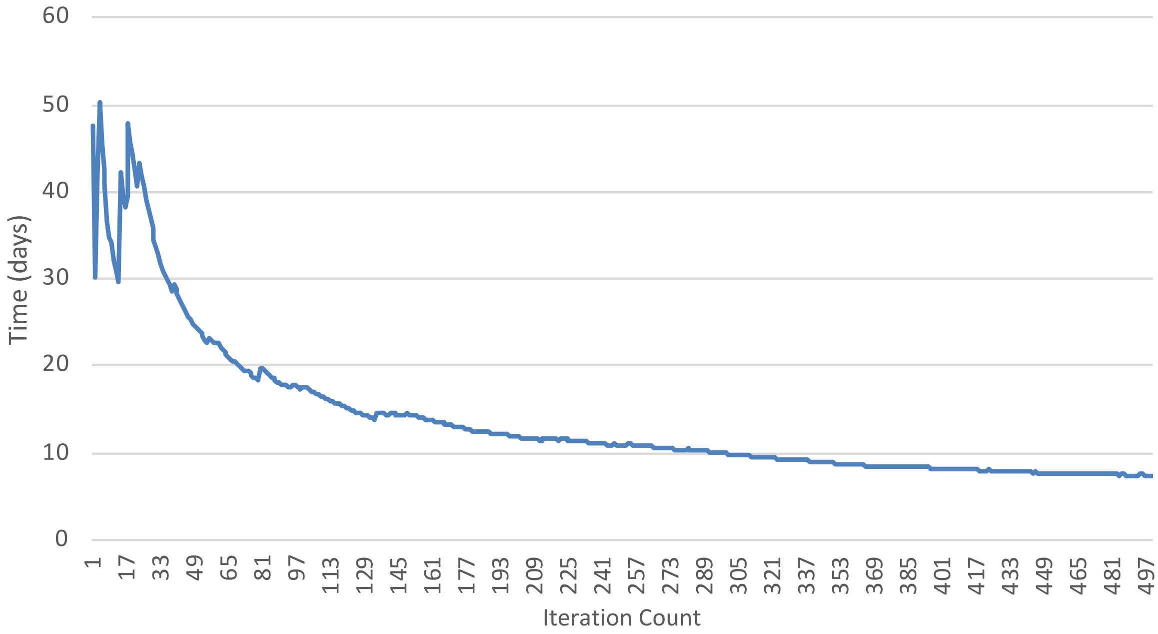


Figure 16: 95% Confidence Interval of Vancouver Island marine transportation operations. The 95% confidence interval of the 500 iterations is 7.4 days.

4.3 Minimum Service Recovered to Communities

The recovery time results are presented using box and whisker plots, where—due to the skewed nature of the results—the Y-axes are logarithmic. Like other box plots, these box plots show the minimum value, the 25th, 50th, and 75th percentiles, and the maximum value of the 500 iterations. Figure 17 shows the recovery time for different services to communities. In this figure, because roadway damage has been unable to be included in the model yet, community service recovery is the same for both Victoria and Nanaimo. In this context, the term "community service" means that there is at least some level of BCF service and some level of SFC service from the mainland to a particular community. The term "access" refers to there being either ferry service to the community from the mainland or road connection to a community with service. Therefore, if one of Victoria or Nanaimo is serviced, the other will automatically have access, provided that the road connection is intact. Passenger ferry service is provided by BCF; freight ferry service is provided by SFC. Figure 17 shows that in 75% of the iterations BCF service to Nanaimo terminals recovered within 2.2 days; meanwhile, the 75% iteration recovery of BCF service returning to Swartz Bay—Victoria's terminal—doesn't occur until 7.4 days. The 75% iteration recovery of SFC service recovery to Nanaimo terminals and Victoria terminals does not occur until 5.6 days and 90.1 days, respectively. Nanaimo routes and terminals recover more quickly because they are less likely to be damaged due to this area having a lower expected PGA for this earthquake than Victoria. This is interesting because the road connection between Victoria and Nanaimo is the area with the highest PGA in the model. So, if this road connection was damaged it is possible that service recovery to Victoria could take many days longer. This is something that needs to be further explored through sensitivity analysis.

Now, regardless of road connection availability, Figure 17 indicates that "community service" recovered for 25% of the iterations within 1.7 days and recovered for 75% of the iterations within 4.5 days. Although 2-5 days without service may not be too far out of the ordinary for some islands, the residents and economy of Vancouver Island are used to being serviced dozens of times per day, every day, year-round. A possible disruption of this length reinforces the importance of households being prepared with emergency supplies (particularly food, water, and medicine) for these types of disruptions. Furthermore, there is the possibility of significantly extended disruption, with the maximum community service recovery time occurring at 122 days over the 500 simulation iterations, as shown by the logarithmic Y-axis.

For the public, these results show that it would be prudent for households of Nanaimo to ensure they have five days' worth of food, water, and medicine in their earthquake preparedness supplies, and seven days' worth for Victoria residents. This is congruent with recommendations from the province, which state that although 72 hours' worth of supplies is the minimum requirement, in a catastrophic event, such as this scenario, residents should prepare to live independently for five to seven days post-disaster (Province of British Columbia, 2015).

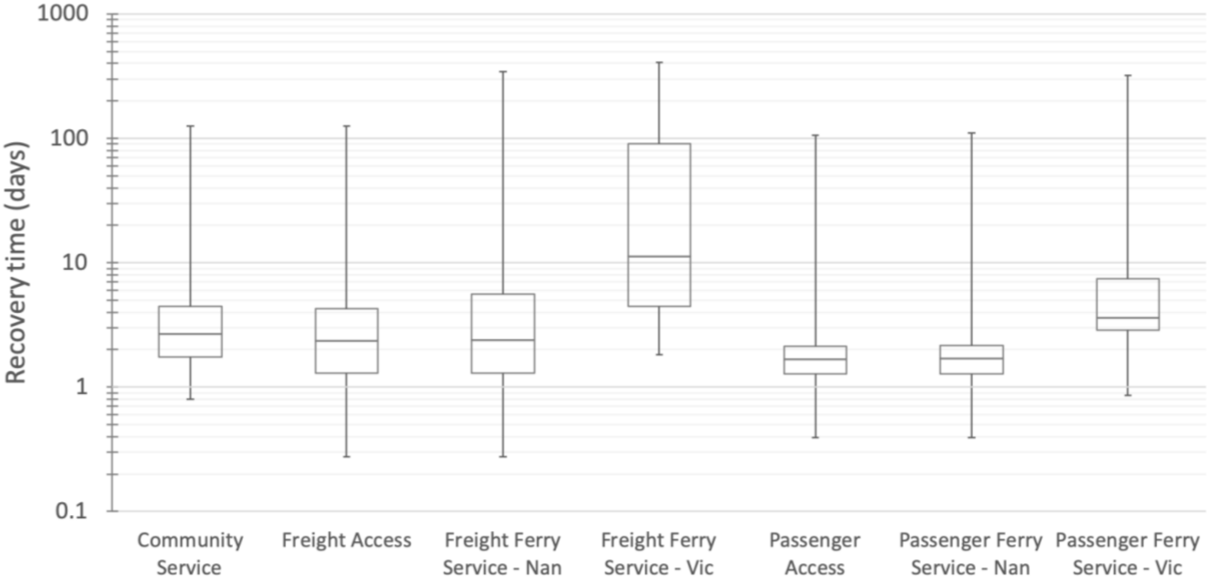


Figure 17: Community service recovery over 500 iterations. Passenger ferry service represents BC Ferries service. Freight ferry service refers to Seaspan Ferries is service. Community service means that a minimum level of passenger and freight terminals have resumed (though road access up island may be necessary); access means terminals of the given type are available (though road access up island may be necessary); and the remaining categories mean the given local terminal is functional.

A further breakdown of how these community service results are composed is available in the sections below for ferry terminal, berth and route, potable water, radio, and electricity recovery.

4.4 Ferry Terminal Recovery

To further understand the timeline of recovery to community service, the terminal recovery times of BC Ferries and Seaspan Ferries are shown in Figure 18 and Figure 19, below. These graphics show that the recovery of these terminals can take between 0.2 days (best case) and 410 days (worst case). For BCF terminals, the recovery range for 25%-75% of the iterations occurs between 1 and 8 days, with the exception of Tsawwassen occurring between 3 and 23 days. The BCF Tsawwassen terminal has a longer recovery time because this terminal requires both the Swartz Bay-Tsawwassen route and Duke Point-Tsawwassen route to be recovered before the terminal itself is considered recovered; this is a greater number of route dependencies than the other terminals have.

SFC terminal recovery is much more varied. For SFC Duke Point and Surrey terminals, the recovery range for 25%-75% of the iterations occurs between 1 and 6 days. Meanwhile, for SFC Swartz Bay and Tilbury Island, the recovery for 25%-75% of iterations occurs between 4 and 101 days. The recovery time has greater variability for SFC due to the resource order prescribed in the model. Terminals in locations that share a location name (e.g., BCF Swartz Bay and SFC Swartz Bay or BFC Duke Point and SFC Duke Point) also share recovery resources. In these situations, the priority of the resources is to recover BCF entities before addressing SFC entities. In this case, the SFC Swartz Bay terminal has a wider recovery time range due to the time for this terminal to obtain a recovered berth, shown in section 4.5 Berth and Route Recovery. Likewise, due to the route connection, the SFC Tilbury Island terminal also depends on an SFC Swartz Bay recovered berth. A strategy to explore for reducing the recovery time of these terminals would be to provide immediate recovery resources to the SFC Swartz Bay berth.

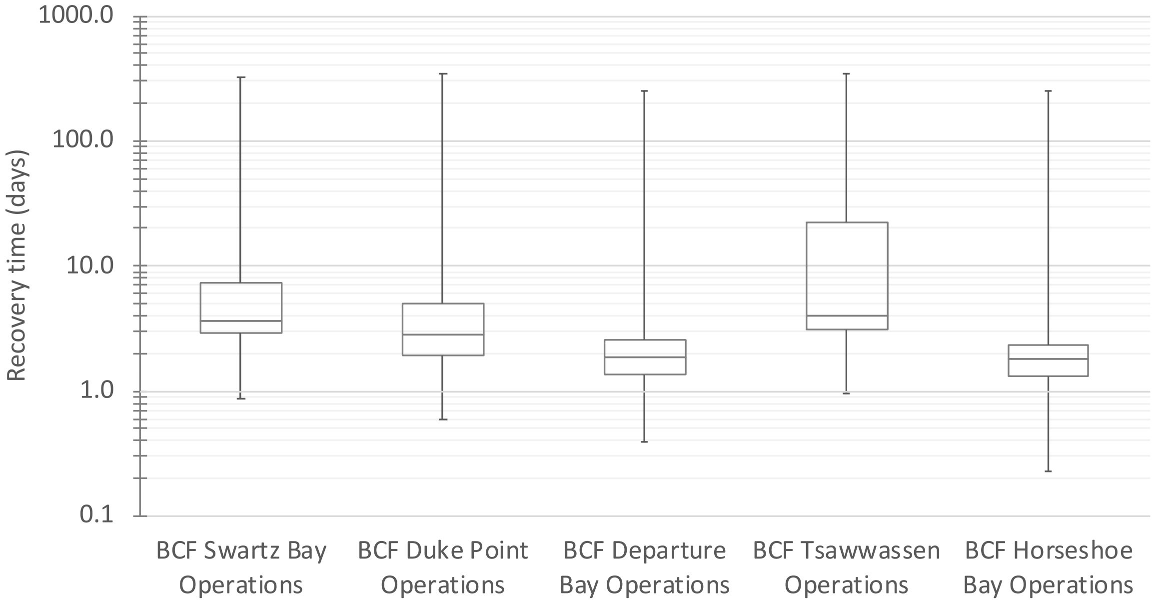


Figure 18: BC Ferries terminal recovery times over the 500 simulation iterations

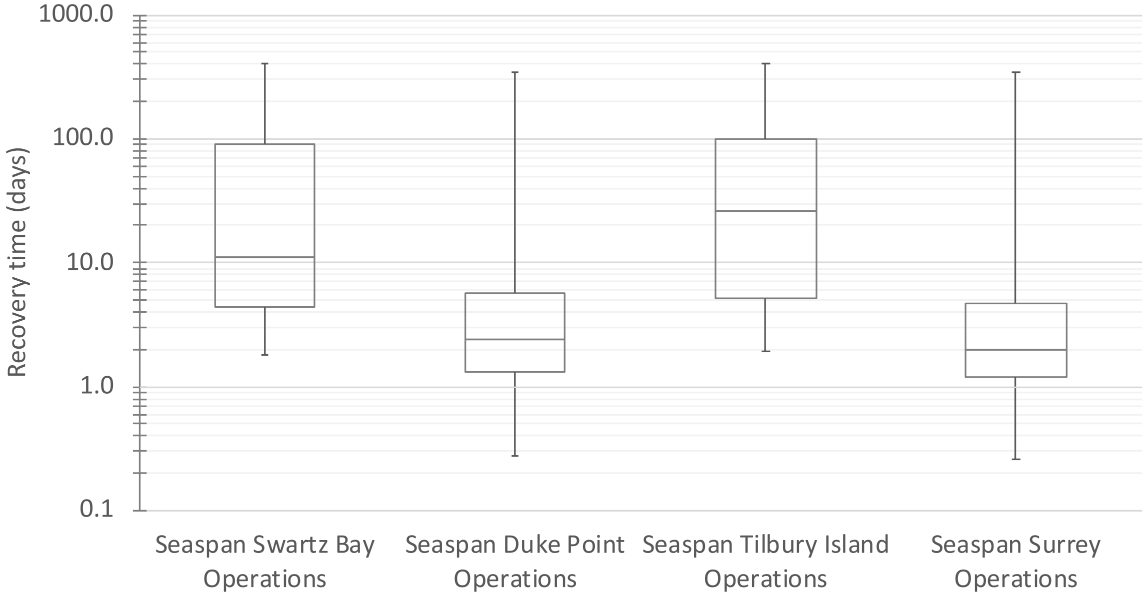


Figure 19: Seaspan Ferries terminal recovery times over the 500 simulation iterations

4.5 Berth and Route Recovery

Berth and route recovery are critical components of terminal recovery. Berth recovery for the nine ferry terminals are shown in Figure 20, with more detail provided in Appendix L: Berth Recovery Results. The dependency nature of the model requires that only one large berth be recovered in order for the terminal operations to be functional. Therefore, the terminal operations sometimes recover after one berth is recovered, but before all berths are recovered. In Figure 20, the minimum recovery time for at least one berth to be recovered at BCF Tsawwassen, BCF Horseshoe Bay, SFC Tilbury Island, and SFC Surrey is 0.0 days; this is indicated by an extended bottom whisker on the log-scale graph. The BCF Duke Point terminal as well as all of the SFC terminals, except for Tilbury Island, only have one berth at the terminal.

Berth recovery happens more quickly for terminals on the BC mainland than for Vancouver Island terminals because the probability of damage is lower for the mainland. Similarly, Swartz Bay terminals have the highest recovery times because their damage is greater than berths in Nanaimo. Finally, SFC Swartz Bay and SFC Duke Point berths have the highest recovery times because these terminals share resources with the respective BC Ferries terminals and these resources are allocated in the model to first recover BC Ferries berths before recovering Seaspan Ferries berths.

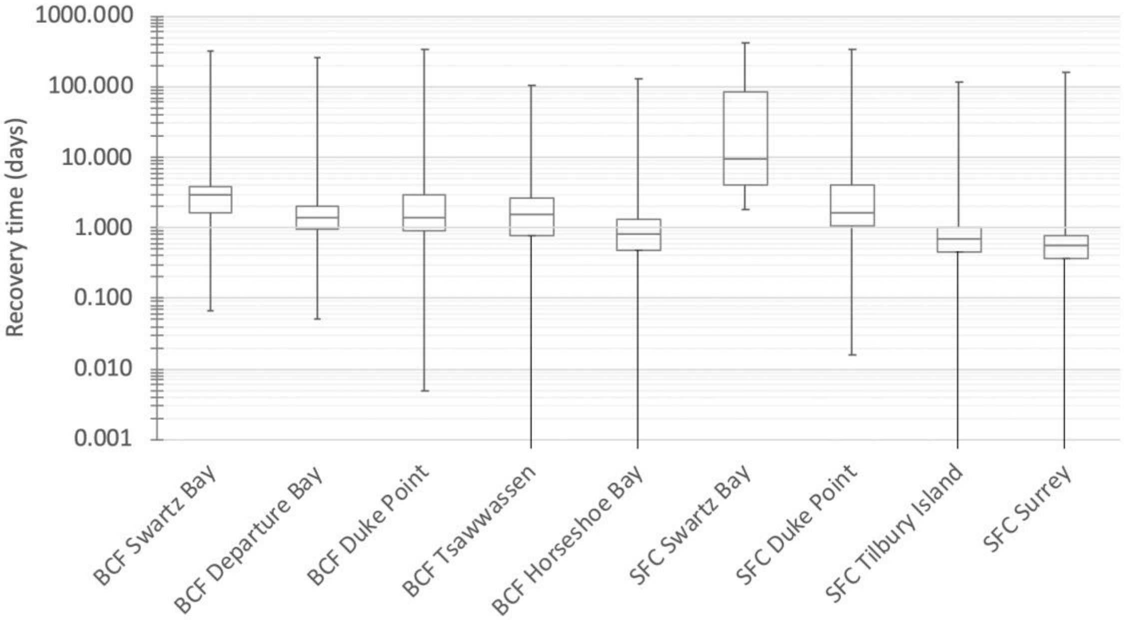


Figure 20: Recovery of at least one berth per terminal over the 500 simulation iterations

The route recovery times are shown in Figure 21 along with the community service recovery for Victoria and Nanaimo for comparison's sake. The recovery of routes follows the same trend as the recovery of berths, with the Seaspan Ferries Swartz Bay-Tilbury Island taking the longest to recover due to the recovery time of SFC Swartz Bay berths.

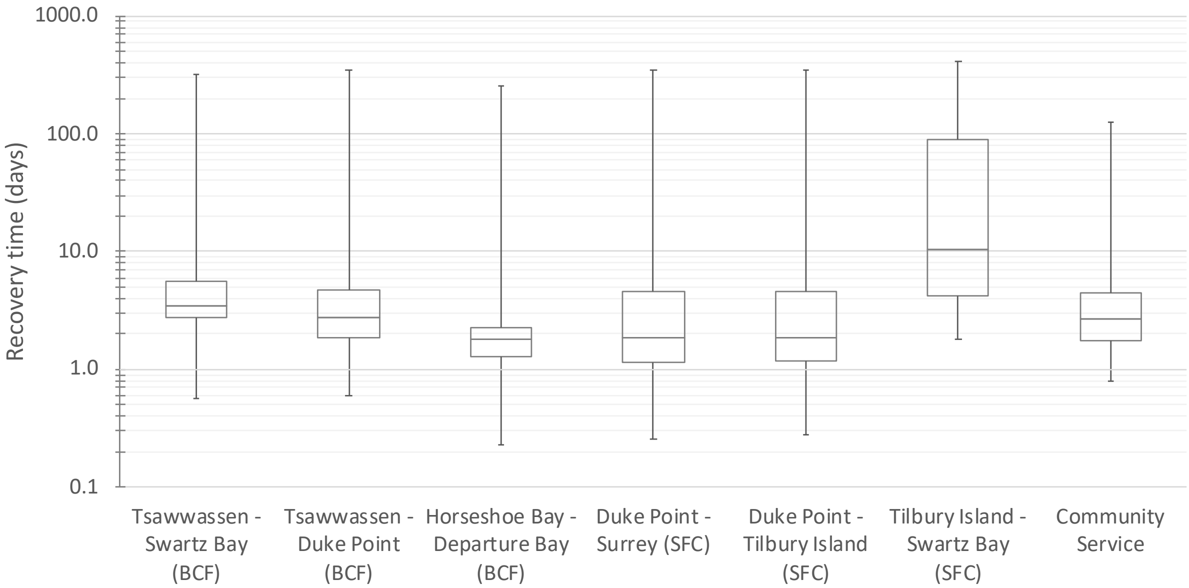


Figure 21: Route recovery over 500 simulation iterations

4.6 Electricity, Potable Water, and Radio Recovery

Electricity, potable water, and radio are the remaining required dependencies for terminal recovery in the model. Although required, these dependencies are generally not the constraint on terminal recovery. This is shown in Table 8, where it is only between the 75th-100th percentiles of the 500 iterations that the recovery times for these entities become significant. Otherwise, it is the berth/ramp recovery that is the limiting factor. It is worth noting, however, that a more detailed model of these sectors may be beneficial to refine initial estimates of these recovery times.

One of the critical dependencies of ferry terminal operations is electricity for berth ramp operation. However, because all BCF and SFC terminals have back-up power, which is not expected to fail, grid electricity recovery is not a requirement for the terminals to be recovered in the model results. Regardless, understanding how long it may take for grid electricity to return to each terminal, is imperative to prepare the appropriate quantity of back-up power fuel reserve, and indeed ensure that back-up power does not fail.

Table 8: Grid electricity, potable water, and radio 75th percentile and maximum recovery times for the 500 iterations.

	Grid Electricity		**Potable Water**		**Radio**	
	75th Percentile (days)	**Maximum (days)**	**75th Percentile (days)**	**Maximum (days)**	**75th Percentile (days)**	**Maximum (days)**
Swartz Bay (BCF)	1.8	42.7	1.2	148.5	0.6	127.4
Departure Bay (BCF)	1.1	15.0	0.9	108.3	0.6	25.4
Duke Point (BCF)	1.4	114.0	1.0	88.5	0.5	12.7
Tsawwassen (BCF)	0.7	18.3	0.8	105.7	0.5	17.7
Horseshoe Bay (BCF)	0.1	5.4	0.0	36.7	0.0	30.9
Swartz Bay (SFC)	2.2	128.6	1.7	150.1	1.1	42.4
Duke Point (SFC)	1.7	114.5	1.5	204.0	0.6	113.9
Tilbury Island (SFC)	0.5	16.7	0.5	108.8	0.0	16.7
Surrey (SFC)	0.4	6.3	0.0	56.3	0.0	8.9

4.7 Risk Treatments

Upon understanding the baseline recovery timelines for the marine transportation infrastructure that services Vancouver Island, risk treatments designed to diminish these recovery timelines can be considered. Risk treatments come in six forms: dispersion, flexibility, diversity, redundancy, hardening, and restorability (Bristow & Hay, 2016). Sensitivity analysis may be conducted with the model to determine the impact of different risk treatment ideas on the recovery timeline results. A possible risk treatment idea that can be tested is the prioritization of recovery by damage state rather than by entity. Placing the priority of recovery resources on the entities that have the lowest damage state first, as opposed to a pre-assigned order, may aid in reducing recovery times for community service. This is an example of prioritizing restorability within the recovery phase. Another risk treatment that would benefit from sensitivity analysis is removing the resource competition by ensuring there are sufficient resources for all damaged entities to use recovery resources simultaneously. This is an example of increasing redundancy of recovery resources.

Another risk treatment strategy is hardening the infrastructure against earthquake shaking. One way to harden berth and ramp infrastructure is through floating docks. Currently, only one BCF Swartz Bay berth contains a floating dock that would withstand a M9.0 earthquake (Smart, 2017). Hardening the infrastructure is a risk treatment that is unable to be tested in the model, at this time, due to the damage and restoration function data available. Although the Hazus methodology has been exceptionally useful for this research, as it provides a uniform source of damage function and restoration function data on a vast array of infrastructure types, there are also limitations with this resource. Because the data is from the United States, the damage curves do not necessarily represent the BC Building Code requirements at the time of construction. Ideally, there would be location specific damage functions for each of the terminals' entities—especially the berths—and restoration functions would be specific to the region and current year. Unfortunately, this data is not available, and the Hazus data is the best available option for this model. However, should modified fragility curves—for actual and hardened infrastructure—become available, this model could be used to test the impact of those changes, and ultimately be used for future decision making at a provincial planning level.

Other risk treatment options include increasing redundancy, diversity, and dispersion within the infrastructure; however, this is unlikely to have as significant an effect as hardening infrastructure or increasing recovery resource availability because BCF and SFC operations already utilize many of these strategies. Redundancies within the ferries' operations include the existence of multiple terminals on both mainland and Vancouver Island sides, as well as multiple berths at many terminals. Diversity exists from BCF and SFC both being capable of operating as freight transporters. Furthermore, if Seaspan Ferries berths are inoperable, Seaspan Ferries vessels are capable of connecting to BC Ferries berths and ramps—an example of flexibility within the system. Another example of how BCF and SFC utilize these strategies is through their electricity dependency. Although their systems run ideally off of grid electricity, all terminals contain back-up power generators. As a third option, it is also possible for BCF ramps to be connected to and powered by BCF vessel electricity.

4.8 Future Work

The research that composes this thesis is part of a larger ongoing shipping resilience project labeled the Strategic Planning for Coastal Community Resilience to Marine Transportation Disruption (SIREN) project. The future work involved with this element of the SIREN project includes further validation of the model with stakeholders and testing the risk treatment ideas discussed previously in section 4.7. Finally, there are some further topics to consider if the model is to be built on further with future revisions.

4.8.1 Validation

The Hazus damage and restoration curve methodology has been created and tested using expert judgement, along with, where possible, testing against historical earthquake data (Federal Emergency Management Agency, 2013). However, due to limited past earthquakes and available data, complete calibration of the methodology is impossible. Uncertainty is also an unavoidable aspect of loss estimation methodologies. Reasons for uncertainty include incomplete scientific knowledge on the effect earthquakes have on buildings and facilities, approximations and simplifications made to obtain a comprehensive analysis, and incomplete or inaccurate inventories of the building environment (Federal Emergency Management Agency, 2013). In light of the validation challenge the Hazus methodology presents, the results from this work are not a prediction of exactly what will happen in this earthquake scenario, but rather they provide a concrete example of possible disaster recovery timelines to bring back to stakeholders.

4.8.2 Further Considerations

The scope of this model is the operations and dependencies of BC Ferries and Seaspan Ferries. There are possible damages that may affect recovery that have not been accounted for in this model. If this model is being revised for future use, there are a few adjustments that could be made to the model including determining roadway damage, considering the possibility of personnel shortage or redundancies, and defining provincial fuel availability.

If PGD is ultimately able to be obtained, including the failure expectation and recovery timelines of the ferry terminal highway approaches and the Victoria Nanaimo road connection would strengthen the model results.

Failure of personnel to show up at work for reasons other than roadway damage has not been accounted for in this model. However, there are many scenarios that could create a personnel shortage. These reasons may be an unsafe living environment, shortage of fuel for personal vehicles, sick or injured family members, or lack of childcare, post disaster. It is critical that marine transportation operators consider the needs of their crew and their critical personnel's families in order to maintain operation in a post-disaster scenario. While shortages are a concern, there is also the possibility of redundancy or flexibility of personnel in that it may be possible for available personnel to serve on different routes depending on where they are following an earthquake. In the future, the model could be updated to account for these possibilities, as well as the home-terminals—or likely start point after an earthquake—of individual vessels.

The failure of electrical power plants is also out of scope of the current model. Only the failure of distribution circuits within the electrical power system are considered. Although this exclusion does not affect the results themselves, due to the inclusion of back-up power at all terminals, it would still be useful to include this in order to help understand the recovery of communities. It is assumed that the province will divert fuel priority to provide critical marine transport needs, due to their importance. Although a provincial investigation of fuel availability after a Cascadia subduction zone earthquake has never been completed, this assumption is considered valid according to the B.C. Earthquake Immediate Response Plan (Province of British Columbia, 2015). Taken together, these are issues that this model can support in future iterations to support provincial decision making and community planning.

5 Conclusions

This work examines the resilience of marine transportation operators serving Vancouver Island. This thesis presents a model that graphically simulates the system response and recovery timelines following disruption. The model is created using the GMOR platform with operations and disaster response information collected from stakeholder engagement workshops and the Hazus technical manual (Federal Emergency Management Agency, 2013). The model includes the interdependent relationships of systems and provides recovery timeline results with respect to the cascade of failure and recovery dependencies. The case-study examines a M9.0 Cascadia subduction zone earthquake disaster scenario. This thesis identifies the dependencies of BC Ferries and Seaspan Ferries operations with respect to connecting Vancouver Island to Metro Vancouver. Post-disruption recovery timeline scenarios are produced for routes and terminals servicing Vancouver Island communities.

The results indicate that berth and ramp recovery is the limiting factor for terminal recovery in most cases. Possible risk treatment strategies for improving this recovery are discussed and include increasing recovery resources, reprioritizing recovery resources, or hardening berth and ramp infrastructure. For the public, these results show that it would be prudent for households of Nanaimo to ensure they have five days' worth of food, water, and medicine in their earthquake preparedness supplies, and seven days' worth for Victoria residents, when preparing for the Cascadia earthquake. Note, however, that these figures are based on the 75% percentile case; that individual's risk tolerance or needs may vary; and uncertainty remains in any such analysis of potential outcomes of a disaster. In this case, future work could aim to address some of the uncertainty through assessment of PGD for estimating roadway damage and detailed assessments of the fragility of BC infrastructure.

As the only network recovery model for marine transportation operations serving Vancouver Island, this work contributes an important improvement in understanding marine transport risk in BC and can help aid marine transportation operators and stakeholders in preparing for large earthquakes by identifying operational vulnerabilities. Sensitivity analysis of risk treatments and validation through stakeholder review will be conducted by the SIREN project team. Beyond the SIREN project, future work may involve applying this model to other disruption scenarios or incorporating this model with other models to create a larger disruption recovery scope.

Bibliography

BC Ferries. (2018a). Our Fleet. Retrieved January 4, 2019, from https://www.bcferries.com/onboard-experiences/fleet

BC Ferries. (2018b). Where We Sail. Retrieved January 7, 2019, from https://www.bcferries.com/at_the_terminal/where-we-sail.html

BC Ferries. (2019). BC Ferries: Metro Vancouver - Vanoucouver Island and Sunshine Coast Route Maps. Retrieved March 26, 2019, from https://www.bcferries.com/schedules/mainland/maps.html

Bristow, D. N. (2019). How Spatial and Functional Dependencies between Operations and Infrastructure Leads to Resilient Recovery. *Journal of Infrastructure Systems*, *25*(2), 1–8. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000490

Bristow, D. N., & Hay, A. H. (2016). Graph Model for Probabilistic Resilience and Recovery Planning of Multi-Infrastructure Systems. *Journal of Infrastructure Systems*, *23*(3), 1–10. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000338.

British Columbia Ferry Services Inc., & B.C. Ferry Authority. (2018). *Annual Report 2017-2018*. Retrieved from https://www.bcferries.com/files/AboutBCF/AR/bcfs_annualreport_2017-2018.pdf

Canadian Coast Guard. (2019). Marine Communications and Traffic Services MCTS. Retrieved May 15, 2019, from http://www.ccg-gcc.gc.ca/Marine-Communications/Home

Dangerfield, K. (2018, January 23). ‘Inevitable’ 9.0 earthquake, tsunami will hit Canada’s West Coast: expert. *Global News*. Retrieved from https://globalnews.ca/news/3981536/tsunami-earthquake-canada-the-big-one/

Deelstra, A. (2019). *Disaster Recovery Modeling for Multi-damage State Scenarios Across Infrastructure Sectors*. University of Victoria. https://doi.org/10.1017/CBO9781107415324.004

Federal Emergency Management Agency. (2013). *Hazus - MH 2.1 Technical Manual - Earthquake Model*. Washington, DC: U.S. Department of Homeland Security. Retrieved from https://www.fema.gov/media-library/assets/documents/24609

Geological Survey of Canada. (2019). *Personal Communication*.

Islam, S. (2019). Personal Communication. Halifax: Dalhousie University.

Liao, S. S. C., Veneziano, D., & Whitman, R. V. (1988). Regression models for evaluating liquefaction probability. *Journal of Geotechnical Engineering*, *114*(4), 389–411. Retrieved from https://www-sciencedirect-com.ezproxy.library.uvic.ca/science/article/pii/0148906288911680

Murray, N. (2019, March 18). Vancouver Island overdue for the big one, can also expect mega-thrust tsunami. *Victoria News*. Retrieved from https://www.vicnews.com/news/vancouver-island-overdue-for-the-big-one-can-also-expect-mega-thrust-tsunami/

Natural Resources Canada. (2015). *BC Seismic Hazard Map 2015*.

Natural Resources Canada. (2018). Southwestern British Columbia - Earthquakes of the last 5 years. Retrieved May 31, 2018, from http://www.earthquakescanada.nrcan.gc.ca/recent/maps-cartes/index-en.php?maptype=5y&tpl_region=swbc

Province of British Columbia. (2015). *B.C. Earthquake Immediate Response Plan*. Retrieved from https://www2.gov.bc.ca/assets/gov/public-safety-and-emergency-services/emergency-preparedness-response-recovery/provincial-emergency-planning/irp.pdf

Schulz, K. (2015, July 13). The Really Big One. *The New Yorker*. https://doi.org/10.7312/asme16957-009

Seaspan. (2019). About Seaspan. Retrieved January 7, 2019, from https://www.seaspan.com/about-seaspan

Seaspan Ferries Corporation. (2016). Seaspan Ferries Corporation Announces Arrival of First New Liquefied Natural Gas (LNG) Fuelled Vessel. Retrieved May 15, 2019, from https://www.seaspan.com/seaspan-ferries-corporation-announces-arrival-first-new-liquefied-natural-gas-lng-fuelled-vessel

Seaspan Ferries Corporation. (2017). Seaspan Ferries Corporation Announces Arrival of Second New Liquefied Natural Gas (LNG) Fuelled Vessel. Retrieved May 15, 2019, from https://www.seaspan.com/seaspan-ferries-corporation-announces-arrival-second-new-liquefied-natural-gas-lng-fuelled-vessel

Seaspan Ferries Corporation. (2019). Commercial Ferry Service From Vancouver Island to the Lower Mainland. Retrieved April 12, 2019, from https://www.seaspan.com/seaspan-ferries

Seemann, M., Onur, T., & Cloutier-Fisher, D. (2011). Earthquake shaking probabilities for communities on Vancouver Island, British Columbia, Canada. *Natural Hazards*, *58*(3), 1253–1273. https://doi.org/10.1007/s11069-011-9727-6

Smart, A. (2017, March 18). Major quake would destroy B.C. Ferries berths, experts warn. *Times Colonist*. Retrieved from https://www.timescolonist.com/news/local/major-quake-would-destroy-b-c-ferries-berths-experts-warn-1.12165845

Upland Agricultural Consulting. (2016). *District of Saanich Agriculture and Food Security Plan Background Report*. Saanich. Retrieved from https://www.saanich.ca/assets/Community/Documents/Planning/BackgroundReportAFSP0525.pdf

Appendix A: BC Ferries Tsawwassen Operations GMOR Model Diagram

The figures in this appendix compose the entities and relationships of the BC Ferries Tsawwassen operations model. The Tsawwassen operations are also representative of the other BC Ferries terminal operations. The acronyms used in the marine transportation GMOR model are defined in Appendix C: GMOR Model Acronyms. The Tsawwassen operations dependencies are broken down into three figures in this appendix. The terminal dependencies are shown in Figure 22, the berth dependencies are shown in Figure 23, and the alternative emergency routes dependencies are shown in Figure 24.

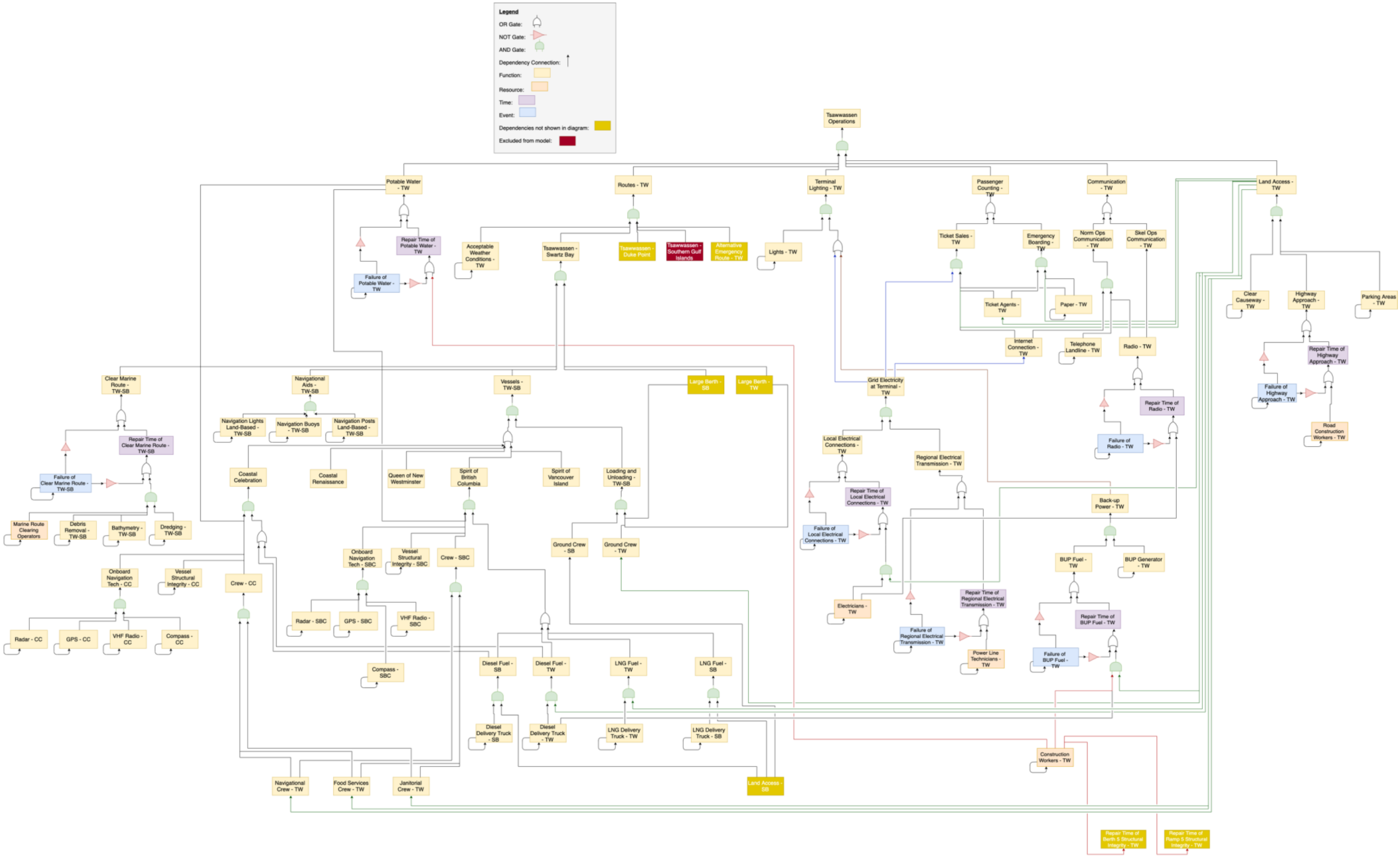
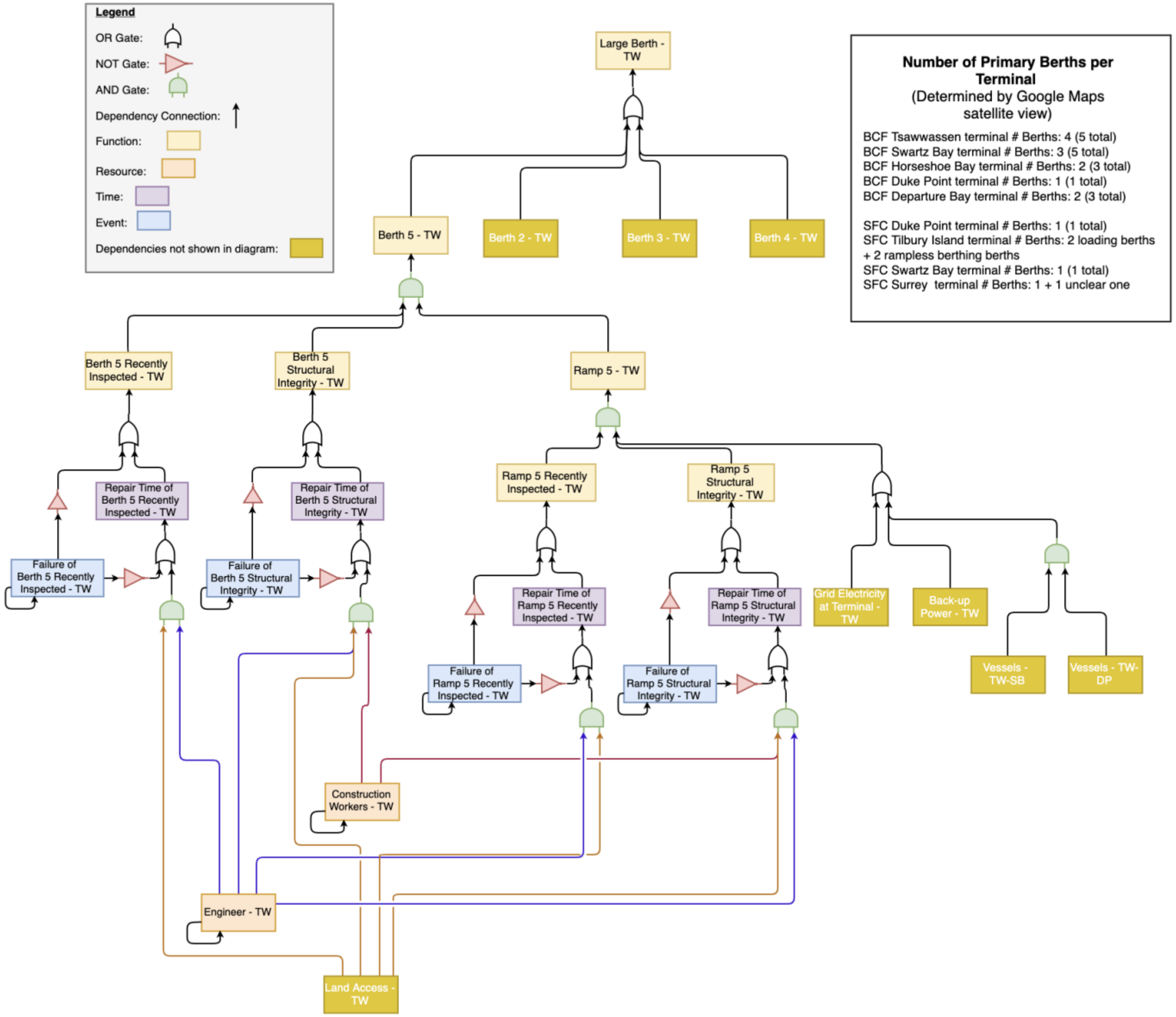


Figure 22: Terminal dependencies for BC Ferries Tsawwassen operations model



Number of Primary Berths per Terminal
(Determined by Google Maps satellite view)

BCF Tsawwassen terminal # Berths: 4 (5 total)
BCF Swartz Bay terminal # Berths: 3 (5 total)
BCF Horseshoe Bay terminal # Berths: 2 (3 total)
BCF Duke Point terminal # Berths: 1 (1 total)
BCF Departure Bay terminal # Berths: 2 (3 total)

SFC Duke Point terminal # Berths: 1 (1 total)
SFC Tilbury Island terminal # Berths: 2 loading berths + 2 rampless berthing berths
SFC Swartz Bay terminal # Berths: 1 (1 total)
SFC Surrey terminal # Berths: 1 + 1 unclear one

Figure 23: Berth dependencies for BC Ferries Tsawwassen operations model

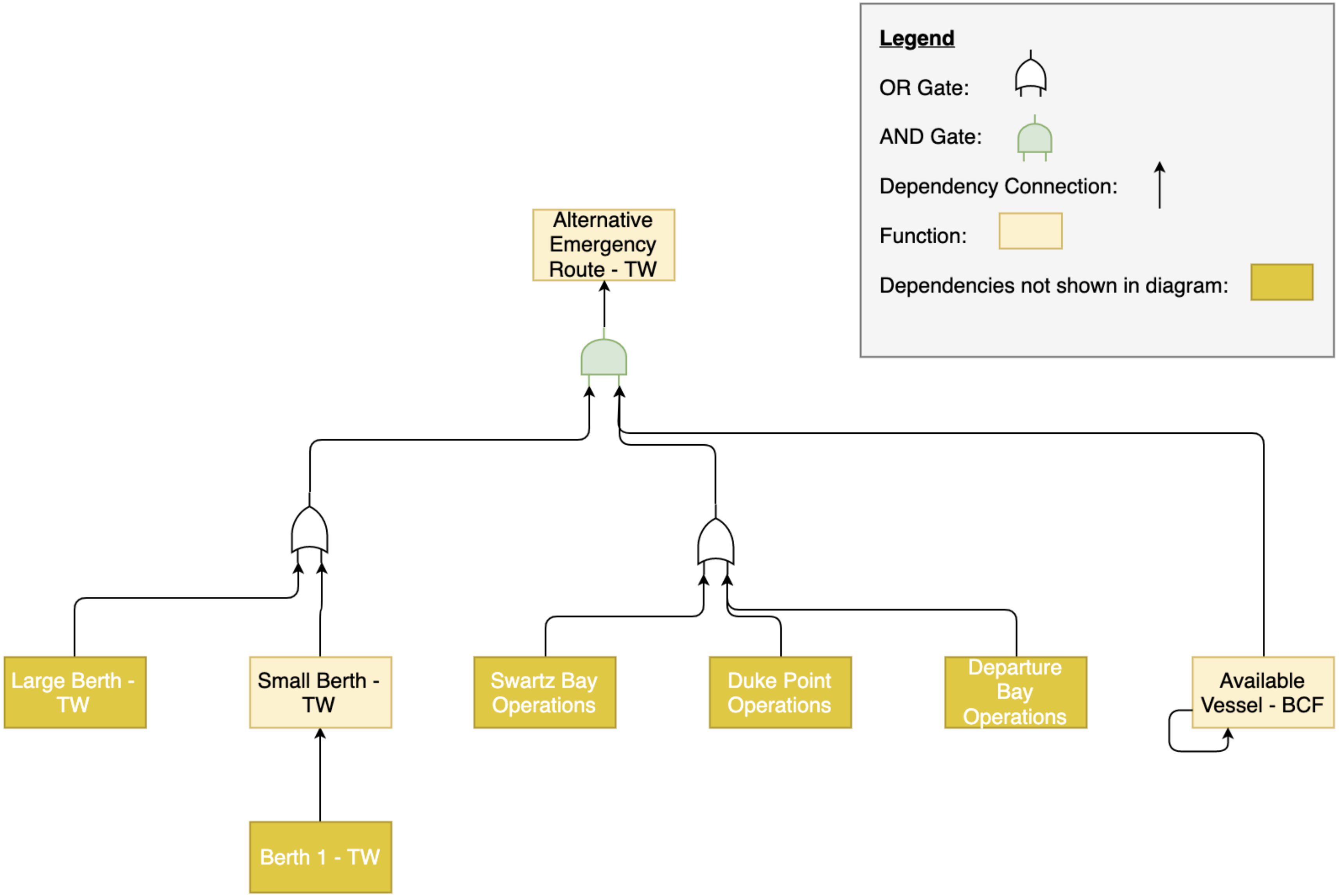


Figure 24: Alternative emergency route dependencies for BC Ferries Tsawwassen operations model

Appendix B: Seaspan Ferries Duke Point Operations GMOR Model Diagram

The figure in this appendix composes the entities and relationships of the Seaspan Ferries Duke Point Operations model. This figure is also representative of the other Seaspan Ferries terminal operations. The acronyms used in the marine transportation GMOR model are defined in Appendix C: GMOR Model Acronyms.

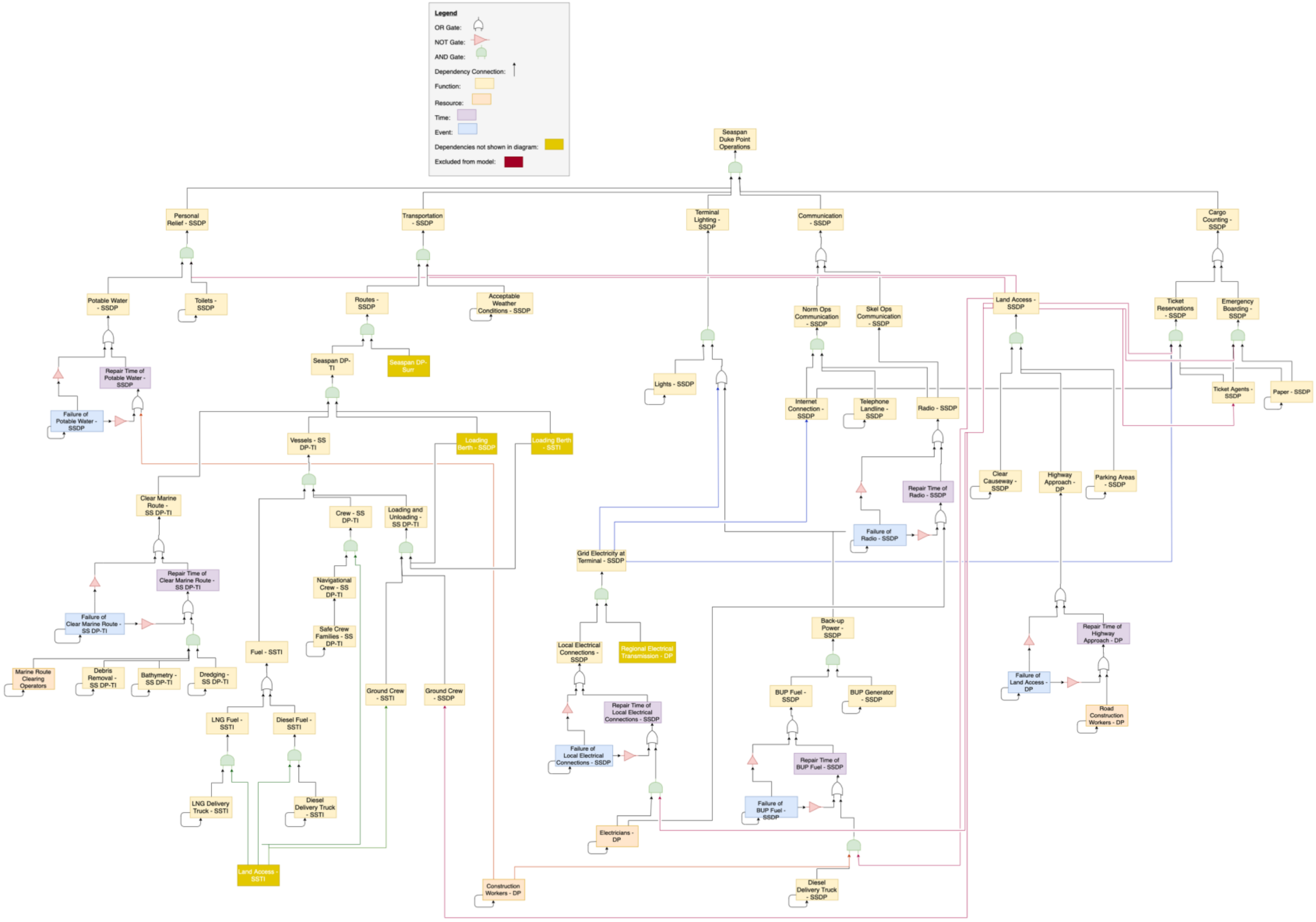


Figure 25: Terminal dependencies for Seaspan Duke Point operations model

Appendix C: GMOR Model Acronyms

Table 9 provides a definition of the acronyms used in the GMOR marine transport model. The rows are coloured according to the type value within the third column to increase readability. Infrastructure components are coloured in orange fill, vessels are blue, locations are green, routes are purple, and companies are yellow fill.

Table 9: Acronyms used for the creation of the GMOR marine transport model. Infrastructure components are coloured in orange fill, vessels are blue, locations are green, routes are purple, and companies are yellow fill.

Acronym	**Name**	**Type**
BUP	Back-up Power	Infrastructure
CC	Coastal Celebration	Vessel
CI	Coastal Inspiration	Vessel
CR	Coastal Renaissance	Vessel
DepB	Departure Bay	Location
DP	Duke Point	Location
HB	Horseshoe Bay	Location
HB-DepB	Horseshoe Bay-Departure Bay	Route
Nan	Nanaimo	Location
QA	Queen of Alberni	Vessel
QCoq	Queen of Coquitlam	Vessel
QCow	Queen of Cowichan	Vessel
QNW	Queen of New Westminster	Vessel
QOB	Queen of Oak Bay	Vessel
SB	Swartz Bay	Location
SBC	Spirit of British Columbia	Vessel
SS	Seaspan	Company
SSDP	Seaspan Duke Point	Location
SSNV	Seaspan North Vancouver	Location

SSTI	Seaspan Tilbury Island	Location
SVI	Spirit of Vancouver Island	Vessel
SoVI	South Vancouver Island	Location
TW	Tsawwassen	Location
TW-DP	Tsawwassen-Duke Point	Route
TW-SB	Tsawwassen-Swartz Bay	Route
Vic	Victoria	Location

Appendix D: Damage State Descriptions from Hazus

The following visual damage state descriptions are provided by Hazus (Federal Emergency Management Agency, 2013).

Slight Damage

Port waterfront structures: minor ground settlement resulting in few piles getting broken and damaged. Cracks formed on the surface of the wharf. Repair may be required.

Fuel facilities with unanchored equipment: elephant foot buckling of tanks with no leakage or loss of contents, slight damage to pump building, or loss of commercial power for a very short period and minor damage to backup power (i.e., damage to diesel generators, if available).

Potable water systems: malfunction for a short time or light damage.

Electrical distribution circuits: failure in 4% of all circuits.

Communication/radio: slight damage to the communication facility building, or inability of the centre to provide services during a short period (a few days) due to loss of electric power and backup power, if available.

Major Roads: a few inches of settlement or offset of the ground.

Moderate Damage

Port waterfront structures: considerable ground settlement with several piles (such as for piers or seawalls) getting broken and damaged.

Fuel facilities with unanchored equipment: elephant foot buckling of tanks with partial loss of contents, moderate damage to pump building, loss of commercial power for a few days and malfunction of backup power (i.e., diesel generators, if available).

Potable water systems: malfunction for about a week, considerable damage to mechanical and electrical equipment or moderate damage to buildings.

Electrical distribution circuits: failure in 12% of all circuits.

Communication/radio: moderate damage to the communication facility building, a few digital switching boards being dislodged, or the central office being out of service for a few days due to loss of electric power (i.e., power failure) and backup power (typically due to overload), if available.

Major Roads: several inches of settlement or offset of the ground.

Extensive Damage

Port waterfront structures: failure of many piles, extensive sliding of piers, and significant ground settlement causing extensive cracking of pavements.

Fuel facilities with unanchored equipment: weld failure at base of tank with loss of contents, extensive damage to pump building, or extensive damage to pumps (cracked/sheared shafts).

Potable water systems: non-functional equipment.

Electrical distribution circuits: failure in 50% of all circuits.

Communication/radio: severe damage to the communication facility building resulting in limited access to facility, or by many digital switching boards being dislodged, resulting in malfunction.

Major Roads: a few feet settlement of the ground.

Complete Damage

Port waterfront structures: failure of most piles due to significant ground settlement. Extensive damage is widespread at the port facility.

Fuel facilities with unanchored equipment: tearing of tank wall or implosion of tank (with total loss of content), or extensive/complete damage to pump building.

Potable water systems: building or system collapse.

Electrical distribution circuits: failure in 80% of all circuits.

Communication/radio: complete damage to the communication facility building, or damage beyond repair to digital switching boards.

Major Roads: a few feet settlement of the ground (same extensive damage).

Appendix E: Merge Script for GMOR Transform and Scenario Files

The following is the python merge script written for the GMOR marine transport model. This script merges the model transform files into one collective transform file, and the model scenario files into one collective scenario file.

```
#Anika Bell
import os
import sys
import json
import glob

#The purpose of this script is to combine multiple transform files into one master transform file
and multiple scenario files into one master scenario file

def merge_transforms():
    """
        This section combines multiple transform files into one master transform file
    """

    # Change directory to build

        os.chdir("/Users/canta/Documents/GitHub/siren_models_ab/Marine_Transport_modelAB_V1/build" )

    #finds partial transform files
    read_transform_files = glob.glob("*-partial_transform mr.json")

    #combines partial transform files into a single file
    with open("transform mr.json", "wb") as outfile:
        outfile.write('[{}]'.format(
                          ',\n'.join([open(f, "rb").read().strip("[]\n") for f in read_transform_files])))

    print("Transfrom Files Combined")

    #Print Current Working Directory
    print "Current working dir : %s" % os.getcwd()

def merge_scenarios():
    """
        This section combines multiple scenario files into one master scenario file
    """
```

```
    # Change directory to scenario

        os.chdir("/Users/canta/Documents/GitHub/siren_models_ab/Marine_Transport_modelA
        B_V1/scenario" )

    #finds partial transform files
    read_scenario_files = glob.glob("*-partial_scenario.json")

    #combines partial transform files into a single file
    with open("scenario.json", "wb") as outfile:
      outfile.write('{{{}}}'.format(
                              '},\n'.join([open(f, "rb").read().strip("{}\n") for f in read_scenario_files])))

    _complete_scenario_file = open("scenario.json", "a")
    _complete_scenario_file.write("}" )
    _complete_scenario_file.close()

    print("Scenario Files Combined")

    #Print Current Working Directory
    print "Current working dir : %s" % os.getcwd()


if __name__ == '__main__':

    merge_transforms()

    merge_scenarios()
```

Appendix F: Formula Descriptions for Model Testing

Table 10 contains a description of the “initial_system_state” Excel worksheet used to determine which damage state occurs for each model entity at the beginning of each iteration simulation. Table 11 contains a description of the “Results” worksheet created to test whether the recovery time the model outputs for an entity is the same as the recovery time expected by the modeller. Conditional formatting has also been applied in the results worksheet (Table 11) so that cells within the row turn green if the T column contains “Yes”, pale red if the T column contains “No”, yellow if the Z column contains “Good”, and dark red if the Z column contains “Wrong”.

Table 10: "initial_system_state" worksheet description for model output analysis

Column	Title	Contents Description	Contents Example for Row 2
A	initial order	A numbered series of the entities copied from the SQLite database. Numbered 1 through 3537.	1
B	name from Database	The entity names copied from the SQLite database.	"Acceptable Weather Conditions - DepB"
C	initial system state (iss) from Database	The entity initial system state copied from the database.	1,
D	name: first quotation	Formula using the MID function to remove all characters before the first letter within the B column.	Acceptable Weather Conditions – DepB”
E	name: no quotations	Formula using the MID and SEARCH functions to keep only the text before the quotation from column D.	Acceptable Weather Conditions - DepB
F	iss no front space	Formula using the MID function to remove the space in front of the number in column C.	1,
G	iss no comma	Formula using the MID and SEARCH functions to keep only the text before the comma in column F.	1

H	initial system state value	Formula using the VALUE function to convert text into a recognized number value.	1
I	"Failure of" entity?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE or FALSE depending if the text in column E contains the statement “Failure of”.	FALSE
J	Damage State	Formula using the IF, MID, and LEN functions to display the damage state of the entity if the initial system state is failed. Otherwise, displays FALSE.	FALSE
K	Failure of name without "Failure of "	Formula using the IF and MID functions to display the title of the entity from the E column without the characters “Failure of ” in front. If the E column name does not contain those characters to begin with, it returns FALSE.	FALSE
L	Failure of without failure or DS	Formula using the IF, MID, and LEN functions to display the title of the entity from the K column without the last four characters that depict the damage state.	FALSE
M	Failed Damage State?	Formula using the IF and AND functions to display TRUE if the row corresponds to an entity with a failed damage state, and FALSE if not.	FALSE
N	Unique Failed Damage State Identifiers	Formula using & to concatenate columns L and M with a space in between.	FALSE FALSE

Table 11: “Results” worksheet description for model output analysis

Column	Title	Contents Description	Contents Example
A	*No title*	Generated by GMOR. A numbered series of the entities copied from the database. Numbered 0 through 1786.	8
B	name	Generated by GMOR. The name of the entity. All entities that experience a change in their system state during the simulation are displayed here.	Ground Crew - TW

C	obj_ids	Generated by GMOR. The object ID value corresponding to the entity's spatial information is displayed here.	198
D	res_tab_nm	Generated by GMOR. Not important to the analysis.	Trial1Results
E	root_name	Generated by GMOR. Not important to the analysis.	Ground Crew - TW
F	scen_id	Generated by GMOR. The iteration number of the particular run of the simulation.	1
G	scen_tab_nm	Generated by GMOR. Not important to the analysis.	Trial1
H	time	Generated by GMOR. The number of days post disaster before the entity from column B is recovered.	0
I	Failed damage state?	Formula using the INDEX and MATCH functions to search the initial_system_state sheet and display the corresponding damage state that experienced failure for the entity in Results sheet column B.	#N/A
J	Failed Damage State without Errors	Formula using the IF and ISERROR functions to display the damage state from column I or FALSE if there is no corresponding damage state. This is necessary to remove the error values for subsequent columns.	FALSE
K	Ticket Agents?	Formula using the IF, ISERROR, and SEARCH functions to determine if the entity from column B contains the text "Ticket Agents".	FALSE
L	BUP Fuel?	Formula using the IF, ISERROR, and SEARCH functions to determine if the entity from column B contains the text "BUP Fuel".	FALSE
M	Local Electrical Connections?	Formula using the IF, ISERROR, and SEARCH functions to determine if the entity from column B contains the text "Local Electrical Connections".	FALSE
N	Berth?	Formula using the IF, ISERROR, and SEARCH functions to determine if the entity from column B contains the text "Berth".	FALSE

O	Ramp?	Formula using the IF, ISERROR, and SEARCH functions to determine if the entity from column B contains the text “Ramp”.	FALSE
P	Dependent on Land Access?	Formula using the IF and OR functions to display TRUE if TRUE is displayed for any of columns K, L, M, N, or O. Otherwise displays FALSE.	FALSE
Q	Recently Inspected?	Formula using the IF, ISERROR, and SEARCH functions to determine if the entity from column B contains the text “Recently Inspected”.	FALSE
R	Number of Days to Repair __formula	Formula using the IF, AND, and NOT functions to display the value from column AB if either the Q column is TRUE or the P column is TRUE and the J column does not contain “DS1”. Otherwise the H column is displayed.	0
S	Value for corresponding damage state __formula	Formula using the INDEX and MATCH functions to search the “time_timing from iteration” sheet for the repair time value (in days) corresponding to the entity in column B and the damage state in column I.	#N/A
T	Correct Number of Days to Repair? (excluding sub-dependencies) __formula	Formula using the IF and ROUND functions to display “Yes” if the S column and R column are identical when rounded to 3 decimal places. Otherwise displays “No”.	#N/A
U	"End Repair of" Entity?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the B column entity contains the text “End Repair of”. Otherwise displays FALSE.	FALSE
V	"Initiate Repair of" Entity?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the B column entity contains the text “Initiate Repair of”. Otherwise displays FALSE.	FALSE
W	Primary Entity?	Formula using the IF and AND functions to display TRUE if both the U column and V column contain FALSE. Otherwise display FALSE.	TRUE

X	Location & DS	Formula using the MID, SEARCH, and LEN functions to display only the text that appears after “ - ” in column B.	TW
Y	Location	Formula using the IF, ISERROR, SEARCH, MID, and LEN functions only the location portion of the X column.	TW
Z	Manually Checked	Will either be manually filled in with either “No”, “Good”, or “Wrong”.	No
AA	Land Access Recovery Time	Formula using the INDEX and MATCH functions to search the Results sheet and display the Land Access recovery time for the corresponding location in the Y column.	0
AB	Difference between entity recovery time and Land Access recovery time	Formula using the ROUND function to display the difference between column H and column AA.	0
AC	Comments	May be manually filled with comments about this entry.	

Appendix G: Formula Descriptions for Apply Failures

The applying failures function of GMOR combines the earthquake scenario information with the damage function information from Hazus to calculate the probability of damage states. The GMOR command to perform this function is "do_apply_failures". This work takes place in the “time_events” worksheet of the “revised scenario mr ens” Excel workbook. Table 12 contains a description of this worksheet. The contents descriptions and formulas of this worksheet have been developed as part of this thesis.

Table 12: "time_events" worksheet description of "revised scenario mr ens" Excel workbook

Column	**Title**	**Contents Description**	**Contents Example for Row 2**
A	*No title*	Numbered series of the entities from 0 to 724.	0
B	ent_type	States the entity type. All entities in this worksheet are of type “event”.	event
C	entity	Entity name.	Failure of Berth 1 Recently Inspected - DepB DS1
D	ex_lower_bound	This column is blank and not relevant for this model.	*Blank*
E	ex_upper_bound	This column is blank and not relevant for this model.	*Blank*
F	_"Failure of" removed	Formula using the MID function to remove the first 11 characters of the text in column C.	Berth 1 Recently Inspected - DepB DS1
G	_no DS_	Formula using the MID and LEN functions to remove the last four characters from the text in column F.	Berth 1 Recently Inspected - DepB
H	_no location	Formula using the MID and SEARCH functions to remove the text after and including the “ - ” text in column G.	Berth 1 Recently Inspected
I	_DS (as value)	Formula using the VALUE, MID, and LEN functions to display the corresponding value of the damage state contained in column F.	1

J	_BUP Fuel?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the entity name contains “BUP Fuel” within it. Otherwise, displays FALSE.	FALSE
K	_Highway Approach?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the entity name contains “Highway Approach” within it. Otherwise, displays FALSE.	FALSE
L	_Road Connection?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the entity name contains “Road Connection” within it. Otherwise, displays FALSE.	FALSE
M	_Clear Marine Route?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the entity name contains “Clear Marine Route” within it. Otherwise, displays FALSE.	FALSE
N	_Recently Inspected?	Formula using the IF, ISERROR, and SEARCH functions to display TRUE if the entity name contains “Recently Inspected” within it. Otherwise, displays FALSE.	TRUE
O	_PGA_mean	Formula using the INDEX and MATCH functions to search the “Re-Org DmgFunct Hazus AB” worksheet and return the mean PGA value that corresponds to the H and I columns of this worksheet.	#N/A
P	_PGA_Beta	Formula using the INDEX and MATCH functions to search the “Re-Org DmgFunct Hazus AB” worksheet and return the lognormal standard deviation PGA value that corresponds to the H and I columns of this worksheet.	#N/A
Q	fc_dist	Formula using the IF and OR functions to display “const” (meaning constant) if any of the columns J-N contain TRUE or if the damage state in column I is equal to	const

		1. Otherwise displays “lognorm” (meaning lognormal distribution).	
R	fc_params	Formula using the IF and OR functions to display “1” for damage state 1 entities with a constant damage function distribution, and “0” for all other damage states of entities with a constant damage function distribution. For entities with a lognormal damage function distribution, the damage function parameters are displayed in a concatenated string. This includes the standard deviation from column P, concatenated the distribution location (0.0), concatenated with the mean value in column O.	1
S	hazard_dir	The name of the folder within the build folder where the earthquake scenario files are found. This is case study specific and identical for all entities.	PGA
T	hazard_file	The name of the earthquake scenario file within the folder from column N. This is case study specific and identical for all entities.	CSZM9p0
U	mean	Deprecated	1
V	obj_ids	The object ID value for the entity.	[‘151’]
W	prob_occurrence	This column’s values are overwritten by the “do_apply_failures” GMOR command. These values represent the probability that this damage state will occur given that the previous damage states have not occurred.	
X	state	Entity state when state is set deterministically	1
Y	state_type	Describes the type of event as probabilistic rather than deterministic.	probabilistic
Z	std	Deprecated	0

AA	time	Entity’s restoration time when set deterministically	-1
AB	time_dist	This column is blank and not relevant for this model.	
AC	time_params	This column is blank and not relevant for this model.	
AD	time_type	Instructs GMOR whether to use deterministic (i.e., single) or probabilities restoration time	single

Appendix H: Attempt to Determine Permanent Ground Deformation

After repeated attempts, determining the PGD for this iteration of the model simulation was ultimately abandoned. The reasons for this include insufficient information on soil types and ground water depths in the area as well as an incomplete methodology from Hazus. Details on the attempt, are further provided below. Ultimately, the impact of possible road damage and land access barriers is discussed qualitatively in the discussion rather than quantitatively in the model simulation results.

For determining soil type, data that provided both the soil type as well as the age of deposit was not found on BC Open Data. However, because this project is dealing specifically with developed areas—roads and ferry terminals, in this case—it is assumed that these are locations where the soil has been manipulated. Therefore, using Hazus technical manual Table 4.10, the soil is classified as artificial compacted fill less than 500 years old (modern). For this classification, the likelihood that cohesionless sediments would be susceptible to liquefaction when saturated is low. This results in a 5% proportion of the map unit susceptible to liquefaction (P_{ml}). From the Hazus methodology, the probability of liquefaction for a given susceptibility category ($P[Liquefaction_{SC}]$) can be calculated using Equation 7 (Federal Emergency Management Agency, 2013). To perform this calculation, the conditional probability of liquefaction for a given susceptibility category at a specified level of PGA ($P[Liquefaction_{SC}|PGA = a]$), the moment magnitude correction factor (K_M), and the ground water correction factor (K_w) are also required.

Equation 7: The probability of liquefaction for a given susceptibility category from Hazus technical manual Equation (4-20) (Federal Emergency Management Agency, 2013)

$$P[Liquefaction_{SC}] = \frac{P[Liquefaction_{SC}|PGA = a]}{K_M \cdot K_w} \cdot P_{ml}$$

where (Federal Emergency Management Agency, 2013),

$P[Liquefaction_{SC}|PGA = a]$ is the conditional probability of liquefaction for a given susceptibility category at a specified level of PGA (determined through using Hazus Figure 4.6);

K_M is the moment magnitude (M) correction factor (determined through Hazus Equation 4-21);

K_w is the ground water correction factor (determined through Hazus Equation 4-22);

P_{ml} proportion of map unit susceptible to liquefaction.

$P[Liquefaction_{SC}|PGA = a]$ is determined using Hazus technical manual Figure 4.6 (p. 4-25), originally produced by Liao et al., 1988 (Liao, Veneziano, & Whitman, 1988). Figure 26, below, shows the $P[Liquefaction_{SC}|PGA = a]$ values that correspond to PGA values of 0.266 and 0.303, which occur at the Swartz Bay Highway Approach and the Victoria Nanaimo Road Connection, respectively. The numerical values are listed in Table 13, and were determined graphically through printing of copy of the Liao et al., 1988 and measuring the intercepts with a ruler. Unfortunately, these values are not synonymous with the accompanying equations that Hazus provides in its table 4.12 to determine these values numerically. The results from using the corresponding Hazus equation, shown in Equation 8, are different than those listed in Table 13 found using Figure 26.

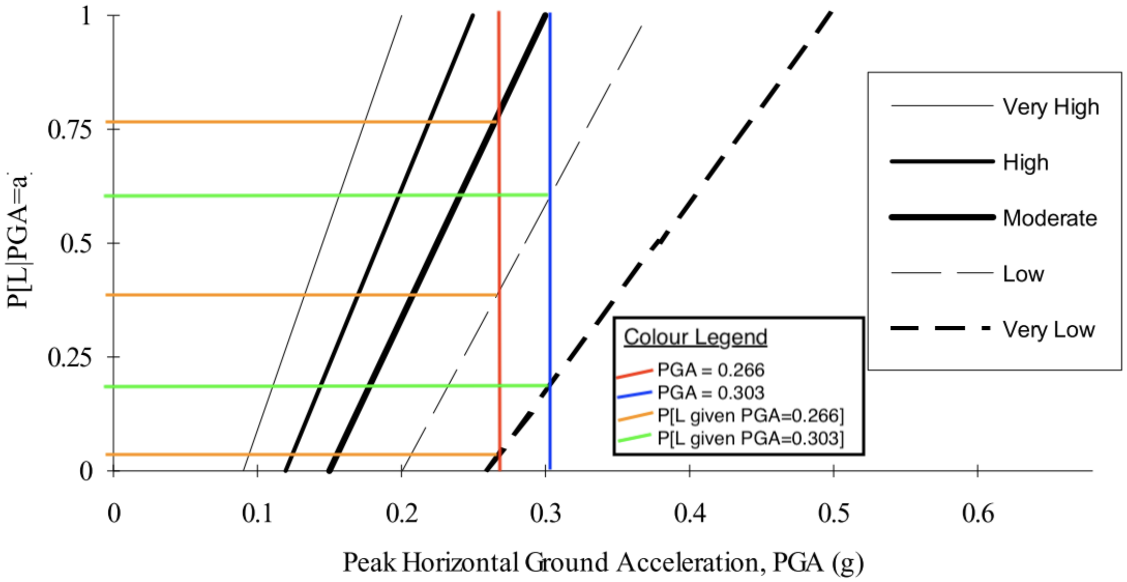


Figure 26: Conditional Liquefaction Probability Relationships for Liquefaction Susceptibility Categories (Liao et al., 1988) *modified for this thesis with coloured lines corresponding to PGA values of 0.266 and 0.303.*

Table 13: The graphically determined conditional probability of liquefaction for a given susceptibility category at a specified level of PGA

Susceptibility Category	PGA = 0.303	PGA = 0.266
Very High	1	1
High	1	1
Moderate	1	0.755
Low	**0.614**	**0.386**
Very Low	0.182	0.034

Equation 8: Conditional probability equation for low liquefaction susceptibility. Evaluation conducted for a PGA of 0.303 and a PGS of 0.266.

$$0 \le 5.57a - 1.18 \le 1.0$$

$$5.57(0.303) - 1.18 = 0.50771$$

$$5.57(0.266) - 1.18 = 0.30162$$

Moving beyond $P[Liquefaction_{SC}|PGA = a]$, the correction factor (K_M) for moment magnitudes other than $\boldsymbol{M}$ =7.5 can be found from Equation 9, where $\boldsymbol{M}$ is the magnitude of the earthquake (Federal Emergency Management Agency, 2013). For the magnitude 9.0 earthquake of the Cascade subduction zone megathrust scenario, the $K_M = 0.8749$.

Equation 9: Correction factor for moment magnitudes other than 7.5 (Federal Emergency Management Agency, 2013). *Evaluated for a 9.0 earthquake magnitude.*

$$K_M = 0.0027\boldsymbol{M}^3 - 0.0267\boldsymbol{M}^2 - 0.2055\boldsymbol{M} + 2.9188$$

$$K_M = 0.0027(\mathbf{9.0})^3 - 0.0267(\mathbf{9.0})^2 - 0.2055(\mathbf{9.0}) + 2.9188 = 0.8749$$

The correction factor for groundwater depths other than five feet can be found from Equation 10, where d_w is the depth to the groundwater in feet (Federal Emergency Management Agency, 2013). Unfortunately, data on groundwater levels for the areas in question was not available from BC Open Data and the data that was available was located too far from the regions in question to be considered accurate.

Equation 10: Correction factor for groundwater depths other than five feet (Federal Emergency Management Agency, 2013)

$$K_w = 0.022d_w + 0.93$$

Ultimately it was decided that gaps in the data and the concerns with the Hazus methodology left too much uncertainty for determining the PGD and the roadway damage states. Therefore, the inclusion of roadway damage remains as future work.

Appendix I: Community Service Recovery Dependency Diagram

Figure 27 displays the dependency relationships and definitions for community service recovery to Victoria and Nanaimo.

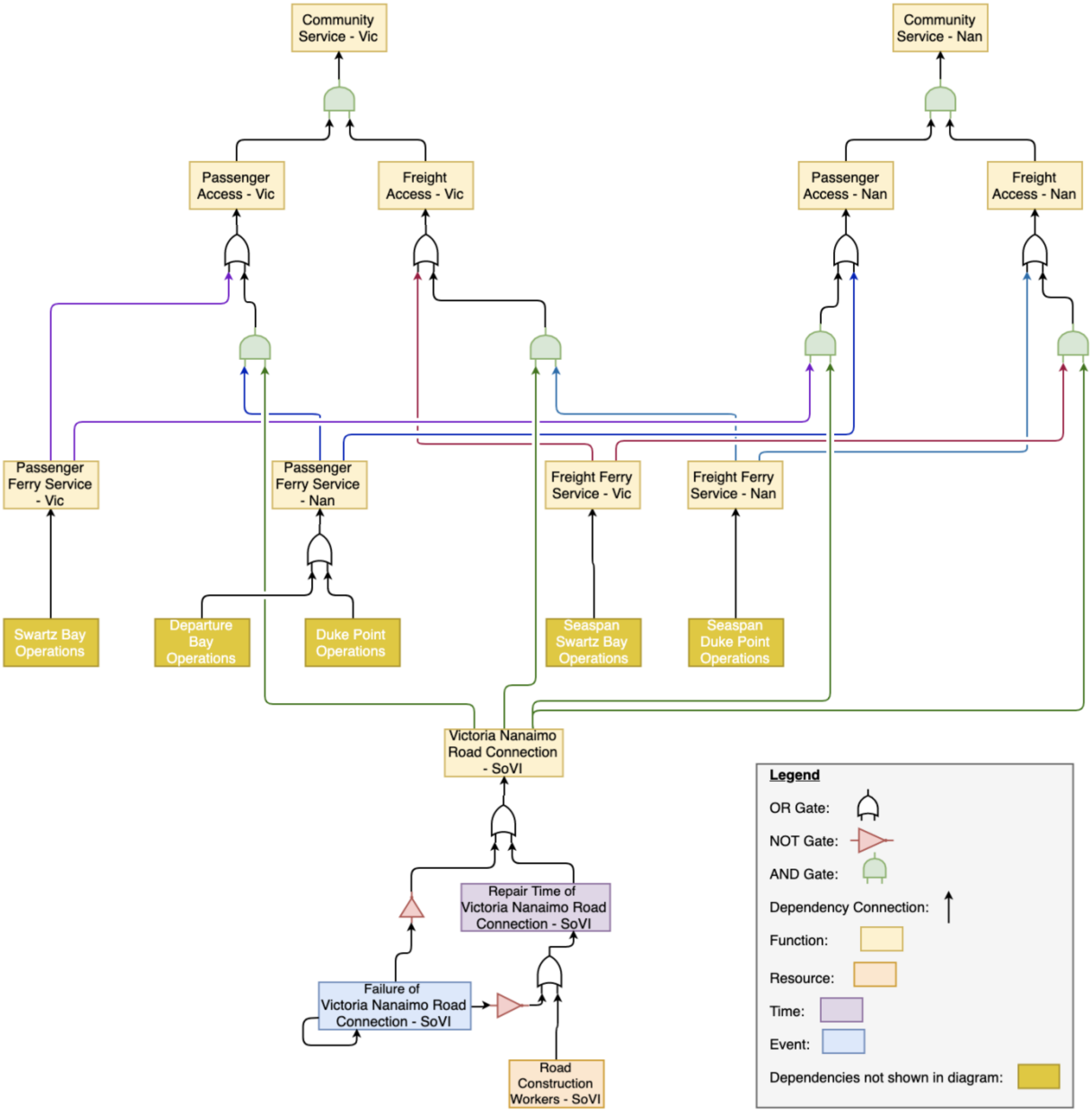


Figure 27: Community service recovery dependency diagram for Victoria and Nanaimo

Appendix J: Damage Functions

The mean and standard deviation of the lognormally distributed damage functions from Hazus that have been compiled for use in the marine transport model are shown in Table 14.

Table 14: Damage functions from Hazus (Federal Emergency Management Agency, 2013). *Median represents the mean of the function. Beta represents the standard deviation of the function.*

Case	**Hazus ID**	*PGA Slight Median*	*PGA Slight Beta*	*PGA Moderate Median*	*PGA Moderate Beta*	*PGA Extensive Median*	*PGA Extensive Beta*	*PGA Complete Median*	*PGA Complete Beta*
Berth 1 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Berth 1 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Berth 2 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Berth 2 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Berth 3 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Berth 3 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Berth 4 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Berth 4 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Berth 5 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Berth 5 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
BUP Fuel	FFF	10.1000004	0.1	10.1000004	0.1	10.1000004	0.1	10.1000004	0.1

Clear Marine Route	ext_Clear_Marine_Route	0	0	0	0	0	0	0	0
Highway Approach	HRD1	10	0.1	10	0.1	10	0.1	10	0.1
Loading Berth 1 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Loading Berth 1 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Loading Berth 2 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Loading Berth 2 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Loading Ramp 1 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Loading Ramp 1 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Loading Ramp 2 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Loading Ramp 2 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Local Electrical Connections	EDC	0.25	0.60000002	0.40000001	0.60000002	0.69999999	0.60000002	1.35000002	0.64999998
Potable Water	PDFLT_water	0.25	0.60000002	0.40000001	0.60000002	0.69999999	0.60000002	1.35000002	0.64999998
Radio	CBR	0.25	0.60000002	0.40000001	0.60000002	0.69999999	0.60000002	1.35000002	0.64999998
Ramp 1 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Ramp 1 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Ramp 2 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Ramp 2 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999

Ramp 3 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Ramp 3 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Ramp 4 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Ramp 4 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Ramp 5 Recently Inspected	ext_FMF_inspect	0	0	0	0	0	0	0	0
Ramp 5 Structural Integrity	FMF	0.2	0.69999999	0.5	0.69999999	0.80000001	0.69999999	1.29999995	0.69999999
Regional Electrical Transmission	EDC	0.25	0.60000002	0.40000001	0.60000002	0.69999999	0.60000002	1.35000002	0.64999998
Victoria Nanaimo Road Connection	HRD1	10	0.1	10	0.1	10	0.1	10	0.1

Appendix K: Restoration Functions

The mean and standard deviation of the lognormally distributed restoration functions from Hazus that have been compiled for use in the marine transport model are shown in Table 15.

Table 15: Restoration functions from Hazus (Federal Emergency Management Agency, 2013). *Median represents the mean of the function. Sigma represents the standard deviation of the function.*

Case	Hazus ID	*No Damage Mean*	*No Damage Sigma*	*Slight Mean*	*Slight Sigma*	*Moderate Mean*	*Moderate Sigma*	*Extensive Mean*	*Extensive Sigma*	*Complete Mean*	*Complete Sigma*
Berth 1 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Berth 1 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Berth 2 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Berth 2 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Berth 3 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Berth 3 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Berth 4 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Berth 4 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Berth 5 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Berth 5 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
BUP Fuel	FFF	0	0	0.89999998	0.05	1.5	1.5	15	15	65	50

Clear Marine Route	ext_Clear_Marine_Route	0	0	0.2	0.1	0.3	0.2	0.4	0.3	0.5	0.4
Highway Approach	HRD1	0	0	0.89999998	0.05	2.2	1.8	21	16	21	16
Loading Berth 1 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Loading Berth 1 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Loading Berth 2 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Loading Berth 2 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Loading Ramp 1 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Loading Ramp 1 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Loading Ramp 2 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Loading Ramp 2 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Local Electrical Connections	EDC	0	0	0.30000001	0.2	1	0.5	3	1.5	7	3
Potable Water	PDFLT_water	0	0	0.89999998	0.30000001	1.9	1.2	32	31	95	65
Radio	CBR	0	0	0.5	0.2	1	1	7	7	40	40
Ramp 1 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Ramp 1 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Ramp 2 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Ramp 2 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Ramp 3 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2

Ramp 3 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Ramp 4 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Ramp 4 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Ramp 5 Recently Inspected	ext_FMF_inspect	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2	0.25	0.2
Ramp 5 Structural Integrity	FMF	0	0	0	0	1.5	1.5	50	50	150	120
Regional Electrical Transmission	EDC	0	0	0.30000001	0.2	1	0.5	3	1.5	7	3
Victoria Nanaimo Road Connection	HRD1	0	0	0.89999998	0.05	2.2	1.8	21	16	21	16

Appendix L: Berth Recovery Results

This appendix provides the recovery results of berths at each terminal. The number of berths at each terminal, including berth size, are listed in Table 16. Figure 28 through Figure 36 provide the recovery results of at least one berth at a terminal and of all berths at a terminal compared to the recovery results of the terminal operations, for all terminals evaluated in the model. In figures where the bottom whisker extends beyond the plot, the minimum recovery time value was 0.0 days—however, a zero value is unable to be displayed in log-scale graphs.

Table 16: Number of berths at ferry terminals

Terminal	**Number of Large Berths**	**Total Number of Berths (Including Small Berths)**
BCF Tsawwassen	4	5
BCF Swartz Bay	3	5
BCF Horseshoe Bay	2	3
BCF Duke Point	1	1
BCF Departure Bay	2	3
SFC Duke Point	1	1
SFC Tilbury Island	2 (loading berths)	4 (2 loading + 2 ramp-less)
SFC Swartz Bay	1	1
SFC Swartz Bay	1	1

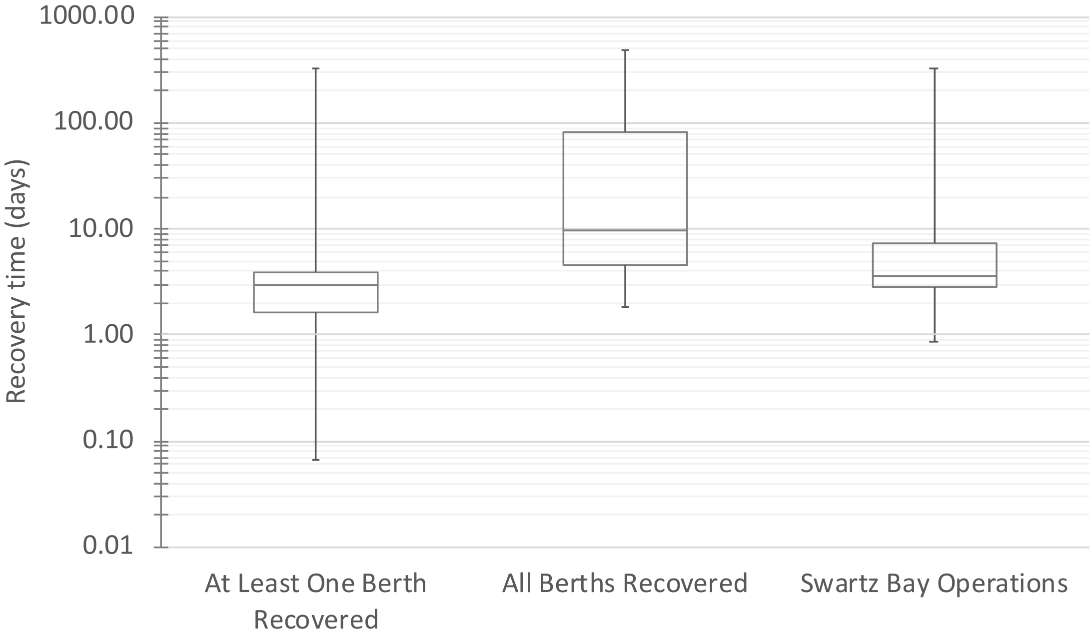


Figure 28: BC Ferries Swartz Bay berth recovery over 500 simulation iterations

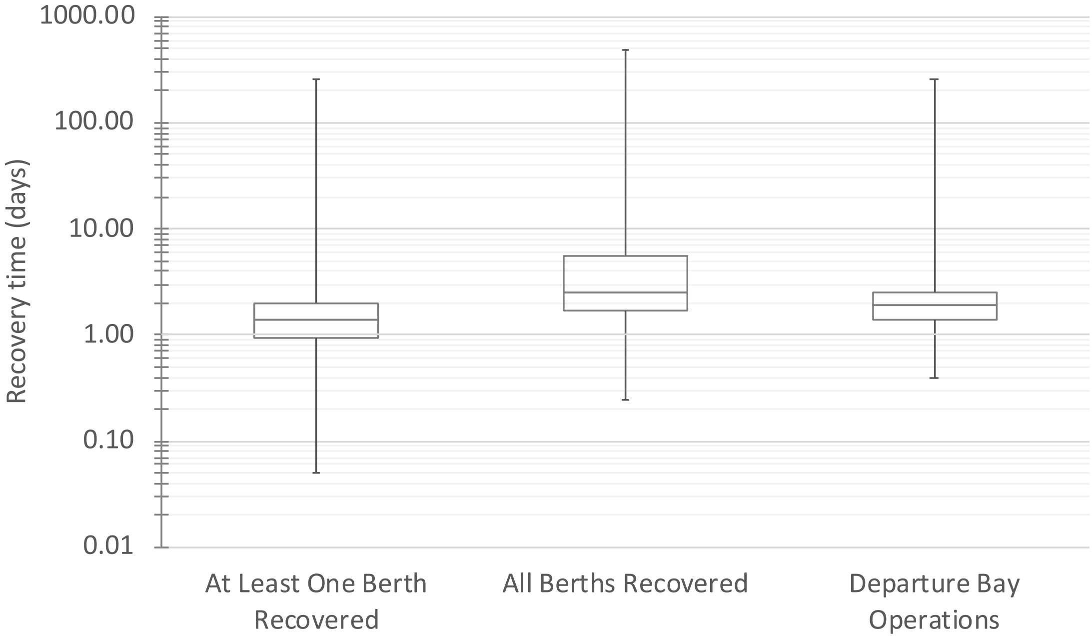


Figure 29: BC Ferries Departure Bay berth recovery over 500 simulation iterations

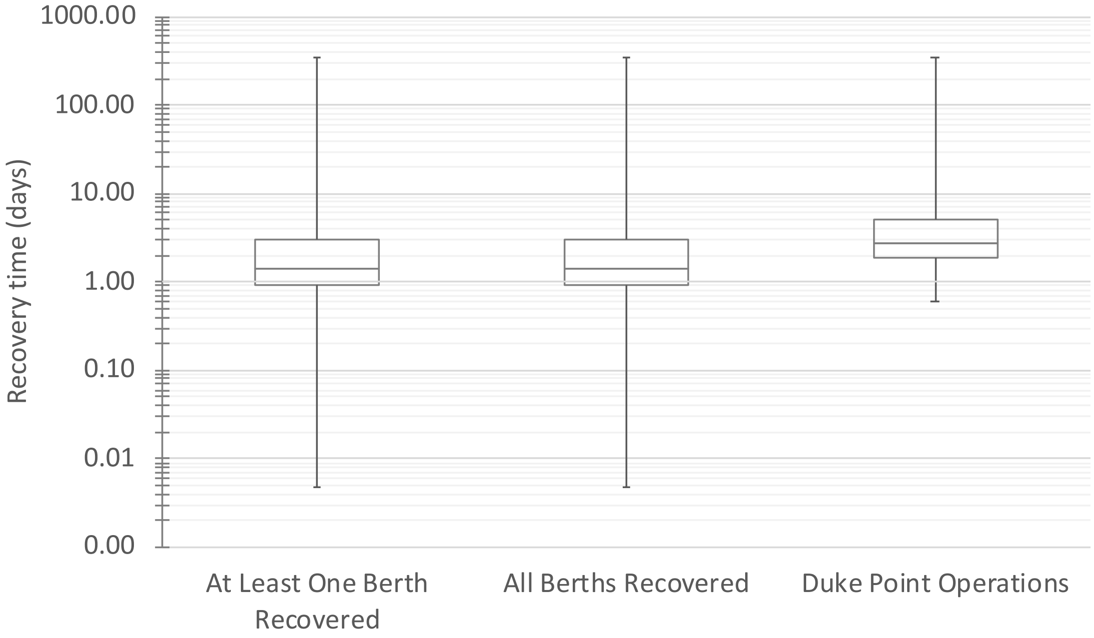


Figure 30: BC Ferries Duke Point berth recovery over 500 simulation iterations

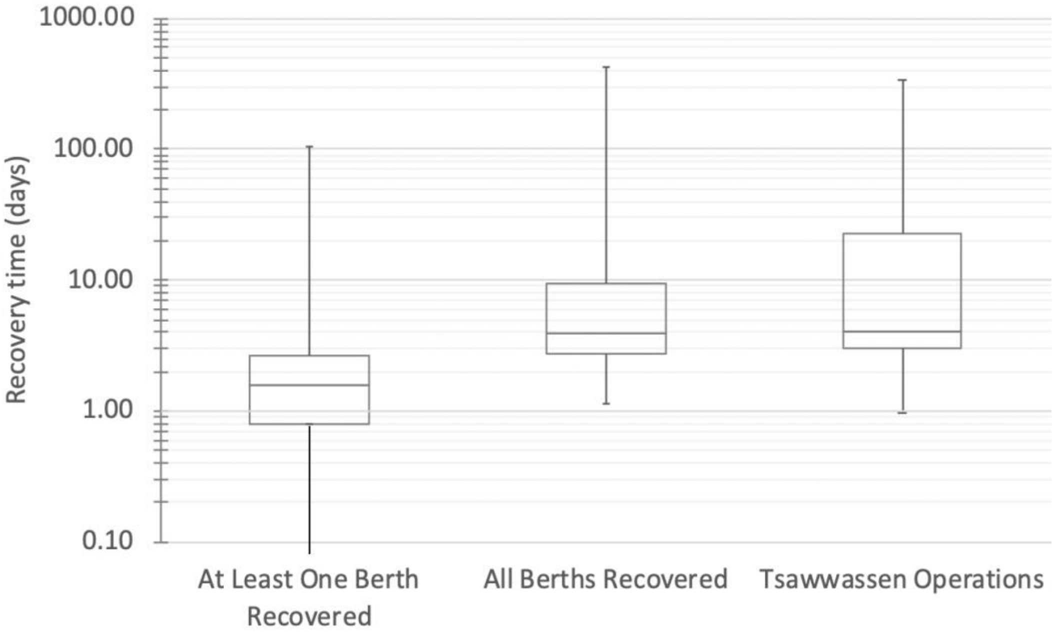


Figure 31: BC Ferries Tsawwassen berth recovery over 500 simulation iterations

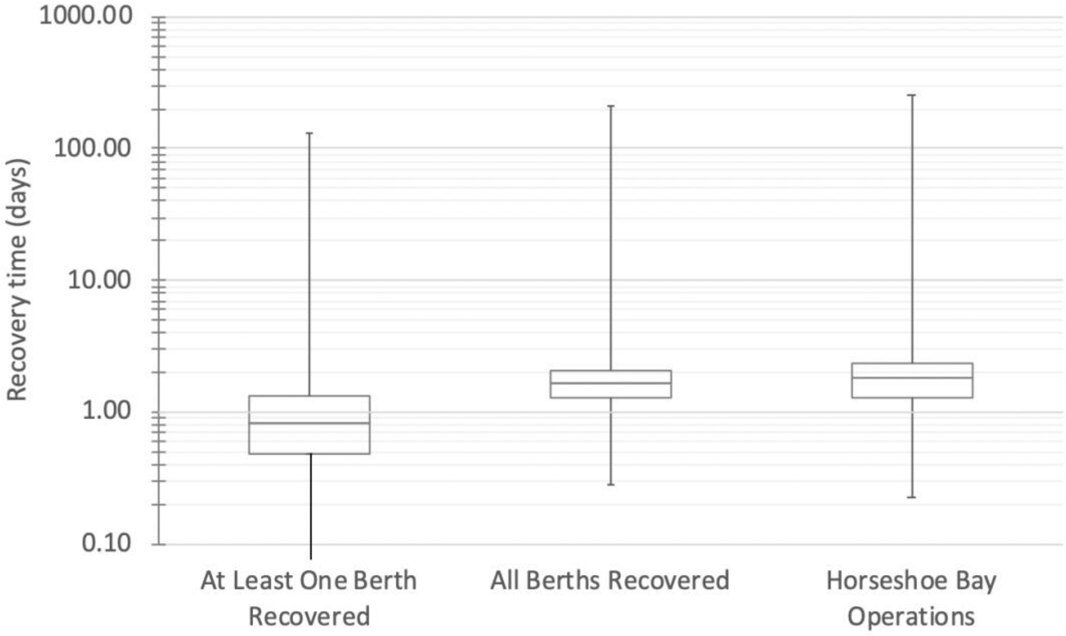


Figure 32: BC Ferries Horseshoe Bay berth recovery over 500 simulation iterations

Figure 33: Seaspan Ferries Swartz Bay berth recovery over 500 simulation iterations

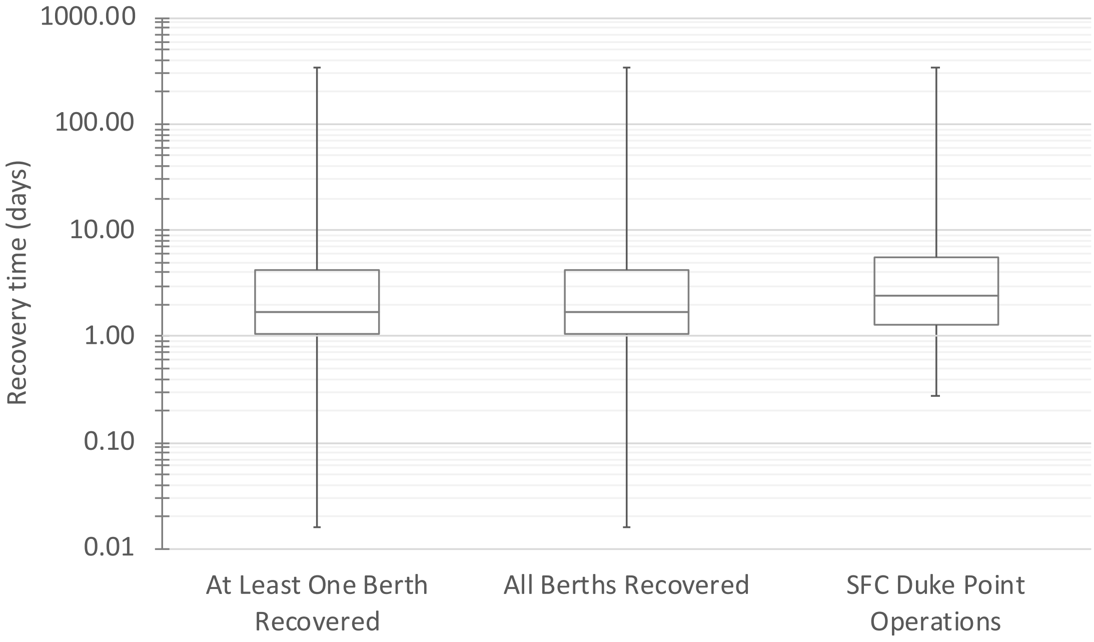


Figure 34: Seaspan Ferries Duke Point berth recovery over 500 simulation iterations

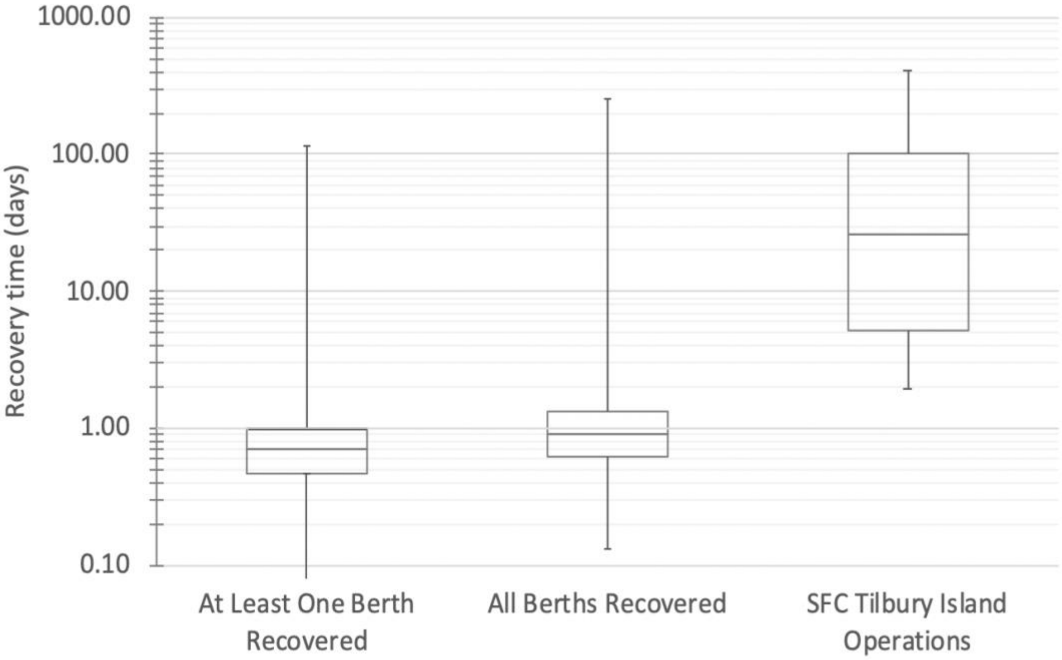


Figure 35: Seaspan Ferries Tilbury Island berth recovery over 500 simulation iterations

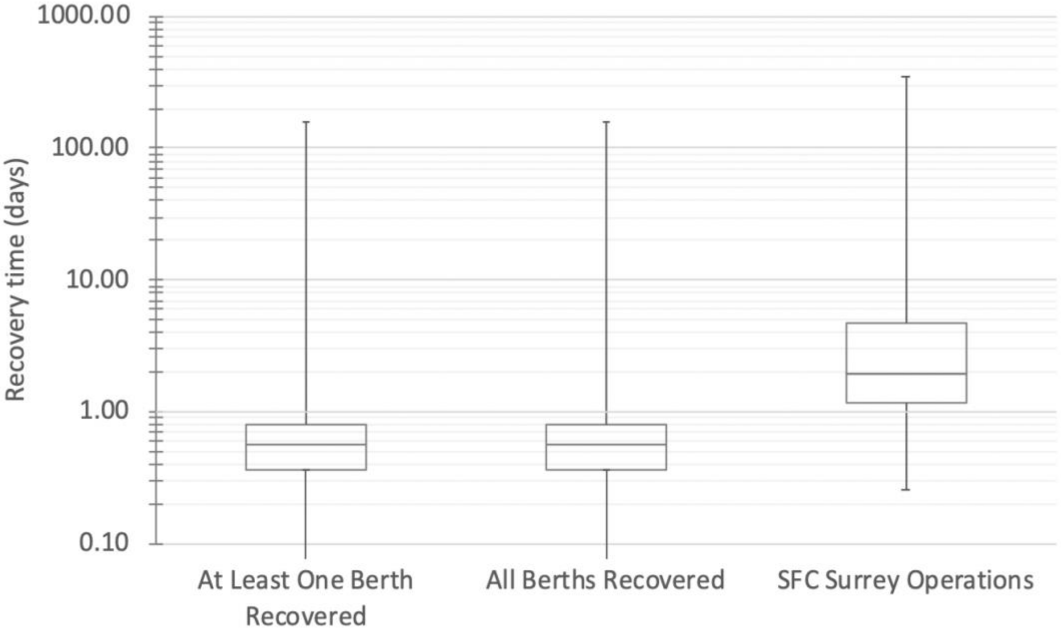


Figure 36: Seaspan Ferries Surrey berth recovery over 500 simulation iterations