Sensitivity Analysis of a Road Clearing and Relief Supplies Distribution Model for Vancouver Island in the Event of a Cascadia Megathrust Earthquake

By

Pranitha Vattoni

Submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science

at

Dalhousie University

Halifax, Nova Scotia

August 2023

Contents

List of Tables

List of Figures

Abstract

Southwestern British Columbia is one of the most seismically active regions in Canada because of its proximity to the Cascadia Subduction zone at the interface between the North American and the Juan De Fuca tectonic plates. Over the last few years, several studies have been pursued to find ways to improve the preparedness of the communities in the region in the event of a major Cascadia earthquake. One such project led to the development of a Road Clearing and Relief Supplies Distribution (RCRSD) model. With data available for a Cascadia earthquake scenario, it can be used to find an optimal way to clear post-disaster debris on roads and route supplies to stranded communities on Vancouver Island. The RCRSD model uses a large number of assumptions and produces non-deterministic outputs. Therefore, performing sensitivity analysis is necessary to improve and validate the robustness of the model. In this study, the inputs to the model were classified and with a chosen set of input parameters extensive sensitivity analysis was conducted on the RCRSD model. The results of the model were tabulated, mapped, and analyzed to determine patterns in road clearing and relief supply activities. These patterns can be helpful in finding critical roads, regions, and communities on the island that may be key factors in proactive emergency planning for a megathrust earthquake.

List of Abbreviations

ARCP	Arc Routing Connectivity Problem
BC	British Columbia
CD	Community Demand
CIF	Community Impact Factor
CP	Community Population
CPARP	Clustered Prize Arc Routing Problem
GRASP	Greedy Randomized Adaptive Search Procedure
KPC-ARCP	Multi-vehicle Prize Collecting Arc Routing Connectivity Problem
PC-ARCP	Prize Collecting Arc Routing Connectivity Problem
RCRSD	Road Clearing and Relief Supplies Distribution
SIREN	Strategic Planning for Coastal Community Resilience to Marine Transport Disruption
TS	Tabu Search
WCPARP	Windy Clustered Prize Arc Routing Problem

Acknowledgements

I would like to thank my primary supervisor Dr. Ronald Pelot for his guidance and kindness throughout my time at Dalhousie University. I would also like to thank Dr. Floris Goerlandt, my co-supervisor for his time and expertise on this research. I am extremely grateful for the both of them. Besides my supervisors, I would like to mention my thanks to Dr. Pemberton Cyrus and Dr. M. Ali Ülkü for being a part of my committee and for their time evaluating my thesis.

A special thanks to Dr. Luana Souza Almeida and Lauryne Rodrigues for their time spent sharing their knowledge with me and their kind words over the last few years. I would like to thank all my friends in the MARS research group for making my time at Dalhousie memorable. I would also like to thank everyone involved in the SIREN project for their invaluable work and guidance.

I would like to thank my parents Praveen and Anitha, my sister Pravitha, my grandparents, and my extended family for their love and support over the last few years.

Chapter 1. INTRODUCTION

The Cascadia Subduction zone is the tectonic boundary between the Continental North American and the Oceanic Juan De Fuca plates. This massive region covers over a thousand kilometers in length, extending from Southern British Columbia (BC) to the North of California. A Cascadia Earthquake, a type of megathrust earthquake, occurs when the Juan De Fuca plate slips under the North American plate, resulting in a seismic event of extreme magnitude (Natural Resources Canada, 2010).

Southwestern BC lies on top of the Cascadia Subduction zone, making it the most seismically active region in all of Canada. On average, around 200 earthquakes occur every year in this region. Figure 1 shows all the earthquakes in the region that occurred during the months of May and June of 2023 (Earthquakes Canada (nrcan.gc.ca)). All these earthquakes are caused by shifting tectonic plates, whereas Cascadia earthquakes are much rarer with their intervals of recurrence lying anywhere between 100 and 1000 years (Clague, 2002).

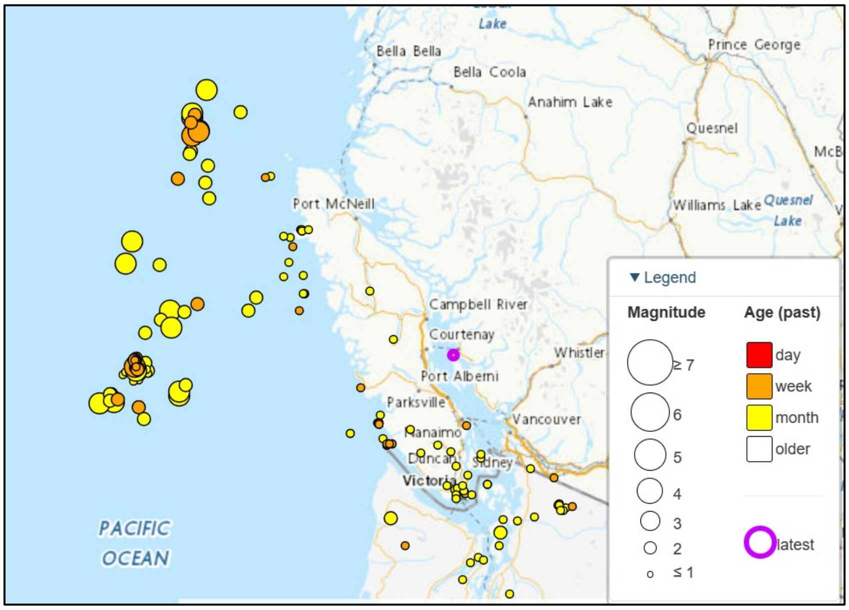


Figure 1. All earthquakes between 14/05/2023 and 14/06/2023

The closest densely populated regions to the subduction region: the communities on Vancouver Island and the smaller islands around it called the Gulf Islands are the most vulnerable places to earthquakes of large magnitudes. Most earthquakes today in North

America are measured in the moment scale, of which a magnitude of M6 is considered moderate and anything M8 or above is considered a large earthquake (Rogers, 1998). When a major earthquake hit BC in 1946 (magnitude of M7.3), in the towns around the epicenter there were damaged residential units, roads, and utility lines. If an earthquake of the same magnitude were to happen today, the losses to life and property are predicted to be much greater because the same regions have seen extensive development over the last few decades (Clague, 2002). Another factor that adds to the risk that the islands face is their dependency on mainland Vancouver and the shipping routes that connect these land masses. A disruption in shipping or transportation could have a significant impact on the flow of essential goods between and within the islands.

To understand the difficulties that arise with such scenarios and support decision-making to improve preparedness of communities and stakeholders in such events, the Strategic Planning for Coastal Community Resilience to Marine Transport Disruption (SIREN) project was established with support from the Marine Environmental Observation, Prediction and Response Network (MEOPAR), Network of Centres of Excellence (NCE), and the Province of British Columbia. Methods to analyze the potential damage and disruption to road and marine routes around Vancouver Island were developed. Solutions for timely reconstruction and relief measures for the affected communities in the event of a Cascadia earthquake were also developed.

Studies were conducted to predict the damage a Cascadia Earthquake may induce on and around Vancouver Island, as well as network reconstruction and relief supplies distribution plans to deal with the aftermath (Chang et al., 2020). Other studies have also been done where models for reconstruction of roads and routing of relief supplies were developed and executed on data available from past disasters (Souza Almeida and Goerlandt, 2022). However, little research is available on sensitivity analyses of these models, be it on existing case studies or simulated disaster data. This thesis deals with analyzing the results of one such model for a simulated Cascadia earthquake scenario on Vancouver Island.

The SIREN project is split into smaller projects. Some are tasked to analyse the extent of impact that a Cascadia earthquake could have on transportation and the communities themselves, and the others to provide effective strategies to enable prompt assistance to the affected communities.

The Critical Infrastructure (CI) Analysis of Regional Disruption & Ferry Route Interruption model (Bell & Bristow, 2020) was developed to characterize the various damages to infrastructure, marine and road transport, and shipping routes. This model resulted in the development of two cases, A and B, with each describing a different extent of possible impact of the Cascadia earthquake. Case A provides details of a *Partial disconnection* in which a realistic extent of damage is assumed to occur. Case B, labeled as *Extensive disconnection* provides damage data for a worst-case scenario of the megathrust earthquake (Chang et al., 2020). The Community Impact model (Chang & Tanner, 2022) produced a scale for impact level measured by the effect of an earthquake on infrastructure, transportation, and connectivity considering the preparedness of the communities and the resources available. The impact level ranges from 1 to 5, with 1 being the least amount of disruption and 5 the highest.

Scenario-based estimation of delays of marine shipping operations caused by earthquakes, using a Bayesian Network approach (Goerlandt & Islam, 2021) was used in (Chang et al., 2020) to estimate the most probable delay times in ship routes for both the partial disconnection and extensive disconnection cases.

For the response phase, a road clearance model to restore the road network and a relief supplies delivery model to distribute emergency supplies to communities were developed. These models, along with models to estimate damage and disruption to shipping vessels and routes in the context of a Cascadia earthquake are presented in (Goerlandt et al., 2022).

The models for the SIREN project were developed with the aim to assess risk and improve preparedness of southwestern BC in the event of a Cascadia earthquake. The road clearance model was used to reconnect isolated communities and the multi-modal distribution of relief supplies takes advantage of these reconnected roads to reach affected communities. The two models are synchronised and referred to as the Road Clearing and Relief Supplies Distribution (RCRSD) model in this thesis.

The RCRSD is a multi-modal network model consisting of several sub-models, each with a different objective function bounded by a time constraint, and each using a Greedy Randomised Adaptive Search Procedure (GRASP) heuristic to reach a solution. The model uses many inputs, some of which are obtained from the results of the other models developed for SIREN and a large number of assumptions to come up with solutions due to the lack of historical data for an earthquake of such scale and the associated great uncertainties. These inputs and assumptions are explained in the methods section of this thesis.

The RCRSD model can be used as a tool to develop a potential plan for the relevant governing authorities, as well as industry and community stakeholders to improve the emergency preparedness for Vancouver Island. The RCRSD model generates a solution for damaged roads' reconstruction, while simultaneously finding the optimal way to distribute supplies via sea, land, and air to the affected communities.

The primary aim of this thesis is to perform sensitivity analysis of the RCRSD model with the damage data available for Vancouver Island for a Cascadia megathrust earthquake. Performing an analysis of the model can provide high-level insights into what regions would need assistance the most in such an event.

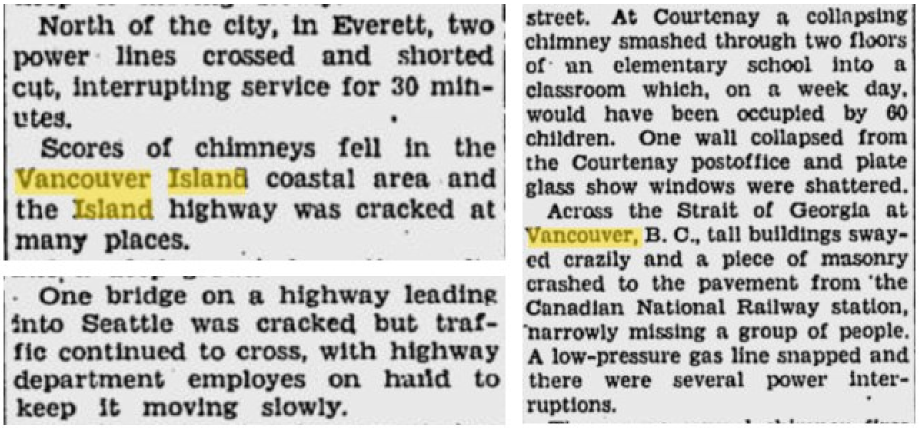
The purpose of doing analyses in the RCRSD model is to obtain insights in some common occurrences in the results of numerous model runs and thus to identify roads and regions on Vancouver Island that may be prioritized in the event of a Cascadia earthquake. This study is also done to identify communities that receive frequent supplies and those that do not receive much relief supplies. Effects of port closures and ship availability changes are studied to observe how supplies to communities differ when these elements are unavailable. From the results obtained from these analyses, stronger plans to improve the resilience of Vancouver Island in the context of a Cascadia earthquake can be developed. Additionally, different ways to explore the outputs of the RCRSD model is also studied. The RCRSD model generates outputs for Vancouver Island and the nearby Gulf Islands. In this thesis, although some results for the Gulf Islands are shown, they are not included in the input changes for the sensitivity analysis that was performed. The results obtained from this study are presented in various tables and maps.

Chapter 2. LITERATURE REVIEW

Southwestern British Columbia is one of the most vulnerable regions to earthquakes and tsunamis in Canada. On average, about 4000 earthquakes happen every year in the country, out of which the largest and the most frequent ones occur along the west coast (Cassidy et al., 2010).

The largest recorded earthquake to happen in Southwestern British Columbia was in 1946, with a magnitude of M7.3 (Cassidy et al., 2010). Figure 2 shows the damage to Kelsey Bay highway in Northern Vancouver Island after the 1946 earthquake (Natural Resources Canada, 2010). Due to technological limitations during the era, not many formal records of damage assessments from the earthquake are available. Most information available today about the earthquake are from oral records and newspaper clippings as seen in Figure 3. The earthquake, caused by a shift in the North American tectonic plate, is believed to have caused extensive damage to Vancouver Island, as well as parts of Northwestern USA.

Figure 2. Kelsey Bay highway after the 1946 earthquake



North of the city, in Everett, two power lines crossed and shorted cut, interrupting service for 30 minutes.

Scores of chimneys fell in the Vancouver Island coastal area and the Island highway was cracked at many places.

One bridge on a highway leading into Seattle was cracked but traffic continued to cross, with highway department employes on hand to keep it moving slowly.

street. At Courtenay a collapsing chimney smashed through two floors of an elementary school into a classroom which, on a week day, would have been occupied by 60 children. One wall collapsed from the Courtenay postoffice and plate glass show windows were shattered.

Across the Strait of Georgia at Vancouver, B. C., tall buildings swayed crazily and a piece of masonry crashed to the pavement from the Canadian National Railway station, narrowly missing a group of people. A low-pressure gas line snapped and there were several power interruptions.

Figure 3. Clips of Ellensburg daily record, June 24, 1946

Considered one of the worst in history, the 2010 earthquake that hit Port-au-Prince in Haiti resulted in the loss of over 200,000 lives and estimated damage of about 7.8 billion USD. The earthquake destroyed critical infrastructure like hospitals, roads, bridges, and government centres, which made the response and recovery process very difficult to coordinate (Edwards & American Society of Civil Engineers, 2012). The geographical area of Haiti is comparable in some respects to Vancouver Island since both are isolated from the mainland and have similar landmass areas. Both islands also depend on marine transportation routes for supplies of essential goods. However, the aftermath and relief strategies for these regions cannot be directly compared. Since the 1950s, a Seismic value was introduced into the national building code for different regions in Canada (*British Columbia Building Code 2018*), whereas there is no building code for infrastructures in Haiti for earthquake resistance (Edwards & American Society of Civil Engineers, 2012).

Japan is another island country that is considered one of the most at-risk places seismically. The Kobe earthquake, or the great Hanshin earthquake that happened in the Hyogo prefecture of Japan in 1995 served as an eye-opener for how important it is to have disaster management measures in place the event of an earthquake. This earthquake, which had a magnitude of M6.9, left the country's economy crippled for several years (Unjoh, 2004). Japan was hit by another earthquake in March 2011, followed by a tsunami that resulted in the loss of over 15000 lives, many missing, and had an economic impact of 16 to 25 trillion yen (Koshimura et al., 2014). Over the years, the country has implemented several structural codes to improve the seismic resistance of buildings, roads, bridges, and other structures. Even with its improved preventative measures, Japan suffered a great loss of life and property when an M6.7 earthquake struck the Hokkaido prefecture in Northern Japan in 2018.

In the aftermath of a moderate to large earthquake, many services are expected to be operating at reduced or no capacity. Studies have been done on evaluating the working of rescue teams, rehabilitation operations, reconnection of communities, damage data collection, etc. One of the first activities to happen after an earthquake would be search and rescue of people stuck under debris. Ahmadi et al., (2022) proposed a framework for decision support while planning for search and rescue operations by using a two-stage mixed integer programming approach. A factor to consider in the post-rescue stage is the operability of critical infrastructure such as hospitals. A reduction in functionality and an increase in demand are expected in hospitals in a post-earthquake situation. A case study for an M9 Cascadia earthquake in the city of Vancouver was used to develop a method for evaluating the possible surge in demand in the emergency department (Palomino Romani et al., 2023).

Apart from search and rescue, another activity that takes priority in the event of a Cascadia earthquake would be to reconnect the communities that are isolated because of damaged district roads and highways. Over the years, several optimization models have been proposed for reconnecting damaged roads and infrastructure, as well as providing relief to the communities that are cut off. Some of these models are compared in Kasaei & Salman (2016).

The earthquake-damage scenario can be treated as an Arc Routing Connectivity Problem (ARCP), with the nodes representing various locations on Vancouver Island, and the arcs representing roads. For a similar scenario in Istanbul, Turkey, Akbari & Salman (2017b) developed a model to reconnect various communities using ARCP. Each arc has a ‘cost’ which in this case is the time taken to traverse it. In addition to the traversing time, damaged arcs are assigned another cost which represents the time taken to repair them. If an arc is considered undamaged, it can be simply passed through. Otherwise, there is an additional waiting time during which it is repaired. The objective of this model is to minimize the total unblocking and traversing time while reconnecting the nodes of the network, using road repair teams that are referred to as *vehicles.* Multiple vehicles can traverse through separate arcs simultaneously. If one vehicle arrives at an arc while another is currently unblocking it, the former must wait until the unblocking is completed by the vehicle that reached the arc first.

Akbari & Salman (2017a) later proposed a Multi-vehicle Prize Collecting Arc Routing for Connectivity Problem (KPC-ARCP) method. In this method, all the connected nodes are called 'components', and one of these components contains the depot from which the vehicles are dispatched. A 'prize' is assigned to each component, which in this case is the number of nodes contained in it. The objective of this problem is to collect as much prize as possible by connecting the depot component with the other components within a specified time limit.

Kasaei & Salman (2016) compared the two methods ARCP and PC-ARCP in which the former aims to minimize the total time taken to repair roads by the vehicles and the latter aims to maximize the prize collected by reconnecting parts of the network within a given time. When comparing ARCP and Prize Collecting Arc Routing for Connectivity Problem (PC-ARCP) for the same problem, it was seen that PC-ARCP performs significantly better than ARCP. For 80% of the runs, PC-ARCP showed better results in terms of arcs traversed, whereas for the other 20% the results were the same for both methods.

Other variations of the PC-ARCP are also available, such as the Clustered Prize Collecting Arc Routing Problem (CPARP) in which each arc is part of a cluster, and prizes are assigned to the clusters instead of individual arcs. The objective here is to collect the maximum prize by connecting the clusters (also called components) (Aráoz et al., 2009). The CPARP can be further modified to fit different networks. One such example is the Windy CPARP or WCPARP in which the graph, although undirected, has two different values for each arc depending on the direction of the walk (Corberán et al., 2011).

The Arc Routing network problems require a lot of computation and hence the processing times for these problems can extend to days depending on the number of arcs and nodes in the network and the computing power available (Kasaei & Salman, 2016). In such cases, heuristic solution approaches are used to avoid large computation times. Various heuristic methods were tested on a Location Arc Routing Problem and the results show that the best and fastest results were obtained using the Tabu Search – Greedy Randomised Adaptive Search Response (TS – GRASP) method (Lopes et al., 2014). Akbari & Salman also proposed a similar method in which GRASP is used to identify a select number of closed roads to be reconstructed (Akbari & Salman, 2017a).

Souza Almeida et al. (2022) proposed considering the resilience of communities as a parameter to the KPC-ARCP problem. A GRASP metaheuristic method is used to solve the road clearing, as well as the ships (ferries and barges), trucks, and helicopter routing problems. Although a powerful computation method to solve the routing problem is produced, only limited analyses of the results have been done in this study.

For supplying emergency goods to affected communities, Almeida et al. (2019) formulated a two-echelon Split Delivery Vehicle Routing Problem with Time Windows and tested the model on data available from the aftermath of hurricane Igor in Newfoundland. A two-echelon problem means that there are two stages of relief activities: one from the sources to distribution centres, and then from the distribution centres to the communities. This study also compared different approaches to solving the problem with two different heuristics.

A literature review on the different papers addressing repair of damaged roads and relief supplies distribution was done by Souza Almeida et al. (2022). It is seen that although there are many different solutions based on different heuristics for the same type of problems, there is limited study available on what computational method is better for arc routing problems. Souza Almeida and Goerlandt' s paper on solving a KPC-ARCP suggests that while comparing the results of a road repair problem using three different methods: GRASP, ant colony optimization, and a matheuristic, GRASP seemed to be the best option when comparing objective value, processing time, and complexity (Souza Almeida & Goerlandt, 2022). It is also shown that although there are several studies on roads connectivity and relief prior to 2016, the synchronization of road clearing, and multi-modal distribution is a relatively new course in the field. This was achieved in Souza Almeida et.al (2024) where repair of roads and relief supply activities are considered simultaneously in a synchronized manner.

With each earthquake that occurs, the precautionary measures taken for such disasters by various regions have also seen proportional improvements. It becomes necessary to include the preparedness of communities to face a large-scale earthquake as an important parameter while finding a solution to route relief supplies to the communities. A resilient community is one that does not see a decline in any of its critical services when it experiences a hazard, and if it does face one, recovery is possible within a reasonable time limit (Chang & Tanner, 2022). The community resilience values used in the analyses in this thesis are a result of Chang and Tanner’s study.

Chapter 3. METHODS

3.1 Brief overview of the RCRSD model

To conduct extensive sensitivity analysis of the Road Clearing and Relief Supplies Distribution (RCRSD) model, it is important to first understand the working of the model. The model is explained in detail in (Souza Almeida et.al, 2024), but a brief overview of the model and the components of the model that are essential to this study are outlined in this section.

The basic function of the RCRSD model (Souza Almeida et.al, 2024) whose results were analyzed in this study, is to develop routing strategies for the road clearing teams, ships, trucks, and helicopters on and near Vancouver Island. In this study, the model is used to solve a road reconstruction and relief supply distribution problem in the event of a Cascadia subduction zone megathrust earthquake. The sequence of activities that take place according to the model is shown in Figure 4.

For each block shown in Figure 4, an optimization model is utilized, and they are run sequentially. Each of these models will be referred to as sub-models in this thesis, and together they make up the entire RCRSD model. In routing problems, there are *nodes* and *arcs.* For this study, the RCRSD model uses a network of 2543 nodes, and these nodes represent the geographical locations of communities, intersections in roads, ports, airports, and heliports on Vancouver Island, the surrounding smaller islands (Gulf Islands), and mainland British Columbia. Each node also has a weight associated with it. The weights associated with the first sub-model, which is the Road Clearing sub-model are shown in Table 1.

Node type	**Weight**
Community	Community Demand (CD)
Road intersection	0
Port	Sum of all community weights
Heliport	Sum of all community weights
Airport	Sum of all community weights

Table 1.Weights of nodes used in the Road Clearing sub-model

The Community Demand (CD) shown in Table 1 is calculated as $CD = CP * 2^{CIF}$ where,

CD = Community Demand

CP = Community Population

CIF = Community Impact Factor

This formula was developed by Souza Almeida et al. (2024) and from a limited study it was seen that 2^{CIF} was the best way to represent CIF. The community impact factor (CIF) is a metric obtained from (Chang & Tanner, 2022) which gives a measure of a community's resilience to the Cascadia earthquake. According to (Chang & Tanner, 2022), $CIF = [1,5]$ with 1 being the most resilient value and 5 meaning the community has the least resilience to the earthquake (The CIF takes a fractional scale between 1 and 5). As the CIF increases, the demand of the community also increases.

The nodes are connected to each other using arcs that represent the time taken to traverse between two nodes by the distinct types of vehicles. A brief overview of the working of all sub-models of the RCRSD model (as shown in Figure 4) are explained in the paragraphs below.

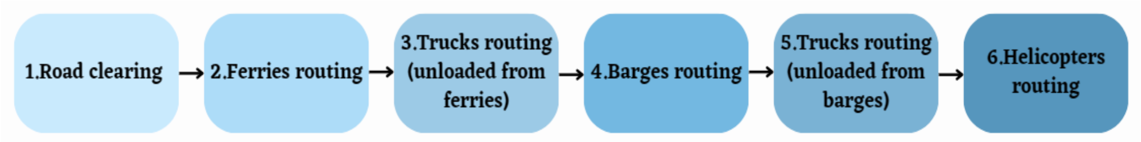


Figure 4. Working order of the RCRSD model

The first sub-model in the sequence is the road clearing sub-model which is a Multi Prize Collecting Arc Routing Connectivity Problems (KPC-ARCP). In this sub-model, several road clearing teams are dispatched from a depot location (node) to clear up unusable roads. In this thesis, four road clearing teams are assumed to be available to clear roads and all teams originate from the same node. This sub-model aims to connect community nodes to port nodes, and the arcs are the road segments connecting the nodes on Vancouver Island. If a road segment (arc) between two nodes is undamaged, then the arc takes the value of a traversing time. However, if a segment is considered damaged then the arc takes a much longer time value called unblocking time during which the road is cleared. Once an arc is 'cleared', the other teams can simply pass through it. If more than one team approaches a damaged road segment, the first one to approach clears the segment while the other waits until the segment is cleared. The objective function of this sub-model is to connect ports and communities and it does so by trying to maximize the total prize that gets accumulated.

At the end of the road clearing sub-model, some ports and communities are connected, and this becomes the basis for the following sub-models which perform the multi-modal relief supplies delivery to the communities. A simple 2-echelon split delivery algorithm is used for relief supplies distribution. The first phase of the delivery is done using ferries and barges to deliver supplies from mainland Vancouver to the islands. The second phase is the distribution of goods from the ports on Vancouver Island to the communities via trucks. To the communities that are left isolated, helicopters are used to bring supplies. In this study, it is assumed that each box of supply can serve a single person for a week. Details regarding the size and capacity of the boxes are shown in the appendix of this thesis.

The first sub-model that is executed following the road clearing sub-model is the ferry routing sub-model. The nodes in this sub-model are the ferry ports on Vancouver Island and mainland Vancouver. The weight of each port node on Vancouver Island is the sum of the weights of all communities connected to that port via roads. With the updated demand for ports, ferries are routed from the mainland to Vancouver Island. An assumption made here is that the mainland has infinite supplies and that there are enough tractor-trailers for every container that arrives at the ports on Vancouver Island. The objective function here is to deliver as much supplies as possible to the ports on Vancouver Island and the Gulf Islands within the time horizon.

Once the truck containers are unloaded at the ports, they are dispatched to the communities connected to the ports via the initial undamaged roads and the cleared roads. For this sub-model, the starting point of all trucks are the ports where they are unloaded. The objective of this sub-model is to satisfy the demands of the communities as much as possible within the time horizon. Once the communities are each supplied the possible number of boxes (the lower of its demand or the capacity to deliver there), the demands of all the communities are recalculated by subtracting the satisfied demands from the initial demands. Each truck has the capacity to carry 380 boxes of relief supply at a time.

The next sub-model, which is the barge-routing sub-model works exactly like the ferry routing sub-model. Once the barges are sent out their destination ports or docking areas, the trucks unloaded from the barges are routed similarly to the ones unloaded from the ferries. Finally, for the communities that still did not get their demands met, helicopters are routed from the mainland to the communities on Vancouver Island using the helicopters routing sub-model. In this thesis, it is assumed that there are four helicopters available with each having a capacity of 95 boxes of relief supplies.

For each of the sub-models in the RCRSD model, a Greedy Randomised Adaptive Search Procedure (GRASP) heuristic is employed to find the optimal solution. The heuristic is employed because of the large number of nodes in the problem and finding a deterministic solution would take enormous amounts of time as well as processing power. The model is coded in Python and run on VS Code. It uses the NumPy library to perform large matrix operations and the NetworkX library for the formation and manipulation of network structures.

3.2 Regional division of Vancouver Island

The results of the RCRSD model were studied with respect to 4 different regions of Vancouver Island namely North Island, Central Island, Pacific Rim, and South Island. Sunshine Coast and Gulf Islands as seen in Figure 5 (Chang et al., 2020), although used in the model, were excluded from the analyses done for this study.

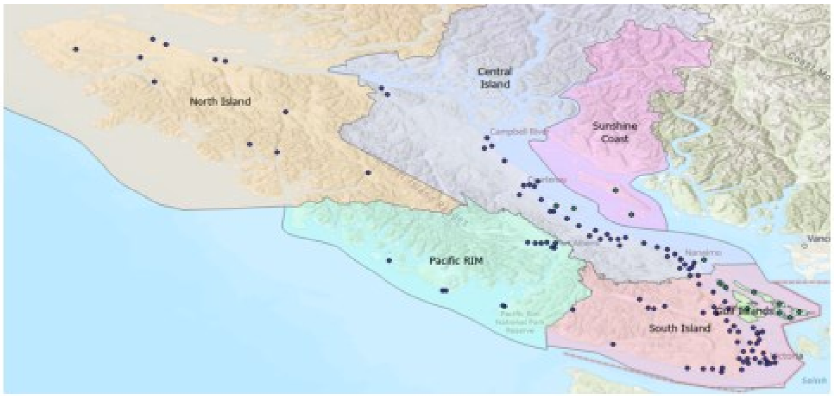


Figure 5. Communities and regional division of Vancouver Island

3.3 Input variables

To perform extensive sensitivity analysis, it is important to understand the input and output variables of the RCRSD model. This section goes over the input variables of the model. Over 50 input variables are used in the model, and they were classified into four different types: fixed, decision, what-if, and computational variables. In this study, decision and what-if input variables were varied and the results of the model were analyzed. Fixed and computational input variables remained unchanged, and hence they are referred to as parameters in this thesis. The values of these parameters are obtained from (Souza Almeida et al., 2023) and they are shown in the appendix of this thesis.

3.3.1 Fixed Parameters

Fixed variables are those that remained unchanged throughout this study. Fixed parameters form the largest classification in this study and some of the variables are listed in Table 2.

Parameter name	**Description**
Ferries Ports Vancouver Island	List of Ferry ports on Vancouver Island
Ferries Ports Mainland	List of Ferry ports on Mainland Vancouver
Barges Ports Vancouver Island	List of barge docks on Vancouver Island
Heavy machine speed	Speed of the road clearing teams
Roads’ distance	Matrix of distances between road segments on Vancouver Island

Parameter name	Description
Population	List of populations of Vancouver Island communities
Truck speed	Speed of supply trucks

Table 2. Examples of fixed parameters

3.3.2 Decision Variables

Decision variables are some of the input variables that were chosen to be varied for the analyses. These are variables of which the values would not be affected by the earthquakes. All the decision variables are listed in Table 3.

Variable name	Description
Time horizon	Time for which the model is run. i.e., Time within which roads are cleared and communities are served.
Road (clearing teams) depot	Location of the road clearing teams' starting point
Community Resilience	Represented by the community impact factor (CIF). Although developed from another model made for SIREN, this variable is classified as a decision variable because it is independent of the earthquake scenarios.
Roads' prize	Weights of nodes used the RCRSD model that are calculated from the population and resilience values to assign priorities to communities for network optimization.

Table 3. List of decision variables

3.3.3 What-if Variables

What-if variables are those that are changed for the analyses and are affected by the impact of the Cascadia megathrust earthquake. All the what-if variables are listed in Table 4.

Variable name	Description
Ports Opening Time	Time at which the ports open on Vancouver Island
Affected communities	Communities affected by the earthquake

Variable name	Description
Roads unblocking matrix	Matrix of time taken to unblock road segments in hours
List all ferries	List of all available ferries
List all barges	List of all available barges
Ships traversing time	Matrix of time taken by ferries and barges to travel from one port to another

Table 4. List of what-if variables

3.3.4 Computational Parameters

Computational parameters are those which are completely independent of the earthquake scenario. These are the algorithmic variables that affect the performance of GRASP in the model. They remained unchanged throughout the study. All the computational parameters are listed in Table 5.

Parameter name	Description
Roads iterations	Number of iterations in the road clearing GRASP
Trucks iterations	Number of iterations in the trucks routing GRASP
Ferries iterations	Number of iterations in the ferries routing GRASP
Barges iterations	Number of iterations in the barges routing GRASP
Helicopters iterations	Number of iterations in the helicopters routing GRASP

Table 5. List of computational parameters

3.4 Output parameters

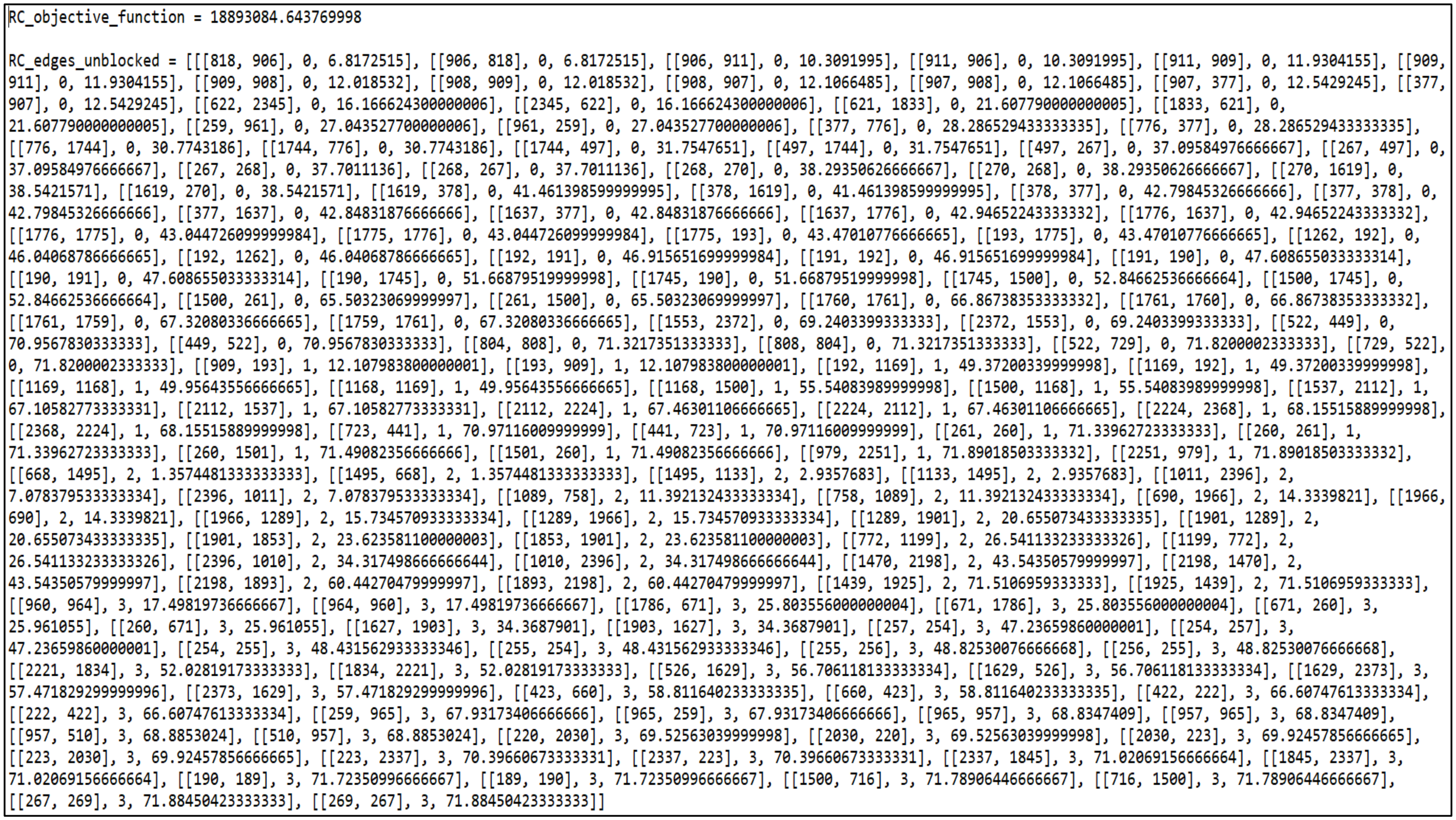
The outputs generated by the RCRSD model, and how the results are generated from the outputs, are explained in this section. For each run of the RCRSD model, 15 output files are generated as seen in Table 6. An example of an output file is shown in Figure 6.

Output name	Output ID	Name of generated .txt file	Content details
Initial demand	ID	Initial_demand	List of demands of every community on Vancouver Island in terms of number of boxes of supplies
Road clearing edges	RCE	RC_ObjFunc_UnblockEdges	Objective value of road clearing sub-model and list of unblocked edges with the

Output name	Output ID	Name of generated .txt file	Content details
			time taken and ID of the team that clears it
Road clearing routes	RCR	RC_routes	Route taken by each road clearing team
Ferries island delivery	FID	Ferries_Island_Delivery	Demands delivered on ferries to each of the smaller islands in terms of number of trucks
Ferries demands	FD	Ferries_ObjFunc_Demands	Objective value of the ferries routing optimization model and the demands delivered to each port via ferries in terms of number of trucks
Ferries routes	FR	Ferries_Routes	Routes details for every ferry
Ferries truck delivery	FTD	Ferries_Truck_Delivery	Demands delivered by trucks that arrived on Vancouver Island via ferries to each community in terms of number of boxes
Ferries trucks routes	FTR	Ferries_Trucks_Routes	Routes details of trucks that arrived on Vancouver Island via ferries
Barges island delivery	BID	Barges_Island_Delivery	Demands delivered on barges to each of the smaller islands in terms of number of trucks
Barges demands	BD	Barges_ObjFunc_Demands	Objective value of the barges routing optimization model and the demands delivered to each port via barges in terms of number of trucks
Barges routes	BR	Barges_Routes	Routes details for every barge
Barges truck delivery	BTD	Barges_Truck_Delivery	Demands delivered by trucks that arrived on Vancouver Island via barges to each community in terms of number of boxes
Barges trucks routes	BTR	Barges_Trucks_routes	Routes details of trucks that arrived on Vancouver Island via barges

Output name	**Output ID**	**Name of generated .txt file**	**Content details**
Helicopter community demands	HD	Heli_Communities	Demands delivered by helicopters to communities on Vancouver Island
Helicopter routes	HR	Helicopters_routes	Routes details of helicopters
Communities with unsatisfied demands	UC	Isolated_Communities	List of communities whose demands are not 100% met
Communities completely supplied	SC	Supplied_Communities	List of communities whose demands are completely met

Table 6. List of all output files generated from a single run of the RCRSD model



```
RC_objective_function = 18893084.643769998

RC_edges_unblocked = [[[818, 906], 0, 6.8172515], [[906, 818], 0, 6.8172515], [[906, 911], 0, 10.3091995], [[911, 906], 0, 10.3091995], [[911, 909], 0, 11.9304155], [[909,
911], 0, 11.9304155], [[909, 908], 0, 12.018532], [[908, 909], 0, 12.018532], [[908, 907], 0, 12.1066485], [[907, 908], 0, 12.1066485], [[907, 377], 0, 12.5429245], [[377,
907], 0, 12.5429245], [[622, 2345], 0, 16.166624300000006], [[2345, 622], 0, 16.166624300000006], [[621, 1833], 0, 21.607790000000005], [[1833, 621], 0,
21.607790000000005], [[259, 961], 0, 27.043527700000006], [[961, 259], 0, 27.043527700000006], [[377, 776], 0, 28.286529433333335], [[776, 377], 0, 28.286529433333335],
[[776, 1744], 0, 30.7743186], [[1744, 776], 0, 30.7743186], [[1744, 497], 0, 31.7547651], [[497, 1744], 0, 31.7547651], [[497, 267], 0, 37.09584976666667], [[267, 497], 0,
37.09584976666667], [[267, 268], 0, 37.7011136], [[268, 267], 0, 37.7011136], [[268, 270], 0, 38.29350626666667], [[270, 268], 0, 38.29350626666667], [[270, 1619], 0,
38.5421571], [[1619, 270], 0, 38.5421571], [[1619, 378], 0, 41.461398599999995], [[378, 1619], 0, 41.461398599999995], [[378, 377], 0, 42.79845326666666], [[377, 378], 0,
42.79845326666666], [[377, 1637], 0, 42.84831876666666], [[1637, 377], 0, 42.84831876666666], [[1637, 1776], 0, 42.94652243333332], [[1776, 1637], 0, 42.94652243333332],
[[1776, 1775], 0, 43.044726099999984], [[1775, 1776], 0, 43.044726099999984], [[1775, 193], 0, 43.47010776666665], [[193, 1775], 0, 43.47010776666665], [[1262, 192], 0,
46.04068786666665], [[192, 1262], 0, 46.04068786666665], [[192, 191], 0, 46.915651699999984], [[191, 192], 0, 46.915651699999984], [[191, 190], 0, 47.608655033333314],
[[190, 191], 0, 47.608655033333314], [[190, 1745], 0, 51.66879519999998], [[1745, 190], 0, 51.66879519999998], [[1745, 1500], 0, 52.84662536666664], [[1500, 1745], 0,
52.84662536666664], [[1500, 261], 0, 65.50323069999997], [[261, 1500], 0, 65.50323069999997], [[1760, 1761], 0, 66.86738353333332], [[1761, 1760], 0, 66.86738353333332],
[[1761, 1759], 0, 67.32080336666665], [[1759, 1761], 0, 67.32080336666665], [[1553, 2372], 0, 69.2403399333333], [[2372, 1553], 0, 69.2403399333333], [[522, 449], 0,
70.9567830333333], [[449, 522], 0, 70.9567830333333], [[804, 808], 0, 71.3217351333333], [[808, 804], 0, 71.3217351333333], [[522, 729], 0, 71.8200002333333], [[729, 522],
0, 71.8200002333333], [[909, 193], 1, 12.107983800000001], [[193, 909], 1, 12.107983800000001], [[192, 1169], 1, 49.37200339999998], [[1169, 192], 1, 49.37200339999998],
[[1169, 1168], 1, 49.95643556666665], [[1168, 1169], 1, 49.95643556666665], [[1168, 1500], 1, 55.54083989999998], [[1500, 1168], 1, 55.54083989999998], [[1537, 2112], 1,
67.10582773333331], [[2112, 1537], 1, 67.10582773333331], [[2112, 2224], 1, 67.46301106666665], [[2224, 2112], 1, 67.46301106666665], [[2224, 2368], 1, 68.15515889999998],
[[2368, 2224], 1, 68.15515889999998], [[723, 441], 1, 70.97116009999999], [[441, 723], 1, 70.97116009999999], [[261, 260], 1, 71.3396272333333], [[260, 261], 1,
71.3396272333333], [[260, 1501], 1, 71.49082356666666], [[1501, 260], 1, 71.49082356666666], [[979, 2251], 1, 71.89018503333332], [[2251, 979], 1, 71.89018503333332],
[[668, 1495], 2, 1.3574481333333333], [[1495, 668], 2, 1.3574481333333333], [[1495, 1133], 2, 2.9357683], [[1133, 1495], 2, 2.9357683], [[1011, 2396], 2,
7.078379533333334], [[2396, 1011], 2, 7.078379533333334], [[1089, 758], 2, 11.392132433333334], [[758, 1089], 2, 11.392132433333334], [[690, 1966], 2, 14.3339821], [[1966,
690], 2, 14.3339821], [[1966, 1289], 2, 15.734570933333334], [[1289, 1966], 2, 15.734570933333334], [[1289, 1901], 2, 20.655073433333335], [[1901, 1289], 2,
20.655073433333335], [[1901, 1853], 2, 23.623581100000003], [[1853, 1901], 2, 23.623581100000003], [[772, 1199], 2, 26.541133233333326], [[1199, 772], 2,
26.541133233333326], [[2396, 1010], 2, 34.317498666666644], [[1010, 2396], 2, 34.317498666666644], [[1470, 2198], 2, 43.54350579999997], [[2198, 1470], 2,
43.54350579999997], [[2198, 1893], 2, 60.44270479999997], [[1893, 2198], 2, 60.44270479999997], [[1439, 1925], 2, 71.5106959333333], [[1925, 1439], 2, 71.5106959333333],
[[960, 964], 3, 17.49819736666667], [[964, 960], 3, 17.49819736666667], [[1786, 671], 3, 25.803556000000004], [[671, 1786], 3, 25.803556000000004], [[671, 260], 3,
25.961055], [[260, 671], 3, 25.961055], [[1627, 1903], 3, 34.3687901], [[1903, 1627], 3, 34.3687901], [[257, 254], 3, 47.23659860000001], [[254, 257], 3,
47.23659860000001], [[254, 255], 3, 48.431562933333346], [[255, 254], 3, 48.431562933333346], [[255, 256], 3, 48.8253007666668], [[256, 255], 3, 48.8253007666668],
[[2221, 1834], 3, 52.0281917333333], [[1834, 2221], 3, 52.0281917333333], [[526, 1629], 3, 56.706118133333334], [[1629, 526], 3, 56.706118133333334], [[1629, 2373], 3,
57.471829299999996], [[2373, 1629], 3, 57.471829299999996], [[423, 660], 3, 58.811640233333335], [[660, 423], 3, 58.811640233333335], [[422, 222], 3, 66.6074761333334],
[[222, 422], 3, 66.6074761333334], [[259, 965], 3, 67.93173406666666], [[965, 259], 3, 67.93173406666666], [[965, 957], 3, 68.8347409], [[957, 965], 3, 68.8347409],
[[957, 510], 3, 68.8853024], [[510, 957], 3, 68.8853024], [[220, 2030], 3, 69.52563039999998], [[2030, 220], 3, 69.52563039999998], [[2030, 223], 3, 69.92457856666665],
[[223, 2030], 3, 69.92457856666665], [[223, 2337], 3, 70.39660673333331], [[2337, 223], 3, 70.39660673333331], [[2337, 1845], 3, 71.02069156666664], [[1845, 2337], 3,
71.02069156666664], [[190, 189], 3, 71.72350996666667], [[189, 190], 3, 71.72350996666667], [[1500, 716], 3, 71.78906446666667], [[716, 1500], 3, 71.78906446666667],
[[267, 269], 3, 71.8845042333333], [[269, 267], 3, 71.8845042333333]]
```

Figure 6. Example of the Road Clearing edges (.txt) output file

The results of the RCRSD model are studied from data extracted from the output files generated after each run. A python script to extract the values from the .txt files and convert them into tabulated data was developed. Because of the large amount of data created after each run, it is difficult to analyze all output files of the model. Therefore, observations were made in two ways: from results derived after each run and from compiled results obtained after multiple runs (explained in sections 3.4.1 and 3.4.2).

3.4.1 Results derived after every run of the model

For each run of the RCRSD model, the communities that are supplied and the roads that are cleared were observed. The runs were compared in terms of the total demand of the communities that are met for each run (i.e., the result of a run is considered 'better' than another if the total demand met by the former is higher than the latter). Additionally, for every input scenario, the RCRSD model was run three times and the average demand results were observed to account for the variations in results due to GRASP.

Table 7 lists all the results that were derived from all the single runs and observed for the study. It also shows the parent output files (from Table 6) from which each result was derived. These result values were calculated after each run (for each input scenario) from the output files and the initial input variable values.

Result ID	Results derived	Parent outputs ID (From Table 6)
R1	Total demand met	FID, FD, FTD, BID, BD, BTD, HD
R2	Total demand met by ships (barges or ferries)	FID, FD, BID, BD
R3	Total demand met by trucks	FTD, BTD
R4	% Of total road segments roads cleared	RCE
R5	% Of damaged road segments cleared	RCE

Table 7. List of output parameters observed for each run of the RCRSD model

The outputs listed in Table 7 were chosen to be studied in the analyses because they represent the efficiency of the road clearing and supply activities on Vancouver Island resulting from the RCRSD model runs. Results R1, R2, and R3 shown in Table 7 were extracted from the outputs shown in the 'Parent outputs' column of the table. To maintain consistency of the results, the supply to communities were also calculated from the results shown in Table 7.

A few additions to the original RCRSD code were made for this study to determine the extent of road clearing activities in each run. The percentage of road segments cleared with respect to the total number of damaged road segments, as well the percentage of road segments cleared with respect to the total number of road segments were calculated and presented as results R4 and R5 in Table 7.

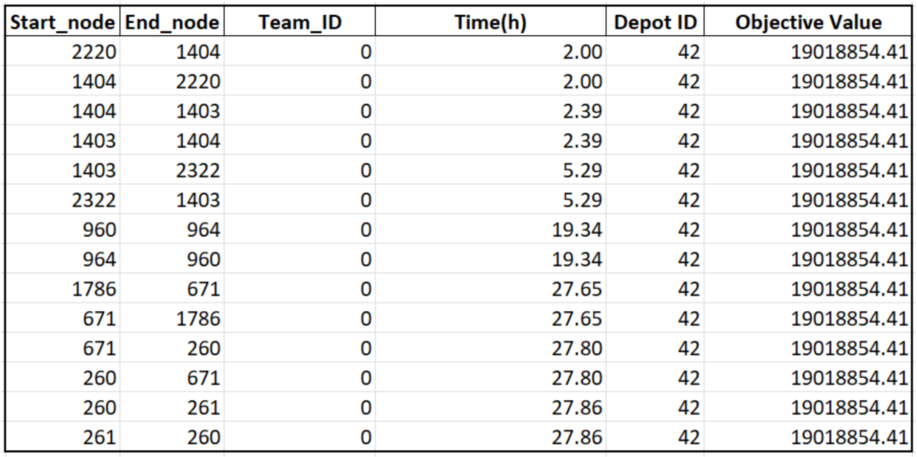
3.4.2 Compiled results from several runs of the model

The outputs listed in Table 7 are useful when the results of a small number of runs are being studied. However, to compare the results of the RCRSD model from several input variations (scenarios), it was necessary to create compiled data sets containing relevant information from all the runs the contents of which can be analyzed easily. For this reason, a script was developed to extract the data from relevant output files and integrate them into two major data sets as shown in Table 8.

Dataset ID	**File name**	**File format**	**File details**
UR	Unblocked routes	.csv	Contains details regarding routes taken by the road clearing teams.
CD	Communities' details	.csv	Contains details regarding the level of supply to each community

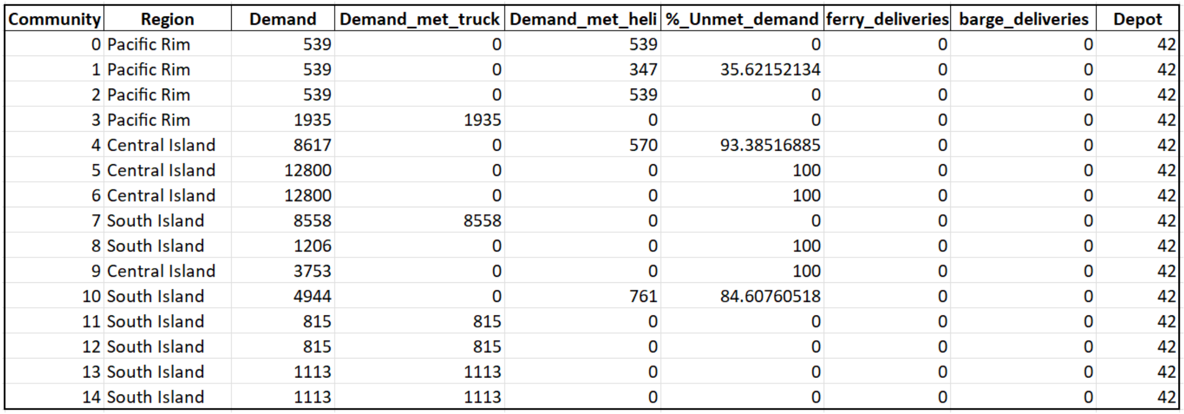
Table 8. Data sets generated for analyses of results of the RCRSD model

Snippets of the two datasets generated from the results of the RCRSD model are shown below. Figure 7 represents UR and Figure 8 represents CD. In UR, the column 'Objective Value' denotes the sum of 'prizes' collected by the road clearing teams in the road clearing sub-model as explained in section 3.1. The prize is a measure of the community demands, and the Objective Value is a measure of the number of communities that are reconnected to ports via roads after the road clearing sub-model is executed.



Start_node	End_node	Team_ID	Time(h)	Depot ID	Objective Value
2220	1404	0	2.00	42	19018854.41
1404	2220	0	2.00	42	19018854.41
1404	1403	0	2.39	42	19018854.41
1403	1404	0	2.39	42	19018854.41
1403	2322	0	5.29	42	19018854.41
2322	1403	0	5.29	42	19018854.41
960	964	0	19.34	42	19018854.41
964	960	0	19.34	42	19018854.41
1786	671	0	27.65	42	19018854.41
671	1786	0	27.65	42	19018854.41
671	260	0	27.80	42	19018854.41
260	671	0	27.80	42	19018854.41
260	261	0	27.86	42	19018854.41
261	260	0	27.86	42	19018854.41

Figure 7. Snippet of Unblocked routes.csv



Community	Region	Demand	Demand_met_truck	Demand_met_heli	%_Unmet_demand	ferry_deliveries	barge_deliveries	Depot
0	Pacific Rim	539	0	539	0	0	0	42
1	Pacific Rim	539	0	347	35.62152134	0	0	42
2	Pacific Rim	539	0	539	0	0	0	42
3	Pacific Rim	1935	1935	0	0	0	0	42
4	Central Island	8617	0	570	93.38516885	0	0	42
5	Central Island	12800	0	0	100	0	0	42
6	Central Island	12800	0	0	100	0	0	42
7	South Island	8558	8558	0	0	0	0	42
8	South Island	1206	0	0	100	0	0	42
9	Central Island	3753	0	0	100	0	0	42
10	South Island	4944	0	761	84.60760518	0	0	42
11	South Island	815	815	0	0	0	0	42
12	South Island	815	815	0	0	0	0	42
13	South Island	1113	1113	0	0	0	0	42
14	South Island	1113	1113	0	0	0	0	42

Figure 8. Snippet of Communities details.csv

To compile the results from every scenario into the data sets shown above, python was used and the NumPy library was utilized for creating and manipulating these data sets. Once the data sets were generated, they were analyzed using R language to identify damaged roads that are frequently restored and communities with frequent supplies or very little supplies. The supply and road clearing activities in each regional division of Vancouver Island shown in Figure 5 were also studied.

3.5 Input changes – sensitivity analysis

Section 3.3 presented the classification and overview of all the inputs used in the model. This section describes the variations in the inputs and the sequence in which they are varied for the analyses, as well as the results that are studied with each variation. The values of the inputs that are changed are shown in the results section of this thesis as some of the input changes are based on the results from their preceding analyses.

The RCRSD model was run using damage datasets available for Southwestern British Columbia, especially focusing on Vancouver Island. The model was studied for two different earthquake scenarios: A medium damage case which is practically more likely to happen (Case A: partial disconnection) and a high damage case (Case B: extensive disconnection). The values of the what-if variables such as ports opening times and road unblocking times are different for each case. A brief overview of the data used for the two cases is given in Chapter 4 and the datasets are provided in detail in (Souza Almeida et al., 2023).

In this thesis, Case A was extensively studied, while Case B was analyzed for a limited set of input changes. This is because on average each run of the RCRSD model takes about 20 minutes to complete execution, with some runs taking over two hours to be completed. For each of the input scenario variations, creating analyzable data from the results of the model run takes an additional two hours. For this reason, the scope of this thesis was limited to studying the results of only Case A extensively. The sequence in which the analyses were done is shown in Figure 9.

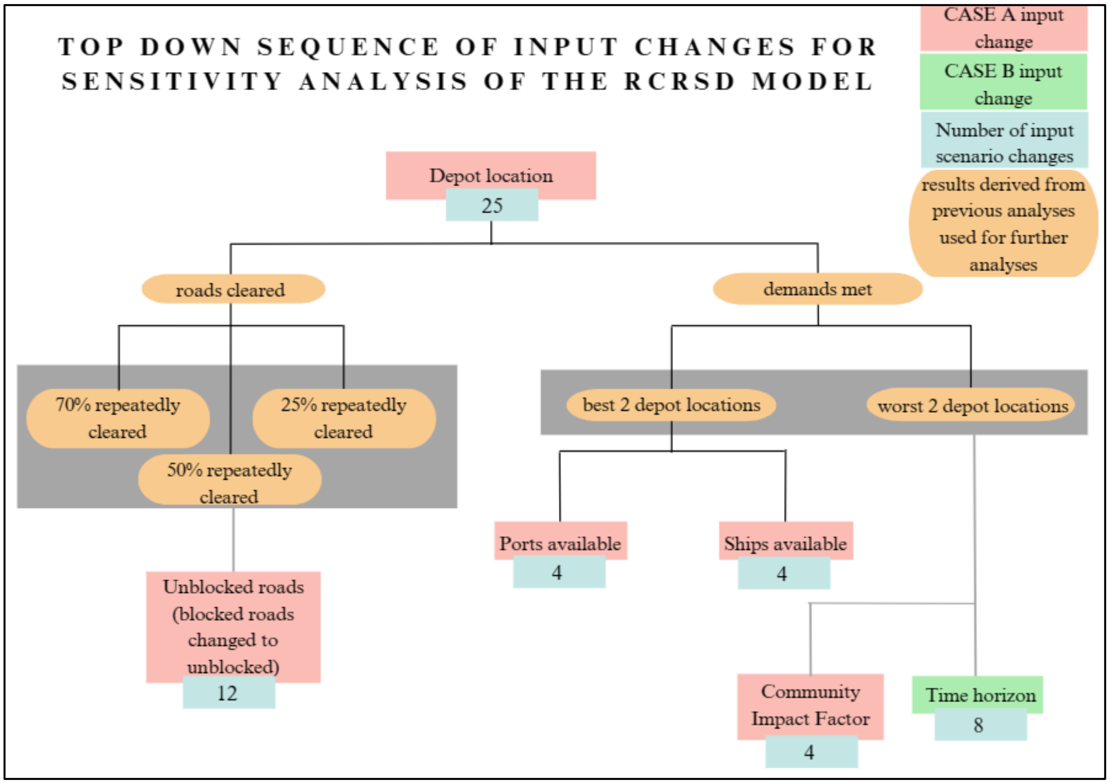


Figure 9. Sequence of input changes done for the sensitivity analyses

As seen in Figure 9, to study the results of the model, Case A was first considered, and the initial analysis was done by changing the depot locations of the road clearing teams (as explained in 3.5.1.1). From this analysis, the roads that were repeatedly cleared for at least 70%, 25%, and 50% were identified. Also identified from the initial analysis were the demands satisfied for every community in each of the runs and hence, the road clearing teams' depot locations that satisfy the least and most demands (referred to as the best and the worst depot locations). For the next set of analyses, the roads that were repeatedly cleared were considered to be undamaged and the results were observed for the best and worst depot locations of the road clearing teams (as explained in 3.5.1.2). Then, for the best and worst depot locations, the availability of ports and ships were changed and the results of the model were observed (as explained in 3.5.1.3 and 3.5.1.4). The following analysis was done to study the effect of CIF on the model results. This was done by changing the CIF values and running the RCRSD model for the best and worst depot locations (as explained in 3.5.1.5). Finally, for Case B, the RCRSD model was run and the results were studied for the best and worst depot locations identified from the Case A results (explained in 3.5.2).

3.5.1 Case A input changes

The initial set of runs are done for the partial disconnection case (Case A). For all the analyses shown in Figure 9, detailed lists of inputs that are changed and their values are shown in the results section (Chapter 5). The input variable changes are listed in the results because as explained earlier, a lot of the input variations depend on the results of the initial analysis done by changing the road clearing teams' depot locations (shown in section 3.5.1.1).

3.5.1.1 Road clearing teams' depot

The first input variable that was changed for the analyses is called *Road depot,* which is the starting location of the road clearing teams on Vancouver Island. Conducting sensitivity analysis by changing the *road depot* locations (see Figure 10) was done with the aim of ranking the depot locations by calculating the demands of the communities that are met for each alternative, determining the region (Figure 5) that may be best suited for depot location, and finding the roads that are fixed by the road clearing teams repeatedly.

This *road depot* variable was chosen for the initial analysis for the following reasons:

- The first 'activity' to be optimized in the model is road clearing. Routing of ships, trucks, and helicopters take place after the roads are cleared and they depend significantly on which roads are cleared.
- Varying this input is simple compared to a lot of the other variables.
- It is a decision variable that causes a significant change in the results when varied.

Figure 10 shows all the locations of the road clearing teams' depots for which the RCRSD model was run for Case A. Table 9 shows the node ID for all the depots shown in Figure 10. For all analyses involving changing the locations of the road clearing depot locations, it is assumed that there are no damages or obstructions in the depot location. That is, it is assumed that the road clearing teams can operate at full capacity.

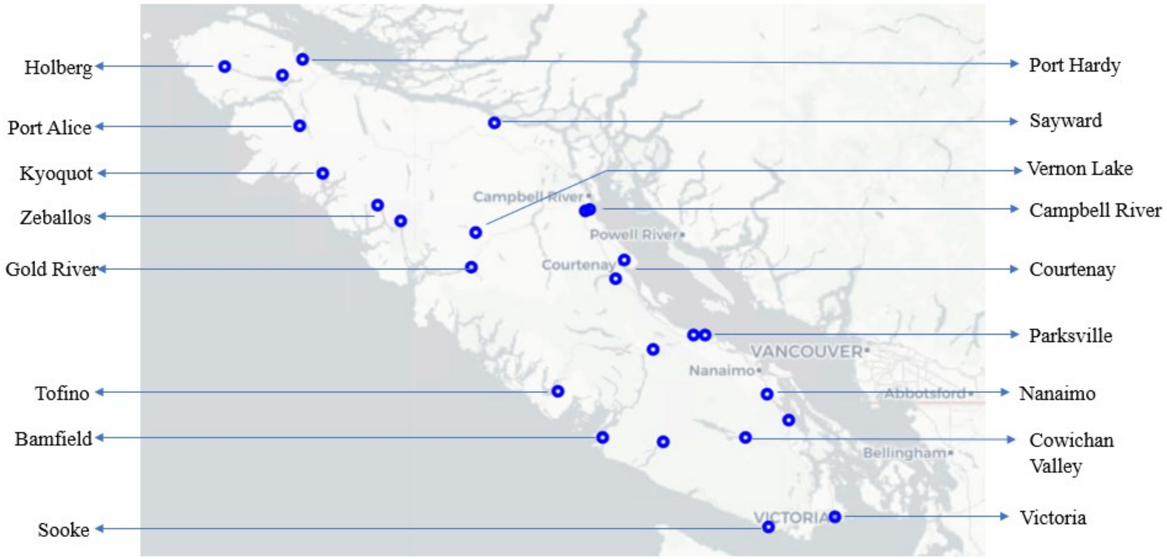


Figure 10. Road clearing teams' depot locations for Case A

Variable changed = Road depot (Depot location of Road clearing teams)	
Scenario ID	Variable value (node ID)
D1	42

Variable changed = Road depot (Depot location of Road clearing teams)	
Scenario ID	**Variable value (node ID)**
D2	46
D3	57
D4	80
D5	219
D6	220
D7	742
D8	778
D9	802
D10	1075
D11	1195
D12	1544
D13	1579
D14	1926
D15	2002
D16	2012
D17	2069
D18	2165
D19	2227
D20	2313
D21	2324
D22	2343
D23	2375
D24	2395
D25	2431

Table 9. Values of Road depot input variable

The depots were chosen based on the locations of staging areas suggested by the province of British Columbia (Edgington, 2022), selecting locations near airports and ports, and finally at random locations near communities to have similar number of depots tested in each region of Vancouver Island (refer Figure 5). For all the runs, the *time horizon,* which is the time limit for all the road clearing and supply activities, was set to three days. The output files were then all compiled into the two datasets as shown in Table 8, and the results shown in section 3.4.2 were generated and presented. From the results of this set of analysis, the depot locations were ranked from best to worst in terms of the total demands that are satisfied. That is, the depot location that results in the highest percentage of total demand of the communities met is ranked as the best depot location and the one resulting in the lowest total demand satisfied is named the worst depot location. The best and worst depot locations are presented in section 5.1.1 of this thesis.

3.5.1.2 Damaged roads

From the results of analyses done by varying the *depot location* input variable, a compiled set of *Unblocked routes* (UR) by the road clearing teams from each run was developed. UR was studied to identify the roads that are frequently unblocked by the road clearing teams. This was done with the aim of finding what roads on Vancouver Island are the most critical when supplying emergency goods using trucks. The road clearing activities with respect to each region were also determined from this analysis.

This analysis was done in the different steps shown in Figure 9. From *Unblocked routes*, the road segments that were cleared in multiple runs were identified. First, road segments that were originally *blocked (or damaged)* and were cleared for over 70% of the runs were changed to *unblocked*. With this new set of damage data for roads, the RCRSD model was run for the two best depot locations to see if improving the initial road conditions would have any significant effect on the supplies going to communities. The aim of this analysis was to see if changing the roads that are initially repeatedly cleared to undamaged shows any improvement in the results. This entire process was then repeated by identifying the blocked roads that were cleared for over 50% and over 25% of the runs to identify the effect of reinforcing some of the damage-prone roads for the best depot locations in each case. The process was then repeated for the worst depot locations to see if improving the road conditions subsequently improve the supply activities in these scenarios. The roads that are fixed frequently and the best and worst depot locations are mapped and presented in section 5.1.1 of results. A table showing each input scenario (values of input variables that are changed) for this set of analysis is also presented in the same section. For each input scenario, the RCRSD model was run three times. The results of this analysis are studied in terms of the total communities' demand met, as well as the demands met in each region of Vancouver Island as seen in Figure 5.

In the RCRSD model, road segments are represented by two nodes: a starting and an ending node. Each road segment is identified as blocked or unblocked by a variable called *unblocking time,* the structure of which is explained in section 4.1.1. A road segment that was originally blocked was changed to unblocked by changing its corresponding unblocking time to 0 hours. Any road segment whose unblocking time is greater than 0 hours is considered to be blocked or damaged in the RCRSD model.

3.5.1.3 Ports

In the previous section, it was seen that critical roads were identified from the *Unblocked routes* dataset generated for this study. Another dataset (file) that was generated to hold the compiled results is called *Communities details* (CD as shown in section 3.4.2), which holds information regarding the supplies that reach the communities. Apart from details regarding the demand and supply of communities, this dataset also provides insights into the amount of supplies that are delivered to the ports from where the supplies are then routed to communities via trucks. In this thesis, the term port refers to ferry ports and barge docks. The port that receives the greatest number of supplies was identified from the information available from CD. This port was then changed to be *closed* to observe the effect this action has on the results of the model. This analysis was done twice: once where the ferry barge dock that receives the most supplies is considered closed and the next where the ferry port that receives the most supplies is considered closed. The list of input scenarios for both of these cases are shown in section 5.1.4. For both these cases, the original damage data of roads available for Case A is used. Additionally, this analysis was done only for the two best depot locations (as shown in 5.1.1 of results) that were determined from the results of the initial set of analyses.

The availability of ports was changed by changing the input variable *Ports opening time* to 72 hours. Since the time horizon for the runs is also 72 hours, this would mean that the port remains closed throughout the entire run. Apart from the opening times of the ports, another variable called *Ships traversing time* (represents traversing times of ferries and barges) also needed to be changed. This is because closing a port does not automatically alter the ship routes. The ships traversing time in the RCRSD model is represented by a start node, an end node, and the time taken to traverse between the two nodes for each ship, with every ship being represented by a ship ID. If the end node was one of the ports considered to be closed for the analyses, then the corresponding traversing time was changed to 72 hours, meaning no ship would be able to travel to that port. The input structures of *Ports opening time* and *Ships traversing time* and their changes are shown in the Data section 4.1.2 of this thesis.

3.5.1.4 Ships availability

The next set of analyses that were done for Case A was changing the availability of ships (as shown in Figure 9) to observe how this affects the delivery of supplies to the communities and subsequently which communities and regions on Vancouver Island are prioritized when resources are limited. Additionally, with the reduction in the number of ships, this set of analyses was also executed to observe if any of the reduced supply was picked up by the other modes of deliveries to the island.

This set of analyses was done by first reducing the number of available barges to 50% and observing the outputs of the RCRSD model. Then, the barge service was restored, and the ferry service was reduced by 100%. To implement these changes to the model, the what-if variable, *Ships traversing time* was manipulated. In this input, each ship (barges and ferries) has a unique ship ID, along with a start node, end node, and a traversing time. Details regarding the input variable values that are changed for this set of analyses are shown in section 5.1.5 of the results. The data structures of the input variables used for these analyses are described in section 4.1.2.

3.5.1.5 Community Impact Factor

The last step of the study on Case A inputs for the RCRSD model was changing the Community Impact Factor (CIF) of all communities. In this analysis, the results of the model were studied by assuming that the CIF does not play a role in the computations. All communities in the original model take a value between 1 and 5. In this case, the CIF of all communities was changed to 5 (high priority) and the model was run. This was done for the best and worst depot locations found from the previous analyses as shown in Figure 9. A table showing the different variations of inputs for this set of analysis is shown in section 5.1.6.

3.5.2 Case B input changes

After the analyses were completed for Case A, some of them were repeated for Case B (extensive disconnection) to see the effect of similar input changes with a different set of input damage data. Although the analyses were not as extensive, some insights into the model behavior and its results were obtained from this set of studies. In theory, if time and computing power permitted, the entire set of changes done for Case A shown in Figure 9 could be repeated for Case B to provide insights into the critical regions and roads on Vancouver Island exclusive to this case.

For Case B, the depot locations of the road clearing teams were changed for the first set of analyses. The two best and two worst depots as found from the Case A analyses were chosen for this. The depot locations are shown in the results section (section 5.1.1). For the next set of analyses, the time horizon for road clearing and supplies distribution was increased to two weeks (360 hours). This was done because the extent of damage in this case is higher than Case A and hence, three days may not be sufficient for significant road clearing or relief supply activities.

These analyses were done for Case B to understand the extent of similarities in results for the two cases when all other inputs remained the same. It was also done to observe for the limited set of input changes, in what regions the road clearing, and supply activities occur more frequently if they do.

3.6 Summary of analysis steps

A complete summary of the steps that were followed to perform sensitivity analysis of the RCRSD model is shown in Figure 11. Sections 3.5.1 and 3.5.2 explained in detail what changes were made to the inputs of the RCRSD model for each analysis. Figure 11 shows the concise step-by-step process in which the changes described in the previous sections were made.

Figure 11. Summary of analysis steps

3.7 Checking variation in results due to GRASP

As mentioned earlier, for all the analyses the RCRSD model was run three times for each input scenario to account for the variation caused in the results due to GRASP. To study the change in model results solely due to the randomness caused by the heuristic, the input scenario represented by D1 in Table 9 was run 15 times. The average demand and the coefficient of variation of the demand were calculated to estimate the difference in demand results arising due to GRASP. All inputs remained the same for all 15 runs.

Chapter 4. DATA

It was described in the previous section that there are two base cases for running the RCRSD model: Case A and Case B. Then, for the analyses, some of the input parameters were changed and the results were observed. In this section, the base data used, and the values of the inputs changed for the sensitivity analyses, are explained.

The RCRSD model has a total of 2543 nodes and each node corresponds to a geographic location on or around Vancouver Island. The breakdown of all nodes is shown in Table 10.The nodes remain the same for Case A and Case B. Most inputs used in the RCRSD model are represented with the help of the nodes by forming lists and matrices corresponding to the nodes. The node and arc details used in this study are obtained from (Souza Almeida et al., 2023).

Node range	**Node type**	**Location**
0 – 108	Community	Vancouver Island
109 – 2414	Road intersection	Vancouver Island
2415 – 2421	Ferry port	Vancouver Island
2422 – 2428	Ferry/barge port	Vancouver Island
2429 – 2457	Barge dock	Vancouver Island
2458 – 2470	Community	Small islands
2471 – 2477	Ferry port	Mainland Vancouver
2478 – 2480	Ferry/barge port	Mainland Vancouver
2481 – 2515	Barge port	Mainland Vancouver
2516 – 2536	Airport/Heliport	Mainland Vancouver
2537 – 2542	Port community	Vancouver Island

Table 10. Types and locations of nodes used in the RCRSD model

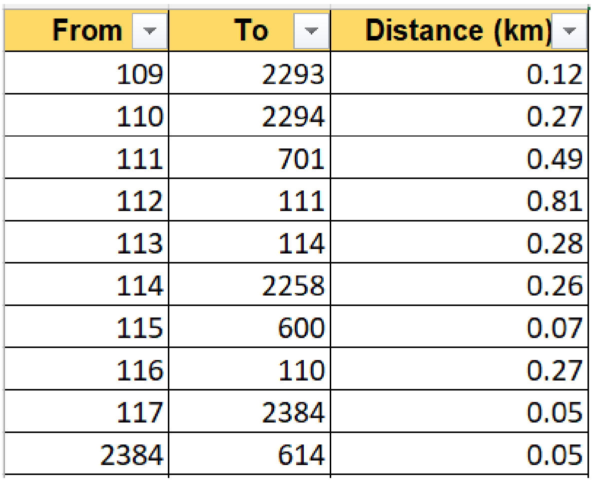
In Table 10, Port communities are the communities that can receive supplies directly from ferries and/or barges. These are the communities on Vancouver Island that have a port nearby from which they can receive supplies directly (i.e., no road clearing required). They were duplicated and included in the table so that they do not receive supplies twice: once from ferries or barges, and again from trucks. That is, the locations represented by nodes 2537 – 2542 are already included in 0 – 108. They are represented twice to keep track of the supplies going directly to them and avoid any redundancy.

4.1 Case A inputs:

In this section, the input variables used for Case A are explained. The overall structure of the inputs for Case B remain the same but the values may differ (i.e., the data types and dimensions of the variables are the same for both cases).

4.1.1 Inputs related to roads

The RCRSD model employs a total of 3707 road segments, all located on Vancouver Island. A road segment is a short section of road between two intersections and is represented by a fixed variable called *Roads distances*, as seen in Figure 12. Here, the distance between two points is the actual distance of the road, not the Euclidean distance.



From	To	Distance (km)
109	2293	0.12
110	2294	0.27
111	701	0.49
112	111	0.81
113	114	0.28
114	2258	0.26
115	600	0.07
116	110	0.27
117	2384	0.05
2384	614	0.05

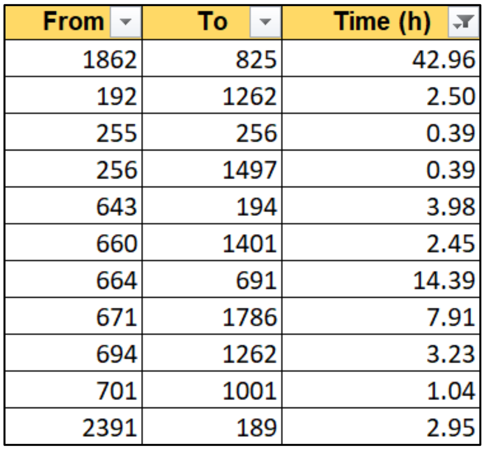
Figure 12. Roads distances table

Each road segment is denoted by a start node (from), an end node (to), and the road distance between the two nodes. The time taken to traverse between two nodes depends on the speed of the vehicle, and this differs for the road clearing teams and the supply trucks. The value of this variable remains the same throughout the analyses.

Unblocking time is a what-if variable that shows the time taken to clear a damaged road segment by the road clearing teams. It is assumed that all road clearing teams take the same amount of time to clear a given road segment if it is damaged or blocked. Out of the 3707 road segments used in the RCRSD model, 1123 are assumed to be blocked in this thesis based on the data available from (Souza Almeida et al., 2023). The available roads and the blocked roads for Case A are shown in Figure 13. The unblocking time data was developed by (Chang et al., 2020) using the damage details obtained from (Bell & Bristow, 2020).

Figure 13. Open and blocked roads for Case A (source: (Souza Almeida et al., 2023)

The Unblocking time variable is represented in the form of a table, and it is shown in Figure 14. This variable is only used in the road clearing sub-model of the RCRSD model. This data is taken from (Souza Almeida et al., 2023).



From	To	Time (h)
1862	825	42.96
192	1262	2.50
255	256	0.39
256	1497	0.39
643	194	3.98
660	1401	2.45
664	691	14.39
671	1786	7.91
694	1262	3.23
701	1001	1.04
2391	189	2.95

Figure 14. Unblocking times for road clearing teams

It can be seen from Figure 14 that the structure of the unblocking time variable is similar to that of the roads distances variable. The only difference here is that instead of the distance between two nodes, the time taken to traverse between two nodes is used. The time is in hours, and it is the time taken by the road clearing teams to clear a blocked road segment. If the value in the 'Time (h)' column shown in Figure 14 is 0 hours, it means that the road segment is undamaged.

As explained in section 3.5.1.2, one of the analyses was done by converting the road segments that were unblocked repeatedly for 70% of the previous runs to unblocked, and then running the RCRSD model with the new dataset. For this analysis, the six road segments shown in Table 11 were initially blocked and were changed to unblocked by making the time value 0. The node IDs of the road segments shown in the table are as seen in (Souza Almeida et al., 2023). The details of this set of analysis is shown in section 5.1.3 of results.

From	To	Time (h)
960	964	0.00
1786	671	0.00
671	260	0.00
260	261	0.00
1760	1761	0.00
1761	1759	0.00

Table 11. Roads cleared for 70% of the previous runs

Similarly, Table 12 shows the road segments that were cleared for 50% of the previous runs and whose values were changed in the unblocking time variable. 13 road segments were changed to unblocked. The changes made to the same variable by assuming roads cleared for 25% of the previous runs were done similarly. In this case, a total of 70 road segments were changed to unblocked. A snippet of the road segments are shown in section 5.1.3 of this thesis.

From	To	Time (h)
960	964	0.00
1786	671	0.00
671	260	0.00
260	261	0.00

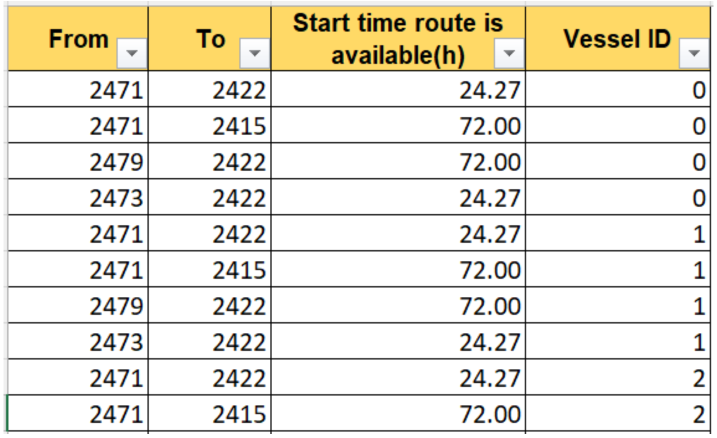
From	To	Time (h)
1760	1761	0.00
1761	1759	0.00
1879	2406	0.00
818	906	0.00
906	911	0.00
911	909	0.00
1011	2396	0.00
2396	1010	0.00
2282	615	0.00
615	267	0.00

Table 12. Roads cleared for 50% of the previous runs

4.1.2 Inputs related to shipping

For the Case A Cascadia earthquake scenarios, The RCRSD model considers that there are 57 available ships, with each ship represented by a vessel ID (0 – 56), of which 35 are ferries and 21 are barges. Each ship has its own capacity of truck containers with emergency supplies that it can carry from mainland Vancouver to Vancouver Island.

In sections 3.5.1.3 and 3.5.1.4, it was indicated that analyses are conducted by changing the values of the *ports opening time* and the *ships traversing time* what-if variables. The structures of these two variables are shown in Figure 15 and Figure 19 respectively. The input values for these variables are taken from (Souza Almeida et al., 2023).



From	To	Start time route is available(h)	Vessel ID
2471	2422	24.27	0
2471	2415	72.00	0
2479	2422	72.00	0
2473	2422	24.27	0
2471	2422	24.27	1
2471	2415	72.00	1
2479	2422	72.00	1
2473	2422	24.27	1
2471	2422	24.27	2
2471	2415	72.00	2

Figure 15. Ports opening time variable used in the RCRSD model.

The ports opening time variable represents the ports that are damaged due to the Cascadia megathrust earthquake (Figure 15 is the data set for Case A). In the RCRSD model, this is represented by a 6597x4 matrix of which the first ten rows are shown in Figure 15. The opening times for ports are represented for each route of each available ship. In Figure 15, there is a 'from' column and a 'to' column that represent the nodes of the origin and the destination ports respectively. 'Start time route is available (h)' represents the times at which the 'to' ports becomes available for ships to dock (i.e., the times at which the 'to' ports become open). Additionally, if a port of origin ('From' column) is considered unavailable, then the corresponding 'Start time route is available (h)' value is et to 72 hours, which means that the port is not open for the entire time horizon of the model run. This format is repeated for each ship, which is represented by the 'Vessel ID' column.

For Case A, all the port locations are shown in Figure 16 and Figure 17. The ferry ports that are available are shown in Figure 16, while Figure 17 represents the barge docks. The barge docking locations are always considered available because it is assumed that barges do not require any particular infrastructure to unload supplies.

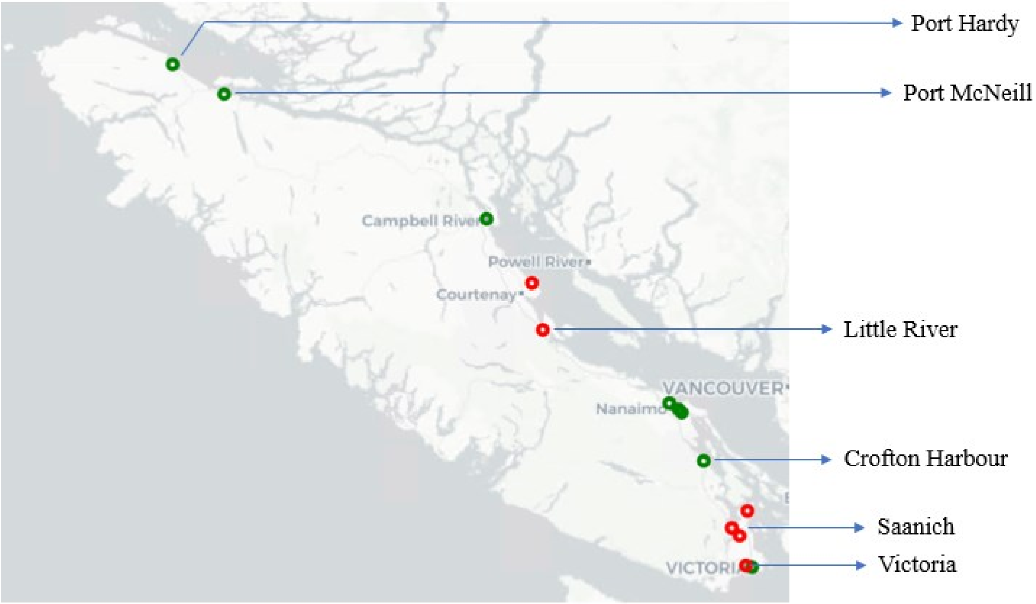


Figure 16. All ferry ports for Case A

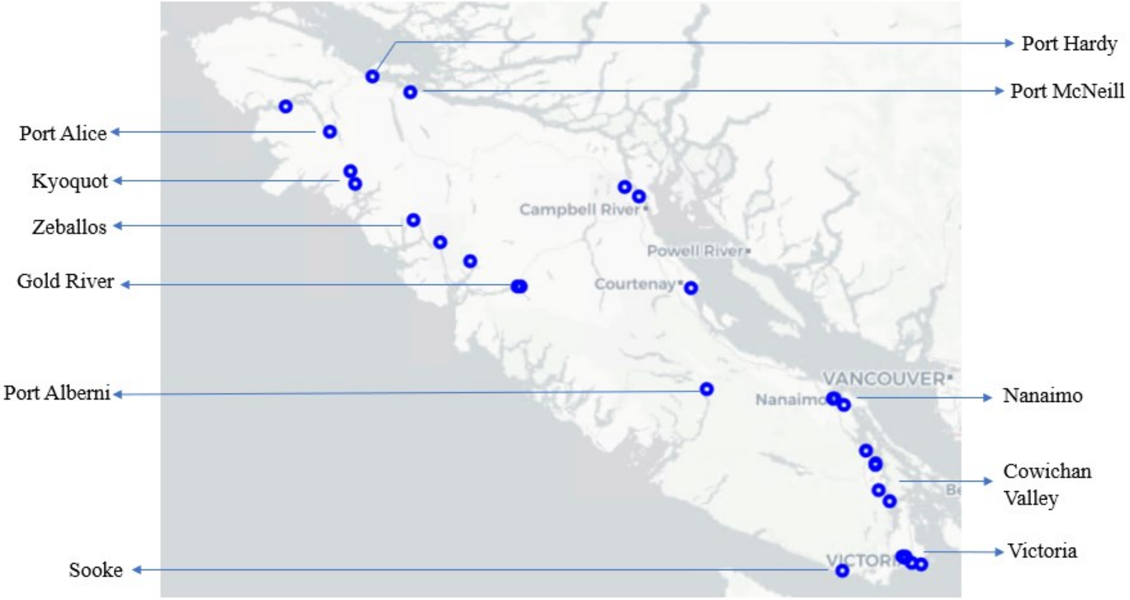
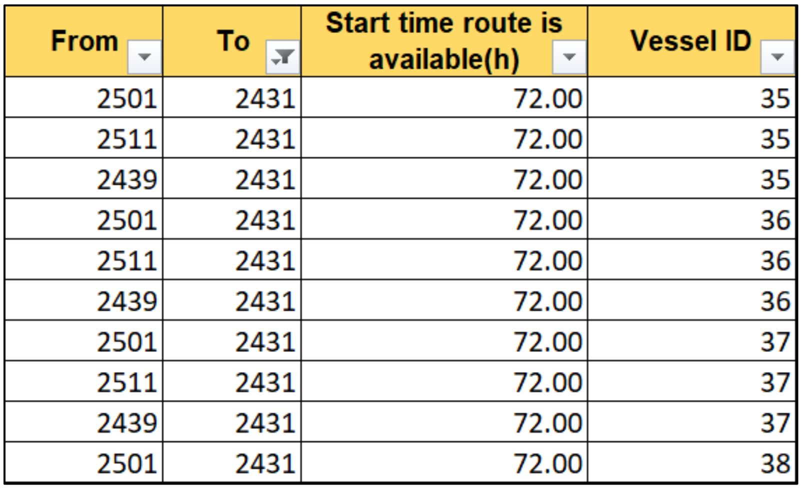


Figure 17. All barge docks for Case A

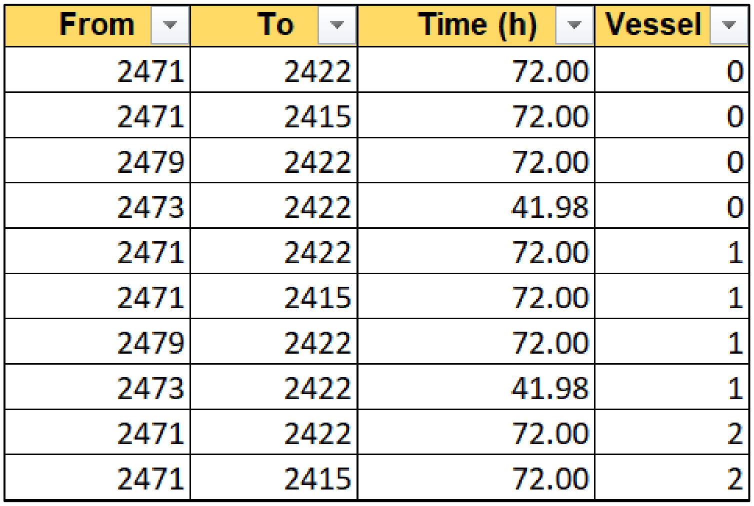
For the analyses where a port is considered closed, the corresponding value of 'Start time route is available' is changed to 72 hours. For example, in one of the analyses, the port represented by node 2431 was considered closed. For this analysis, the rows containing 2431 in the 'from' or 'to' columns of the ports opening time variable are changed as seen in Figure 18.



From	To	Start time route is available(h)	Vessel ID
2501	2431	72.00	35
2511	2431	72.00	35
2439	2431	72.00	35
2501	2431	72.00	36
2511	2431	72.00	36
2439	2431	72.00	36
2501	2431	72.00	37
2511	2431	72.00	37
2439	2431	72.00	37
2501	2431	72.00	38

Figure 18. Change done to ports opening time when a port is considered closed

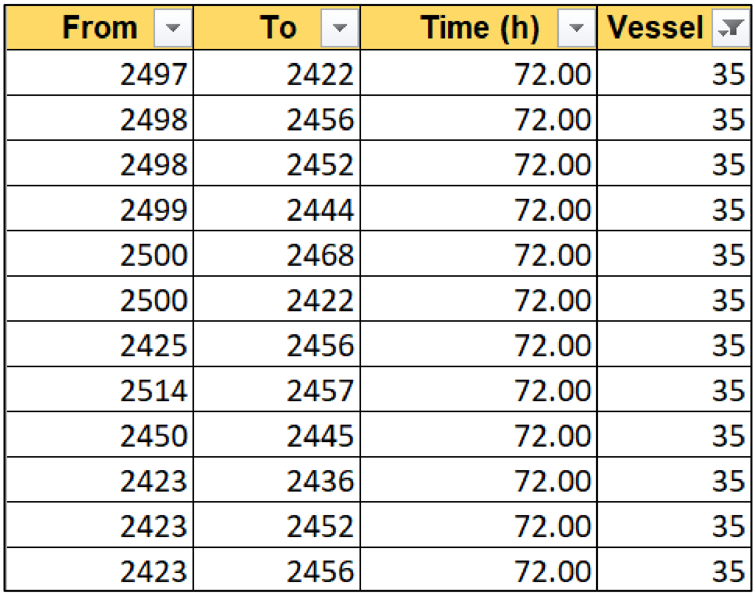
For changing the availability of ships, the what-if variable that is manipulated is called *ships traversing time* which is represented by 6597x4 array. A few rows of the variable are shown in figure 5.



From	To	Time (h)	Vessel
2471	2422	72.00	0
2471	2415	72.00	0
2479	2422	72.00	0
2473	2422	41.98	0
2471	2422	72.00	1
2471	2415	72.00	1
2479	2422	72.00	1
2473	2422	41.98	1
2471	2422	72.00	2
2471	2415	72.00	2

Figure 19. Ships traversing time variable used in the RCRSD model

This variable is similar to the ports opening time variable, with the exception of the 'Time (h)' column which shows the time taken to traverse by a ship between the 'from' and 'to' nodes in hours. The availability of a ship can be changed by making the value of 'Time (h)' corresponding to its vessel ID to 72 hours. For example, in one of the analyses, the number of barges was reduced by approximately 50% by reducing the number of available barges to 11. All ships with vessel IDs 35 and up are barges. The barge availability was reduced by changing the traversing time of half the barges to 72 hours as shown in Figure 20. Details regarding which barges are considered unavailable are given in the section 5.1.5 of this thesis.

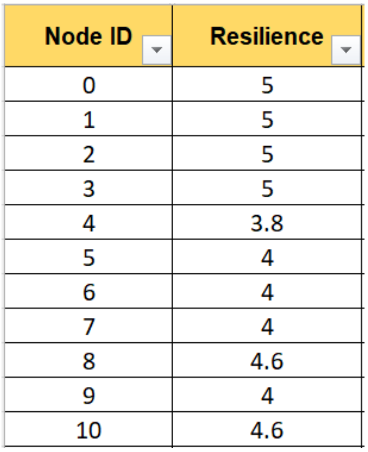


From	To	Time (h)	Vessel
2497	2422	72.00	35
2498	2456	72.00	35
2498	2452	72.00	35
2499	2444	72.00	35
2500	2468	72.00	35
2500	2422	72.00	35
2425	2456	72.00	35
2514	2457	72.00	35
2450	2445	72.00	35
2423	2436	72.00	35
2423	2452	72.00	35
2423	2456	72.00	35

Figure 20. Change in ships traversing time when barges are unavailable

4.1.3 Inputs related to community resilience

The resilience of communities is represented by a one-dimensional array of 2543 numerical values, each representing its corresponding node. Community nodes are given a value between 1 and 5, whereas all other nodes take the value 0. The first 10 elements that were loaded into the model array are as shown in Figure 21. For the analysis that is done without accounting for the CIF, all these values are changed to 5, thus giving the same priority for all communities.



Node ID	Resilience
0	5
1	5
2	5
3	5
4	3.8
5	4
6	4
7	4
8	4.6
9	4
10	4.6

Figure 21. Community Impact Factor (Resilience) used in the RCRSD model

4.2 Case B inputs

The structure of inputs for Case B is same as that of Case A. Some values of the what-if variables are different in this case and most of the other inputs remain the same. Since the structure of the inputs are the same, only the difference in affected roads is shown in this section. The roads that are considered blocked in Case B are shown in Figure 22 (Souza Almeida et al., 2023).

Figure 22.Open and blocked roads for Case B (source: (Souza Almeida et al., 2023))

Sections 4.1 and 4.2 only describe the input structures and the changes made in these inputs used for the analyses relevant to this study. The RCRSD model uses several other inputs whose descriptions and complete datasets are available in (Souza Almeida et al., 2023).

Chapter 5. RESULTS

For all the runs of the RCRSD model that were done in the methods section, the findings and observations are discussed in this section. The initial results are obtained from Case A: Partial disconnection scenario.

5.1 Case A results

5.1.1 Depot changes results

The first step in the sensitivity analysis was to change the location of the road clearing teams' depot. The different depot locations for which RCRSD model was run are shown in Figure 10. For each scenario of input variation, the model was run three times to account for the changes in model results because of the use of GRASP. The results of community demands supplied for every scenario (averaged between three runs of same scenario) were tabulated for each of these runs and the results are as shown in Table 13. The total demand for each run is to deliver 777,646 boxes, which is the total population on Vancouver Island and the Gulf Islands. It is assumed that each box contains supplies that can serve a person for a week. For the scenarios shown in this table, only one input was varied: road clearing teams' depot location.

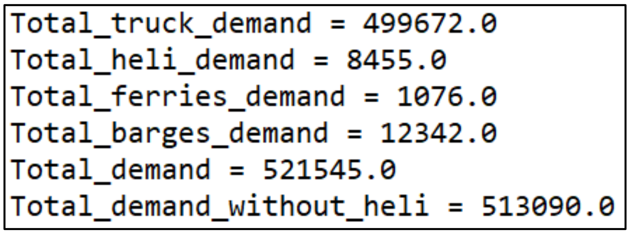
Scenario ID	Depot node ID	Depot location region	% Total demand supplied	% Supplied Communities
D1	42	Central Island	57.1	54.69
D2	46	North Island	63.8	60.68
D3	57	Central Island	49.9	51.04
D4	80	North Island	43.1	33.85
D5	219	Pacific Rim	42.9	33.85
D6	220	South Island	65.7	60.16
D7	742	South Island	62.6	58.85
D8	778	Central Island	61.1	57.55
D9	802	Central Island	47.8	48.70
D10	1075	Central Island	47.8	49.74
D11	1195	Central Island	65.6	61.98
D12	1544	South Island	41.6	35.16

Scenario ID	Depot node ID	Depot location region	% Total demand supplied	% Supplied Communities
D13	1579	Pacific Rim	63.6	58.07
D14	1926	Pacific Rim	43.5	35.42
D15	2002	North Island	41.4	35.71
D16	2012	North Island	42.3	34.90
D17	2069	North Island	43.5	36.46
D18	2165	North Island	43.0	34.64
D19	2227	North Island	43.0	35.16
D20	2313	Pacific Rim	43.3	35.94
D21	2324	Pacific Rim	44.5	38.28
D22	2343	South Island	31.6	24.74
D23	2375	South Island	63.8	60.16
D24	2395	South Island	59.3	53.65
D25	2431	Pacific Rim	53.4	51.82

Table 13. Demands supplied when depot location is changed for Case A

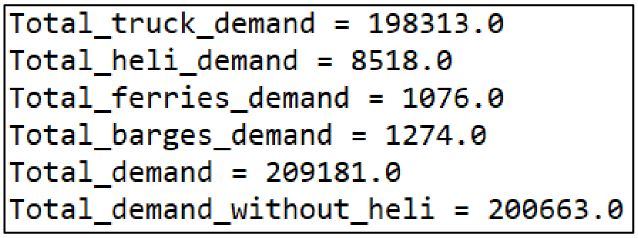
From the results shown in Table 13, the best depot locations (Scenario IDs: D6, D11) and worst depot locations (Scenario IDs: D22, D15) were mapped (see Figure 23). The depot locations were ranked based on the total goods supplied for each scenario. The model was run thrice for each scenario and the demands supplied were averaged and ranked. Similarly, for each scenario, the number of communities supplied for all three runs were averaged and the mean percentages of total communities supplied are listed. The ranking was done based on the demands supplied and not the number of roads cleared because for certain depot locations it was seen that even though there is a high degree of road clearing activity, the demands supplied and the reach to communities is very low. The demands met by the different modes of transport for the best depot location (Scenario ID: D6) and the worst depot location (Scenario ID: D22) are also shown in Figure 24 and Figure 25. These are the results from one of the three runs for each scenario. The results over all three runs of every scenario are then tabulated and averaged to obtain the values shown in Table 13.

Figure 23. Best and worst depot locations



```
Total_truck_demand = 499672.0
Total_heli_demand = 8455.0
Total_ferries_demand = 1076.0
Total_barges_demand = 12342.0
Total_demand = 521545.0
Total_demand_without_heli = 513090.0
```

Figure 24. Demands met for D6 by different modes



```
Total_truck_demand = 198313.0
Total_heli_demand = 8518.0
Total_ferries_demand = 1076.0
Total_barges_demand = 1274.0
Total_demand = 209181.0
Total_demand_without_heli = 200663.0
```

Figure 25. Demands met for D22 by different modes

For some of the further analyses done by varying the availability of roads, ports, and ships, the best and worst depot locations were considered.

The regional division of Vancouver Island considered for this study is as shown in Figure 5. Of the 25 depot locations chosen for the analyses, it is seen that the results are consistently worse for the scenarios where the depot is located on the Pacific Rim region of the island. It is also seen that the worst depot location is on South Island. However, It was observed that the model produces the best results in terms of demands satisfied when the depot is located on the East Coast of the South Island region. The results of the scenarios shown in Table 13 are averaged by region and shown in Table 14.

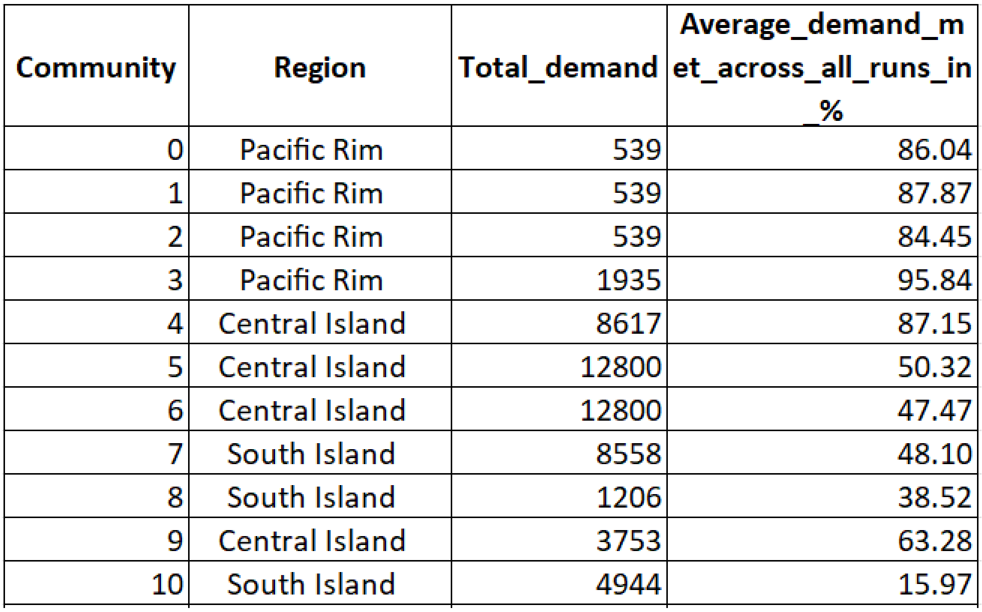
Depot location region	**Scenario IDs used for aggregation**	**Mean % demand met by region**
Central Island	D1 D3 D8 D9 D10 D11	54.88
North Island	D2 D4 D15 D16 D17 D18 D19	45.74
South Island	D6 D7 D12 D22 D23 D24	54.08
Pacific Rim	D5 D13 D14 D20 D21 D25	48.53

Table 14. Region-wise depot location details in terms of total demand met

From Table 14 it is seen that having the Road clearing teams' depot located on either Central Island or South Island yields better results compared to having it located at Pacific Rim or North Island.

5.1.2 Communities supplied

The regional division of Vancouver Island is shown in Figure 5. For the 25 input scenarios shown in Table 13 (three runs for each scenario), the demands satisfied for each community across all these runs (25 x 3 runs) were averaged and tabulated. A snippet of this table is shown in Figure 26. This table contains details of demands satisfied of all 109 communities on Vancouver Island and the smaller Gulf Islands. The demand results averaged for each region of Vancouver Island is plotted on a bar chart and shown in Figure 27.



Community	**Region**	**Total_demand**	**Average_demand_met_across_all_runs_in_%**
0	Pacific Rim	539	86.04
1	Pacific Rim	539	87.87
2	Pacific Rim	539	84.45
3	Pacific Rim	1935	95.84
4	Central Island	8617	87.15
5	Central Island	12800	50.32
6	Central Island	12800	47.47
7	South Island	8558	48.10
8	South Island	1206	38.52
9	Central Island	3753	63.28
10	South Island	4944	15.97

Figure 26. Average demand satisfied for first 11 communities

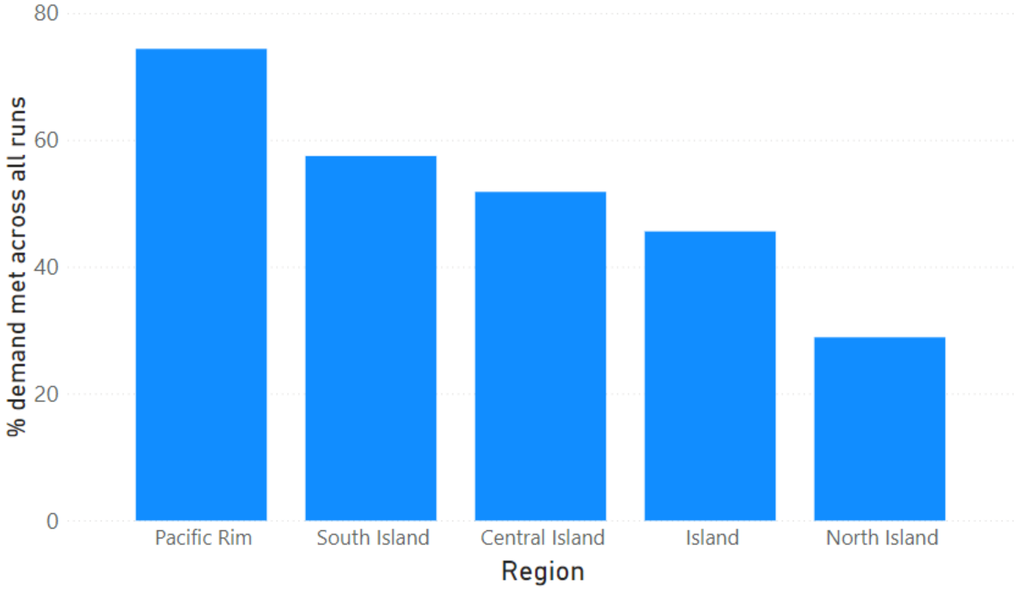
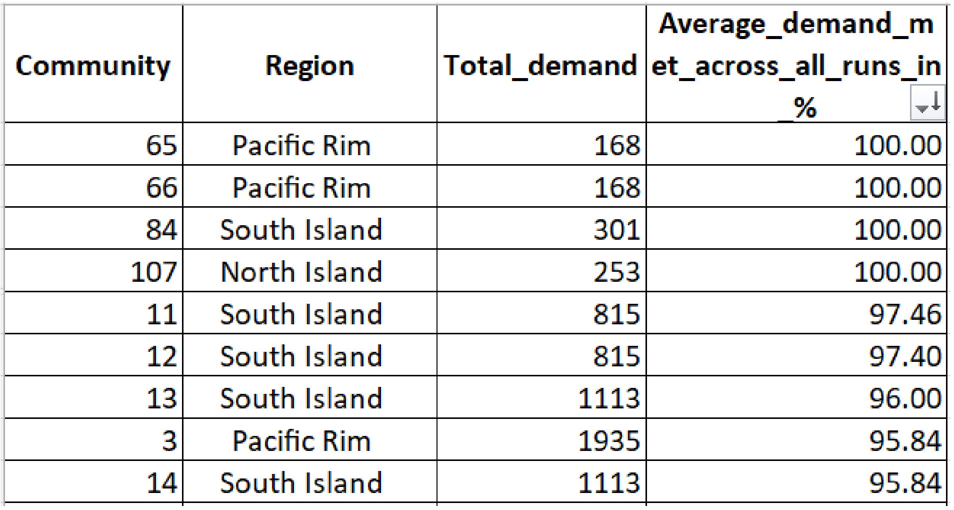


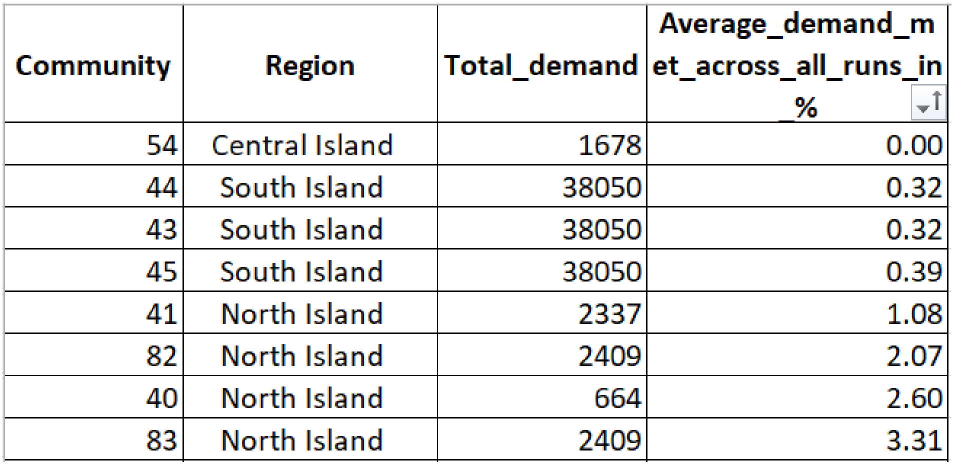
Figure 27. Regional demands satisfied across runs D1 to D25

Across the 25 input scenario variations, the communities on Vancouver Island that received over 95% of their demands satisfied are shown in Figure 28. The communities that received under 5% of their demands met are shown in Figure 29.



Community	Region	Total_demand	Average_demand_met_across_all_runs_in_%
65	Pacific Rim	168	100.00
66	Pacific Rim	168	100.00
84	South Island	301	100.00
107	North Island	253	100.00
11	South Island	815	97.46
12	South Island	815	97.40
13	South Island	1113	96.00
3	Pacific Rim	1935	95.84
14	South Island	1113	95.84

Figure 28. Communities that receive over 95% of their demands met



Community	Region	Total_demand	Average_demand_met_across_all_runs_in_%
54	Central Island	1678	0.00
44	South Island	38050	0.32
43	South Island	38050	0.32
45	South Island	38050	0.39
41	North Island	2337	1.08
82	North Island	2409	2.07
40	North Island	664	2.60
83	North Island	2409	3.31

Figure 29. Communities that received under 5% of their demands met

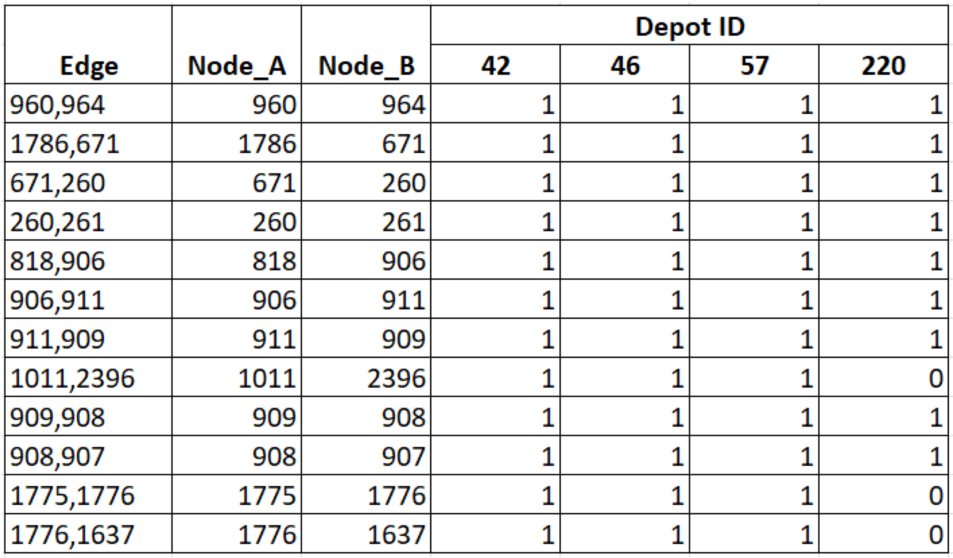
From Figure 27 it is seen that the communities on the Pacific Rim region of Vancouver Island had most of their demands satisfied. The communities on the North Island region were the least likely to receive supplies.

5.1.3 Roads cleared and subsequent analyses

For the runs done by changing the depot locations of the road clearing teams as shown in Table 9, it was seen that out of the 25 input scenarios, there were no roads cleared for 5 scenarios (Scenario IDs: D4, D5, D12, D14, and D16). It is to be noted that for each of these scenarios, no roads were cleared for all three runs. The reason why no roads were cleared for any of these scenarios was because the depot locations were too distant from any port or community to be reconnected within 72 hours. For example, the depot location of scenario D5 is shown in Figure 30. In this figure, it can be seen that the depot location is surrounded by only damaged roads, from which there is no completion of any road clearing activity within the given time window.

Figure 30. Map showing depot location of scenario D5 amidst blocked roads

The road segments that were cleared for each run were separately counted and it was seen that for the runs with at least some road clearing activity, an average of 49 blocked road segments were cleared. The highest cleared was 81 road segments (out of 1123), which was seen for road clearing depot location at node 220 of the model. From all the scenario runs, a matrix is generated for the blocked road edges and the depots as shown in Figure 31. This figure is a small snippet of a larger matrix in which the cell value is 1 if the edge is unblocked for the corresponding depot location and 0 otherwise. This matrix is then analyzed to find the road segments or edges that are frequently unblocked.



Edge	Node_A	Node_B	Depot ID			
			42	46	57	220
960,964	960	964	1	1	1	1
1786,671	1786	671	1	1	1	1
671,260	671	260	1	1	1	1
260,261	260	261	1	1	1	1
818,906	818	906	1	1	1	1
906,911	906	911	1	1	1	1
911,909	911	909	1	1	1	1
1011,2396	1011	2396	1	1	1	0
909,908	909	908	1	1	1	1
908,907	908	907	1	1	1	1
1775,1776	1775	1776	1	1	1	0
1776,1637	1776	1637	1	1	1	0

Figure 31. Road segments (edges) x Depots binary matrix

When all the runs are compared, it is seen that some of the blocked roads are cleared more frequently across the input scenario variations shown in Table 9 than some other road segments. Figure 32 (also represented as a table of nodes in Table 11) shows the road segments that were cleared for at least 70% of the original runs. This set of roads is referred to as RC1 in this thesis. The road segments that were most repeatedly cleared all lie in the South Island region.

Figure 32. Roads cleared for at least 70% of the runs (RC1)

When compared for over 50% and 25% of the scenario changes, the roads shown in Figure 33 and Figure 34 respectively were seen to be cleared repeatedly. The set of roads cleared for over 50% of the input scenarios shown in Table 9 are referred to as RC2 and those cleared for over 25% of input scenario changes are referred to as RC3. In both these cases, it can be seen from the maps that there are significant road clearing activities happening in South Island and a few roads being fixed repeatedly in Central Island.

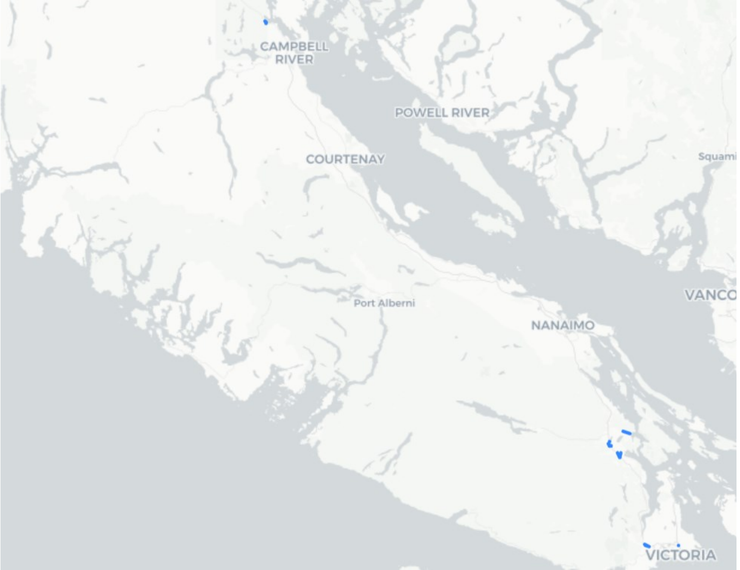


Figure 33. Roads cleared for at least 50% of the runs (RC2)

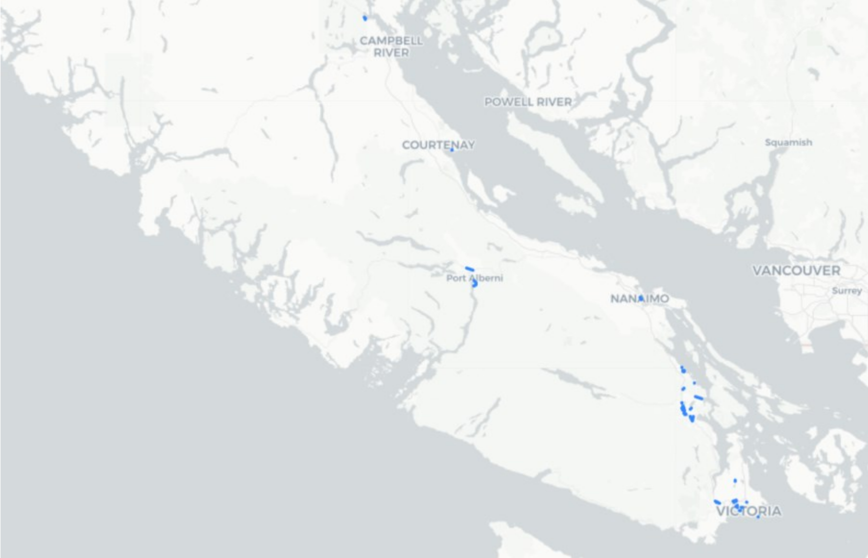


Figure 34. Roads cleared for at least 25% of the runs (RC3)

Figure 35 shows a zoomed-in image of the repeatedly cleared roads near Cowichan Bay which is located in the South Island region of Vancouver Island.

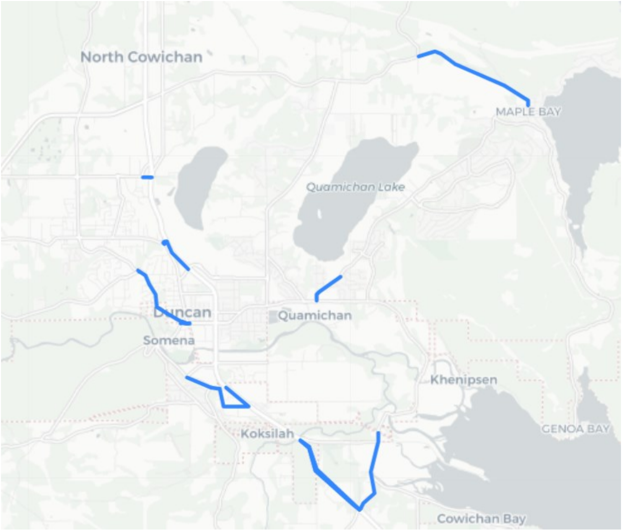


Figure 35. Close up of the repeatedly cleared roads near Cowichan bay

The repeatedly cleared roads shown in Figure 32, Figure 33, and Figure 34 were then used as input changed for some of the further analyses of the RCRSD model as explained in section 3.5.1.2. Table 15 shows the different input scenarios for which the analyses were done by changing the availability of roads.

Run ID	**Input Variable chosen for analysis**	**Input Variable value**
D6RC1	Depot location	220
	Unblocked roads	RC1
D11RC1	Depot location	1195
	Unblocked roads	RC1
D15RC1	Depot location	2002
	Unblocked roads	RC1
D22RC1	Depot location	2343
	Unblocked roads	RC1
D6RC2	Depot location	220
	Unblocked roads	RC2
D11RC2	Depot location	1195
	Unblocked roads	RC2
D15RC2	Depot location	2002

Run ID	Input Variable chosen for analysis	Input Variable value
	Unblocked roads	RC2
D22RC2	Depot location	2343
	Unblocked roads	RC2
D6RC3	Depot location	220
	Unblocked roads	RC3
D11RC3	Depot location	1195
	Unblocked roads	RC3
D15RC3	Depot location	2002
	Unblocked roads	RC3
D22RC3	Depot location	2343
	Unblocked roads	RC3

Table 15. Input variable scenario changes for unblocked roads

For the 2 best depots (D6 and D11) and the two worst depots (D15 and D22), the blocked roads form the original dataset that are frequently cleared were considered to be unblocked as shown in Table 15. The total demand for all communities for each run is 777,646 boxes of supplies.

Table 16 shows the number of boxes that are supplied for each scenario, as well as the percentage of the total demand that is met. For each input scenario, three runs were done, and the average demand results are presented in the table. In the same table, results of the RCRSD model when the roads were considered blocked are also shown for comparison. These observations are shown in the gray columns.

Scenario ID	Demand met in number of boxes	% Total demand met	% Communities supplied	Scenario ID	% Total demand met
D6RC1	491645	63.22	61.33	D6	65.7
D11RC1	485185	62.39	58.98	D11	65.6
D15RC1	486428	62.55	57.42	D15	41.4
D22RC1	438715	56.42	52.01	D22	31.6
D6RC2	453078	58.26	55.08	D6	65.7
D11RC2	504896	64.93	60.94	D11	65.6
D15RC2	477331	61.38	56.64	D15	41.4
D22RC2	484570	62.31	58.98	D22	31.6

Scenario ID	Demand met in number of boxes	% Total demand met	% Communities supplied	Scenario ID	% Total demand met
D6RC3	526870	67.75	60.55	D6	65.7
D11RC3	522386	67.18	62.89	D11	65.6
D15RC3	507548	65.27	60.94	D15	41.4
D22RC3	525983	67.64	62.89	D22	31.6

Table 16. Results observed for changes in unblocked roads

From the results shown in Table 16, it is seen that for the depots with the best results (D6 and D11), there are no significant changes in the demands satisfied when the roads represented by RC1, RC2, and RC3 are considered undamaged. However, for the depots D15 and D22 that earlier showed demands satisfied as less than or around 40%, when the repeatedly cleared are considered unblocked, there are significant improvements in the demands satisfied as well as the number of communities that receive supplies.

5.1.4 Critical ports and subsequent analysis

From the runs that were done by changing the depot locations as shown in Table 9, it was seen that one port (in this case, a barge docking location) was responsible for a significant number of supplies that are dispatched to communities via trucks. Here, the term port is used to represent both ferry ports and barge docks unless otherwise specified. The location of the critical barge dock is shown in Figure 36. It is represented by node ID 2431. It is seen that for the communities serviced by trucks 55% of the supplies went from this location. This result was obtained by finding the average amount of goods that go to ports over three runs of all input scenarios shown in Table 9. To understand why this port (near Gold River) was the busiest, the demands of all ports were observed for the best depot location. It was seen that this port had the highest demand (22 truck containers), out of all the ports on Vancouver Island. It was also seen that for most of the road clearing teams' depot locations, this port was connected to the most number of hence resulting in its demand met being the highest.

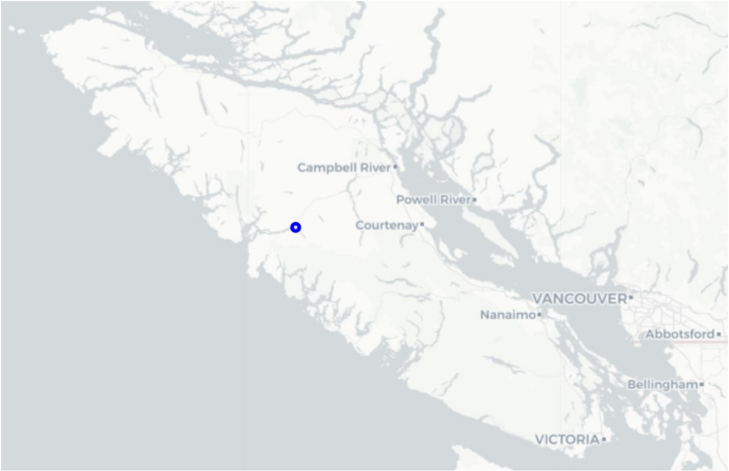


Figure 36. Location of critical barge dock

From the same input scenarios' results, the busiest ferry port was also identified as the one represented by node ID 2423. It is shown in Figure 37. It is seen that out of all the supplies that reached the ports and got distributed to communities by trucks, the busiest ferry port contributed to only about 6% of the total supplies dispatched from the ports.

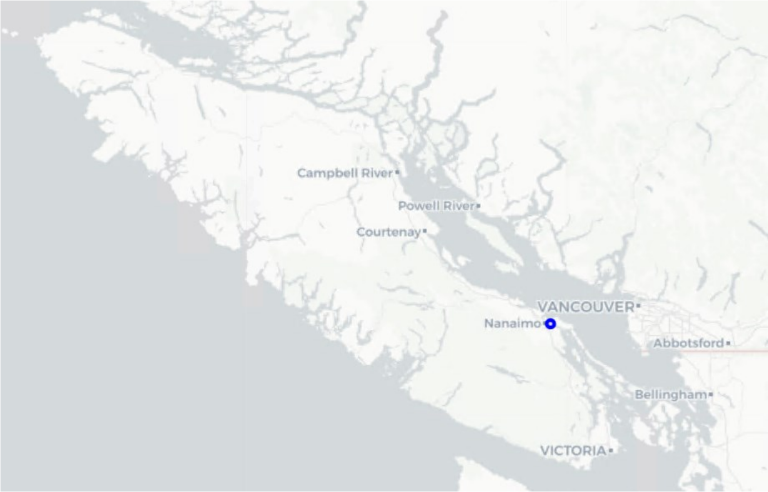


Figure 37. Location of critical ferry port

The next set of analyses were done by considering the critical ports closed. The various input scenarios for which this analysis was done is shown in Table 17.

Scenario ID	Input Variable chosen for analysis	Input Variable value (node ID)
D6P1	Depot location	220

Scenario ID	Input Variable chosen for analysis	Input Variable value (node ID)
	Port closed	2431
D11P1	Depot location	1195
	Port closed	2431
D6P2	Depot location	220
	Port closed	2423
D11P2	Depot location	1195
	Port closed	2423

Table 17. Input variable scenario changes for closed ports

The depot locations that were found to the have the best results were considered. For each input scenario shown in Table 17, the RCRSD model was run thrice, and the results were averaged over the three runs. These average demand results for each scenario are shown in Table 18. The demand details for the same depot locations when the ports were considered open are also shown in the table in gray columns.

Scenario ID	Demand met in number of boxes	% Total demand met	% Communities supplied	Scenario ID	% Total demand met
D6P1	97075	12.48	21.61	D6	65.7
D11P1	26435	3.40	13.80	D11	65.6
D6P2	453662	58.34	53.91	D6	65.7
D11P2	464374	59.72	55.73	D11	65.6

Table 18. Results observed for changes in ports availabilities

From Table 18 it is seen that for the scenarios where the barge dock is considered closed (D6P1 and D11P1) the total demands satisfied are significantly less when compared to the scenarios where they are considered open (scenarios D6 and D11). It is also seen that for the same depot locations when only the ferry port is considered closed (D6P2 and D11P2) the results are better than D6P1 and D11P1. When the results of D6P1 and D11P1 were observed, it is seen that the communities are mostly served by trucks coming from the port location shown in Figure 38. It is also observed that this was the second busiest barge dock for the initial set of runs represented by D1 – D25 in Table 13.

Figure 38. Second busiest port (barge dock)

5.1.5 Availability of ships

From the results observed by closing one of the barge docks, it was seen that the communities rely more on supplies from barges than from ferries. This section shows how the results vary when reduced ship service is considered in the RCRSD model.

Since the barge deliveries are higher than ferry deliveries, the RCRSD model is run by considering only 50% of the barges to be available. A total of 22 barges operated by Seaspan, North Arm Transportation, and Island Tug and Barge Ltd are considered for the scenarios shown in Table 9 in which only the road depots are changed (Souza Almeida et al., 2023). For this analysis, all the barges operated by Seaspan (11 barges) are considered non-functional. This reduces the total capacity of barges in terms of containers of supplies by 47%. This was done for the two best depot locations (node ID: 220, 1195) as shown in Table 19. The case where all ferries are available and only 50% of barges are available is labelled as S1 in the table. The RCRSD model was then run by considering all ferries to be unavailable and all barges to be operational. The details of the inputs changed for these runs are shown in Table 19.

Scenario ID	**Input Variable chosen for analysis**	**Input Variable value**
D6S1	Depot location	220
	Ships available	All ferries, 50% barges
D11S1	Depot location	1195

Scenario ID	Input Variable chosen for analysis	Input Variable value
	Ships available	All ferries, 50% barges
D6S2	Depot location	220
	Ships available	All barges, no ferries
D11S2	Depot location	1195
	Ships available	All barges, no ferries

Table 19. Input variable scenario changes for ships availability

Each scenario shown in the table was run three times and the results were observed to account for the variations in results due to GRASP. The demands met and number of communities supplied were averaged across the three runs for each scenario and shown in Table 20. Results for the same depots when the ships are considered available are shown in gray columns in the table for comparison. The total demand for all runs is 777,646 boxes.

Scenario ID	Demand met in number of boxes	% Total demand met	% Communities supplied	Scenario ID	% Total demand met
D6S1	94104	12.10	14.50	D6	65.7
D11S1	147291	18.90	21.58	D11	65.6
D6S2	435185	55.96	51.56	D6	65.7
D11S2	437010	56.20	51.82	D11	65.6

Table 20. Results observed for changes in ships' availabilities

From the results in Table 20, it is seen that when the barges are reduced by 50%, the total demand satisfied is reduced by a significant amount. For example, for scenario D6, the demand satisfied was 65.7% whereas for scenario D6S1 the demand satisfied is only 12.1%. A similar observation is seen for depot D11S1 where the demand satisfied is seen to have reduced by a large amount. In contrast, for scenarios D6S2 and D11S2 where all ferries are assumed non-operational, the demands met are seen to have reduced by only about 10% from the runs D6 and D11 where all ferries are in use. Thus, it can be confirmed that there is a significant reduction in the supplies that go to communities when only half the barges are available. However, even when no ferries are available, at least 55% of the demand is supplied for each run.

5.1.6 Community Impact Factor (CIF) change

The resilience of all communities to the Cascadia earthquake is represented by a community impact factor. In this section of observations, the RCRSD model was run by removing the CIF from the model for the best and worst road clearing teams' depot locations as shown in Figure 23. A complete list of input variations scenarios used for this analysis is shown in Table 21. The set of input variations in which the CIF of all communities are neglected by making them all the same value is represented by C1 in the table.

Scenario ID	Input Variable chosen for analysis	Input Variable value
D6C1	Depot location	220
	CIF	neglected
D11C1	Depot location	1195
	CIF	neglected
D15C1	Depot location	2002
	CIF	neglected
D22C1	Depot location	2343
	CIF	neglected

Table 21. Input variable scenarios for changes in CIF

For the input scenarios shown in Table 21, the RCRSD model was run thrice, and the results are averaged and tabulated in Table 22. Results for the same depot locations when CIF is considered as an input factor are shown in gray columns in the table.

Scenario ID	Demand met in number of boxes	% Total demand met	% Communities supplied	Scenario ID	% Total demand met	% Communities supplied
D6C1	483812	62.22	53.51	D6	65.7	60.16
D11C1	370800	47.68	42.44	D11	65.6	61.98
D15C1	327414	42.10	34.47	D15	41.4	35.71
D22C1	261209	33.59	24.08	D22	31.6	24.74

Table 22. Results observed for changes in CIF

Comparing the results shown in Table 22 for the same depot locations (scenarios with D6, D11, D15, and D22) it can be seen that there are no significant changes in the total demands met (most variation is by 3%), except scenario D11C1 where total demand dropped from about 65% to 47.68%. However, there is a decrease in the percentage of communities that receive supplies when the CIF is neglected in all scenarios shown in Table 22 compared to the same depots in Table 13. From these results it is seen that neglecting the CIF affects the number of communities that receive supplies.

5.2 Case B findings

For the extensive disruption scenario (Case B), the RCRSD model is run for only a few input changes as shown in Figure 9. The results of the model were observed for the best and worst depot locations of the road clearing teams as found in the Case A analyses. The time horizon for the runs, that is, the time limit within which the road clearing, and relief supply activities should be completed was also changed. The various input scenarios and the variables that are changed along with their values are shown in Table 23.

Scenario ID	Input Variable chosen for analysis	Input Variable value
BD6T1	Depot location	220
	Time horizon	72 hours
BD11T1	Depot location	1195
	Time horizon	72 hours
BD15T1	Depot location	2002
	Time horizon	72 hours
BD22T1	Depot location	2343
	Time horizon	72 hours
BD6T2	Depot location	220
	Time horizon	360 hours
BD11T2	Depot location	1195
	Time horizon	360 hours
BD15T2	Depot location	2002
	Time horizon	360 hours
BD22T2	Depot location	2343
	Time horizon	360 hours

Table 23. Input variable scenarios for Case B

For the input scenarios shown in Table 23, the RCRSD model was run three times for each scenario and the results averaged across the three runs are shown in Table 24.

Scenario ID	Demand met in number of boxes	% Total demand met	% Communities supplied
BD6T1	168171	21.63	22.66
BD11T1	168171	21.63	23.44
BD15T1	168171	21.63	23.05
BD22T1	168218	21.63	22.66
BD6T2	228857	29.43	33.59
BD11T2	218127	28.05	32.81
BD15T2	223158	28.70	33.59
BD22T2	227297	29.23	34.38

Table 24. Results of Case B scenarios

It can be seen from the results shown in Table 24 that for the high damage case where a lot more roads are disconnected and fewer ports are open, when the time horizon is set to 72 hours (represented by T1), all the runs resulted in the same number of boxes being delivered to communities. On examining the result of each run, it was found that changing the depot location does not make a difference in the results of the model because there is no clearing activity occurring in all scenarios with T1. That is, no communities are being re-connected to ports or barge docks within 72 hours. Although slight differences in the modes of supply were seen, the total demands satisfied for each run remained the same. On examining all the supply activities, it was seen that out of the supplies that were dispatched, 5% was done by helicopters, 10% by barges directly, less than 1% by ferries directly, and about 84% by trucks. On examining the routes of the trucks, it was seen that about 79% of these trucks originated from the port in Victoria (as seen in Figure 38).

When the time horizon was increased to 360 hours (scenarios with T2), it is seen that although there is some activity happening, there is only about a 10% increase in the demands supplied when compared to the time horizon of 72 hours (T1). When the individual modes of supplies were observed, 18% of the supplies were helicopters, 66% by trucks, 7% by barges directly, and 8% by ferries directly.

5.3 Changes in results due to GRASP

For the input scenario represented by ID D1, the RCRSD model was run 15 times by keeping all input values the same across all 15 runs. This was done to observe the changes in results of the RCRSD due to the use of GRASP heuristic. The demand details for each run of the input scenario are shown in Table 25. The mean demand and coefficient of variation (COV) for each run are also shown in the table.

Scenario ID	**Demand met in number of boxes**	**Mean demand**	**Coefficient of variation of demand (%)**
D1	448463	439726.1	6.3
	408598		
	407895		
	422066		
	416754		
	466743		
	468063		
	377818		
	435803		
	480921		
	436563		
	468063		
	465803		
	456663		
	435675		

Table 25. Change in demand resulting from GRASP for an input scenario

From the results in the table above, it can be seen that for the same input scenario the average variation relative to the mean of demand met is 6.3%. From the 15 runs, groups of three were randomly chosen to observe how the coefficient of variation changes for three runs of the same scenario. These observations are shown in Table 26.

Random set of three demands	**Coefficient of variation for each set of three demands**	
407895	Mean	415571.7
422066	Std. Deviation	5845.4
416754	Co-efficient of variation (%)	1.4
448463	Mean	433630.7
416754	Std. Deviation	13025.6
435675	Co-efficient of variation (%)	3.0
468063	Mean	446809.7
435803	Std. Deviation	15031.6
436563	Co-efficient of variation (%)	3.4
408598	Mean	437741.3

Random set of three demands	Coefficient of variation for each set of three demands	
468063	Std. Deviation	24290.8
436563	Co-efficient of variation (%)	5.5
422066	Mean	402593.0
407895	Std. Deviation	18449.1
377818	Co-efficient of variation (%)	4.6

Table 26. Change in demands for five sets of three runs for same input scenario

From the above table it is seen that for most sets of three run results, the co-efficient of variation is less than the 6.3% variation across 15 runs. A COV of less than 5% is generally considered good so three runs for each scenario was deemed acceptable as the standard for all the analyses done in this study. Although running the RCRSD model for more than three times for each input scenario may provide more robust results, the runs were limited because of the large computational time required for the model execution.

Chapter 6. DISCUSSION

In this study, the results of a Road Clearing and Relief Supplies Distribution model were studied using datasets developed for South-Western British Columbia in the event of a Cascadia subduction zone megathrust earthquake. The objective behind doing these analyses was to find patterns in the results of the model. These observations were then used to modify other inputs of the model and the results were observed to see if the changes caused any improvements in the model results. Two scenarios of the earthquake were considered for this study: one causing partial disruption to Vancouver Island, which is considered the more practical scenario, and the other causing an extensive disruption of all activities on the island, which is considered to be the worst-case scenario.

The partial disconnection scenario (Case A) was extensively studied, and the observations are summarized here. After classifying the inputs into four categories, decision and what-if variables were chosen to be varied for the analyses. To conduct sensitivity analysis of the RCRSD model, the inputs were varied on an individual basis at first, and then some combinations of input changes were considered. The decision variables were varied first and the results from these runs were analyzed and patterns in the results were observed. These repeating patterns in the results were then used to establish the changes that were to be made to the what-if variables for the next set of analyses.

For the road clearing part of the model, by changing the depot location of the road clearing teams, it was seen that the best location to have the depot would be the Central or the South Island regions of Vancouver Island. The roads that were repeatedly cleared were considered as undamaged and the RCRSD model was run for the best and worst depot locations. It was seen that although there was no significant improvement in the results of the best depot location runs, the depot locations that showed the worst results initially showed significant improvements in their results, almost as good as the best depots. It was identified that if the roads on South Island were reinforced so they stayed unblocked, the supplies are able to reach a larger percentage of the population. On changing the inputs related to shipping such as the ports that are open or the number of ships available, it was seen that over 50% of the supplies to communities went from a single barge dock near the Gold River highway. Additionally, when the critical roads were considered undamaged, it was seen that the supplies to communities increased because the roads to this barge dock were cleared.

The RCRSD model considers a Community Impact Factor (CIF) which is a measure of the communities' resilience and preparedness for a Cascadia earthquake. In the final stage of analyses for Case A, the effect of resilience on the model results was studied by eliminating it from the model parameters. It was seen that neglecting the CIF affects the reach of supplies to communities. That is, although the total demand is not affected significantly, the number of communities that receive supplies are less. No other variations of the CIF are presented in this thesis because the difference in results when the CIF was neglected compared to when it was included in the model was not substantial. It was concluded from this analysis that minor variations in the CIF values would not affect the results of the RCRSD model significantly.

After conducting extensive analyses of the model for Case A, a few changes in the inputs for Case B was considered and the results were observed to see if there are any similarities in the results of Case A and Case B. It was seen that the results of Case A could not be used to draw any conclusions for Case B, and a different set extensive analyses may be necessary to find patterns and critical components for Case B. Future work can be done to cater the decision variables for Case B in accordance with the what-if input variables. For example, observing the results of the RCRSD model for Case B when the time horizon is extended to one month, and varying the initial demands of the communities to meet the requirements of say, two weeks.

This study provides a framework to conduct sensitivity analysis of the RCRSD model. The classification of inputs and setting the sequence of input changes were done to create a guideline for any further analyses that can be done on the model. Identifying patterns in the results of the model helped to study the effect of a few decision and what-if variables in the model. In this study, the raw outputs from the model were extracted and modified to make them easy to read. Programs were developed to create datasets from the results of the model that can be analyzed.

It should be noted that the data used in this study are largely assumptions or results of other studies used to simulate a Cascadia earthquake scenario. The actual effects of a

Cascadia earthquake on Vancouver Island are unpredictable. However, analyzing the results of the RCRSD model helps to be better prepared for the disaster if it were to occur. A recommendation from the results of this study is that Central Island is the best place to have the road clearing teams' depot. Apart from meeting the demand requirements, Central Island is also predicted to have less of an impact from the earthquake compared to South Island and Pacific Rim. If an advanced model that uses multiple depot locations is developed, the depots should be placed in South Island and near the eastern shore of North Island. Additionally, somehow reinforcing the roads on South Island or having a road clearing teams depot nearby is more likely to produce a better reach to communities and have their demands met.

Another recommendation would be to have warehouses in the regions with more resilience to the earthquakes (North Island and Central Island). Although the communities in these regions are predicted to be better prepared to deal with the aftermath of the earthquake, the roads and buildings there are predicted see less damages. Communities shown in this study that get less than 2% of their demands supplied every time can be encouraged to start stockpiling non-perishable supplies.

The results of this study are limited by the limitations of the RCRSD model itself. For example, the model assumes a single depot location for the road clearing teams which is highly unlikely in practice. The RCRSD model provides non-deterministic solutions as it uses GRASP to reduce computational time. In this study, although multiple runs were performed for the same set of input variable scenarios, the results cannot be seen as definite solutions. Therefore, increasing the number of runs for each input scenario may yield better and more accurate results. Another limitation is that the RCRSD model assumes perfect coordination between the road clearing teams and the multiple modes of supply to the communities. In practice, it may not be so. A recommendation is that training or workshops be conducted to ensure co-ordination between the different transportation modes so that they can be better prepared for the earthquake.

In the future, further analysis of the model can be performed to reveal other patterns in the results that may be used to make decisions to improve the emergency preparedness of Vancouver Island. For example, the effect of having more time to complete the road repair and supply activities, how ferry supplies may improve if more ports were considered open, and the effect of having more roads open are all questions that can be answered by conducting further analysis of the model. If an improved road reconnection and routing model were to be developed, this study may be used as a framework to conduct analysis of its results. Further study can be done on how to best represent CIF in the RCRSD model. This study can also be expanded by considering damages to the road clearing teams depots, availability of personnel, damages to equipment, etc. Other future opportunities for extending this research includes using the framework presented in this study to develop Designs of Experiments for routing problems used in the aftermath of other types of natural disasters. The input scenarios developed for this study can also be used to develop validation instances for road reconnection and supplies routing problems using the Cascadia earthquake scenario.

Chapter 7. CONCLUSION

An extensive sensitivity analysis of a Road Clearing and Relief Supplies Distribution (RCRSD) model for Vancouver Island was done in this study. A Cascadia megathrust earthquake scenario (with two damage data sets) was used for the model inputs. Four regional divisions of Vancouver Island were considered to further analyze the results. For the analyses, a sequence of input changes was developed. From the results, it was seen that changing the location of the road clearing teams' depot location had a major impact on the results of the model. By conducting sensitivity analysis of the model, a couple of best (near Courtenay and Crofton Harbour) and worst depot locations (near Sooke and Port Hardy) were identified. Additionally, roads that get frequently repaired (roads on South Island), the ports that are most active for the supply distributions (near Gold River and Victoria), and the regions of communities that get most of their demands met (Pacific Rim communities) were also identified. From these results, another set of analyses were done by changing what roads and ports are available. Finally, the effect of a Community Impact Factor which represents the resilience of the communities was studied. The outputs from the RCRSD model were modified to be mapped, tabulated, and analyzed in this study. The results obtained from this study may be used to perform further analysis of the RCRSD model.

References

Ahmadi, G., Tavakkoli-Moghaddam, R., Baboli, A., & Najafi, M. (2022). A decision support model for robust allocation and routing of search and rescue resources after earthquake: A case study. *Operational Research*, *22*(2), 1039–1081. https://doi.org/10.1007/s12351-020-00591-5

Akbari, V., & Salman, F. S. (2017a). Multi-vehicle prize collecting arc routing for connectivity problem. *Computers & Operations Research*, *82*, 52–68. https://doi.org/10.1016/j.cor.2017.01.007

Akbari, V., & Salman, F. S. (2017b). Multi-vehicle synchronized arc routing problem to restore post-disaster network connectivity. *European Journal of Operational Research*, *257*(2), 625–640. https://doi.org/10.1016/j.ejor.2016.07.043

Almeida, L. S., Pelot, R., & Goerlandt, F. (2019). *Food distribution in emergency response: A network-based model and a case study for Newfoundland*. 61th Annual Conference of the Canadian Operational Research Society (CORS2019), Saskatoon, AB, 12p.

Aráoz, J., Fernández, E., & Franquesa, C. (2009). The Clustered Prize-Collecting Arc Routing Problem. *Transportation Science*, *43*(3), 287–300. https://doi.org/10.1287/trsc.1090.0270

Bell, A. M., & Bristow, D. N. (2020). Modelling the marine transport resilience of Vancouver Island in a Cascadia subduction zone earthquake scenario. *Sustainable and Resilient Infrastructure*, 1–18. https://doi.org/10.1080/23789689.2020.1845482

Cassidy, J. F., Rogers, G. C., & Halchuk, S. (2010). Canada's Earthquakes: 'The Good, the Bad, and the Ugly.' *GEOSCIENCE CANADA*, *37*(1).

Chang S., Bristow D., Goerlandt F., Pelot R., Goodchild A., Lin C., Zhou L. 2020. Planning for a catastrophic earthquake in British Columbia: Marine transportation disruption and coastal community resilience. SIREN Project Report, 112 p.

Chang, S. E., & Tanner, A. (2022). A Community Impact Scale for Regional Disaster Planning with Transportation Disruption. *Natural Hazards Review*, *23*(3), 04022019. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000563

Clague, J. J. (2002). *The Earthquake Threat in Southwestern British Columbia: A Geologic Perspective*. 29. Natural Hazards 26: 7–34, 2002.

Corberán, Á., Fernández, E., Franquesa, C., & Sanchis, J. M. (2011). The Windy Clustered Prize-Collecting Arc-Routing Problem. *Transportation Science*, *45*(3), 317–334. https://doi.org/10.1287/trsc.1110.0370

Edgington, D. W. (2022). Planning for Earthquakes and Tsunamis: Lessons from Japan for British Columbia, Canada. *Progress in Planning*, *163*, 100626. https://doi.org/10.1016/j.progress.2021.100626

Edwards, C. L., & American Society of Civil Engineers (Eds.). (2012). *Haiti Mw 7.0 earthquake of January 12, 2010: Lifeline performance*. ASCE.

Goerlandt, F., Almeida, L. S., Rodrigues, L., & Pelot, R. (2022). *Towards a Modeling Toolbox for Multi-Modal Coastal Community Supply to Support Disaster Preparedness Risk Management in Canada*.

Goerlandt, F., & Islam, S. (2021). A Bayesian Network risk model for estimating coastal maritime transportation delays following an earthquake in British Columbia. *Reliability Engineering & System Safety*, *214*, 107708. https://doi.org/10.1016/j.ress.2021.107708

Kasaei, M., & Salman, F. S. (2016). Arc routing problems to restore connectivity of a road network. *Transportation Research Part E: Logistics and Transportation Review*, *95*, 177–206. https://doi.org/10.1016/j.tre.2016.09.012

Koshimura, S., Hayashi, S., & Gokon, H. (2014). The impact of the 2011 Tohoku earthquake tsunami disaster and implications to the reconstruction. *Soils and Foundations*, *54*(4), 560–572. https://doi.org/10.1016/j.sandf.2014.06.002

Lopes, R. B., Plastria, F., Ferreira, C., & Santos, B. S. (2014). Location-arc routing problem: Heuristic approaches and test instances. *Computers & Operations Research*, *43*, 309–317. https://doi.org/10.1016/j.cor.2013.10.003

Natural Resources Canada. (2010). *Earthquakes in SW British Columbia*. Earthquakes Canada (nrcan.gc.ca)

Palomino Romani, G., Blowes, K., & Molina Hutt, C. (2023). Evaluating post-earthquake functionality and surge capacity of hospital emergency departments using discrete event simulation. *Earthquake Spectra*, *39*(1), 402–433. https://doi.org/10.1177/87552930221128607

Province of BC (2018). *British Columbia Building Code.* (BC Codes)

Rogers, C.G., 1998: Earthquakes and earthquake hazard in the Vancouver area; in Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 17-25.

Souza Almeida, L., & Goerlandt, F. (2022). An ant colony optimization approach to the multi-vehicle prize-collecting arc routing for connectivity problem. *Multimodal Transportation*, *1*(3), 100033. https://doi.org/10.1016/j.multra.2022.100033

Souza Almeida, L., Goerlandt, F., & Pelot, R. (2022). Trends and gaps in the literature of road network repair and restoration in the context of disaster response operations. *Socio-Economic Planning Sciences*, *84*, 101398. https://doi.org/10.1016/j.seps.2022.101398

Souza Almeida L., Goerlandt F., Rodrigues L,, Pelot R. (2024). Modeling multi-modal supply chain vulnerability to earthquakes: A case study on Canada's West Coast. Proceedings of the European Conference On Safety And Reliability, Kraków, Poland, 8pp. (forthcoming)

Souza Almeida, L., Goerlandt, F., Pelot, R., & Sörensen, K. (2022). A Greedy Randomized Adaptive Search Procedure (GRASP) for the multi-vehicle prize collecting arc routing for connectivity problem. *Computers & Operations Research*, *143*, 105804. https://doi.org/10.1016/j.cor.2022.105804

Souza Almeida, L., Rodrigues, L., Goerlandt, F., Ancona-Segovia, J., Pelot, R., Bristow, D., & Chang, S. (2023). Datasets of disrupted transportation networks on Canada's West Coast in a plausible M9.0 Cascadia Subduction Zone earthquake scenario. *Data in Brief*, *46*, 108762. https://doi.org/10.1016/j.dib.2022.108762

Unjoh, S. (2004). *SEISMIC RETROFIT OF HIGHWAY BRIDGES*. 19, Journal of Japan Association for Earthquake Engineering, Vol.4, No.3 (Special Issue).

Appendix

Table 27. Input Parameter Values used in this study

Input parameter name	Description	Values
Type – Fixed parameter (lists or tables)		
Island Ferries	List of all islands serviced by ferries	See (Souza Almeida et al., 2023) for tables of these values
Island Barges	List of islands serviced by barges	
Ferries Ports Vancouver Island	List if Ferry ports on Vancouver Island	
Ferries Ports Mainland	List of Ferry ports on Mainland Vancouver	
Barges Ports VI	List of barges ports on Vancouver Island	
Barges Ports Mainland	List of barges ports on mainland Vancouver	
Heliports Mainland	List of heliports on the mainland. The heliports on the island are just communities.	
Roads distance	2D array of distances between road segments on Vancouver Island	
Population	List of populations of Vancouver Island communities	
Ships capacity	List of ships capacities in terms of number of truck containers	
List all Heli	Number of available helicopters	
Heli capacity	Capacity of helicopters in terms of number of food baskets	
Heli traversing distances	Distance between the heliports on the mainland to the communities on the islands in kms.	
Type – Fixed parameters (integer/float values)		
Heavy machine speed	Speed of the road clearing teams	30 km/hr
Ferries loading/unloading times	Time taken for loading/unloading ferries	2 hr

Input parameter name	**Description**	**Values**
Barges loading/unloading times	Time taken for loading/unloading barges	3 hr
Truck speed	Speed of supply trucks	50 km/hr
Truck container vol	Volume of truck containers	66.83 m^3
Truck max weight	Max weight the trucks can carry	3950 kg
Truck unloading	Time taken for unloading a truck	0.5 hr
Heli speed	Speed of helicopters	180 km/hr
Heli loading time	Time to load a helicopter	3 hr
Heli unloading time	Time to unload a helicopter	3 hr
Food basket vol	Volume of a single food/supplies basket	0.176 m^3
Food basket weight	Weight of a single food/supplies basket	4 kg
Type – Computational parameters		
Roads iterations	Number of iterations in the Road clearing GRASP	100
Trucks iterations	Number of iterations in the trucks routing GRASP	100
Ferries iterations	Number of iterations in the ferries routing GRASP	100
Barges iterations	Number of iterations in the barges routing GRASP	100
Helicopters iterations	Number of iterations in the helicopters routing GRASP	100