Towards a Modeling Toolbox for Multi-Modal Coastal Community Supply to Support Disaster Preparedness Risk Management in Canada

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Abstract: Natural disasters can severely impact multi-modal logistics networks, with both physical infrastructure and transportation assets vulnerable to damage. In the response phase of such disasters, communities rely heavily on these logistics networks for medical evacuation, to support Search and Rescue activities, and for the resupply of essential goods such as fuel, medicine, and food. Especially for large-scale regional natural disasters, the interdependencies between community needs, damage to critical infrastructures, road networks, and transportation assets, and the related response activities are complex, with high uncertainty. This poses significant challenges to understand vulnerabilities and risks, to make response plans and decide on mitigation actions. Given the lack of dedicated models and analysis approaches to understand vulnerabilities and risks, and to support disaster preparedness decision-making, this article provides an overview of ongoing developments to develop a dedicated modeling toolbox. After providing a brief description of the types of natural disasters for which this toolbox is devised, emphasizing the Canadian context, a high-level overview is given of the risk management questions and the associated models which are currently under development. For some models, preliminary results of selected models are shown as an demonstration of the toolbox. The results illustrate the importance of the interdependencies between transport networks, assets, and community needs. Finally, avenues for future research to further develop the toolbox are discussed.

1. INTRODUCTION

Natural disasters such as earthquakes, hurricanes, and flooding are widely considered to be amongst the most significant global risks [36]. Such disasters can lead to very heavy damage to critical infrastructures, housing, and commercial and industrial facilities over large geographical areas, leading to loss of life and other negative impacts to human health and safety. Additionally, natural disasters can have enormous socio-economic impacts, including short- and long-term economic impacts [5, 28], reduced educational attainment [22], and increased social inequality [25]. More generally, natural disasters significantly affect a region's capacity for sustainable development [17].

Given the importance of natural disaster risk, various high-level frameworks for disaster risk reduction have been developed, for instance the highly influential Sendai Framework for Disaster Risk Reduction 2015-2030 [34]. Amongst other things, this framework highlights the importance of understanding disaster risk and enhancing disaster preparedness for effective response. There is wide agreement that hazard, risk, and vulnerability assessments have a central role in establishing a knowledge base to inform decisions on mitigation measures, improve preparedness planning, and increase the resilience of response operations [1, 15, 24].

Natural disaster risks can be characterized as complex, uncertain, and ambiguous, in the sense that there are many interrelated aspects involved in the problem, about which analysts and stakeholders lack knowledge to varying degrees, and with value-laden choices and trade-offs to be made [14]. Considering state-of-the-art guidance on appropriate risk governance strategies for such types of societal risks [35], these are best approached through a participative discourse, where there is a wide, multi-stakeholder debate about the risks and their underlying implications.

To further inform discussions among key stakeholders and decision makers, advanced analytical models can provide essential insights into the hazards, risks, and vulnerabilities. In a Canadian emergency management context, the central role for risk analysis is recognized for instance by the Government of British Columbia, to inform risk mitigation, disaster preparedness and response, and recovery [15]. Apart from generic qualitative analysis methods for assessing the risks, several analytical tools have been developed to estimate the geophysical characteristics of natural disasters, and the direct impacts on infrastructures [1].

In the immediate and sustained response phases following a natural disaster, multi-modal logistics are essential to evacuate victims, to support Search and Rescue activities, and for supplying essential goods such as fuel, medicine, and food [10, 18, 23]. There is a growing academic field dedicated to the development of models and analytical tools for support disaster preparedness and response planning [4, 8, 32, 37]. Major themes include prepositioning of relief supplies and facility location, relief routing and delivery, and network restoration.

Notwithstanding the significant developments in the quantitative analysis of hazards, risks, and vulnerabilities, there are only a few frameworks and quantitative models available to provide insights into logistics-related issues in a Canadian disaster preparedness and response planning context. Some notable advances in this direction include a proposed framework for analyzing the disruptions to regional supply chains [10], and the development of an object-oriented model for analyzing the vulnerability of the fuel distribution network in coastal British Columbia [11]. However, there is a lack of an integrated modeling toolbox to coherently answer interrelated risk management questions for informing regional preparedness and response planning in Canada [10, 32]. Given the importance of marine shipping to supply coastal communities, especially in British Columbia and Newfoundland, the tools should provide a comprehensive view on the impacts of natural disasters on the multi-modal transportation networks and their capacity to function under various disruption scenarios.

Given the above, this article aims to provide a high-level overview of the development of a modeling toolbox to support risk assessment of multi-modal community supply in the context of natural disaster preparedness in Canada.

To contextualize the need for such a toolbox, brief insights are given into some natural disasters of concern to preparedness and response emergency managers in Canada, in Section 2. Subsequently, in Section 3, a summary overview of the risk management questions which the toolbox helps answer is provided, along with a brief description of the models (several of which are currently under development), and their inputs and outputs. For selected models, preliminary results of test scenarios are shown in this section as well, to illustrate the potential of the models to support mitigation, preparedness, and response planning. Subsequently, a discussion is given in Section 4, focusing on avenues for future research and development. Section 5 concludes.

2. NATURAL DISASTERS IN CANADA: CONTEXT AND TOOLBOX NEED

Canada is the second-largest country in the world, spanning nearly 10 million square kilometers in land area. It borders the Atlantic, Pacific, and Arctic Oceans, boasts a very diverse geophysical and geological landscape, and is characterized by multiple distinct climate regions. Consequently, many different types of natural disasters occur in Canada, including avalanches, earthquakes, floods, hurricanes, landslides, severe storms, storm surges, tornados, tsunamis, and wildfires [1].

Of these natural disasters, earthquakes, tsunamis, hurricanes, and floods arguably have the highest potential to lead to large-scale disruptions to regional logistics networks. As seen in Figure 1 (a), earthquakes occur across the major tectonic plate boundaries, with smaller earthquakes being very frequent (weekly or monthly), and larger earthquakes occurring over timespans of decades or even centuries. British Columbia, especially the area near Vancouver Island on the Pacific Coast and the lower mainland area around Vancouver, has the highest risk for major earthquakes with the potential to disrupt regional logistics networks in highly populated areas. Peak ground acceleration maps are of plausible high-risk earthquake scenarios are shown in Figure 1.

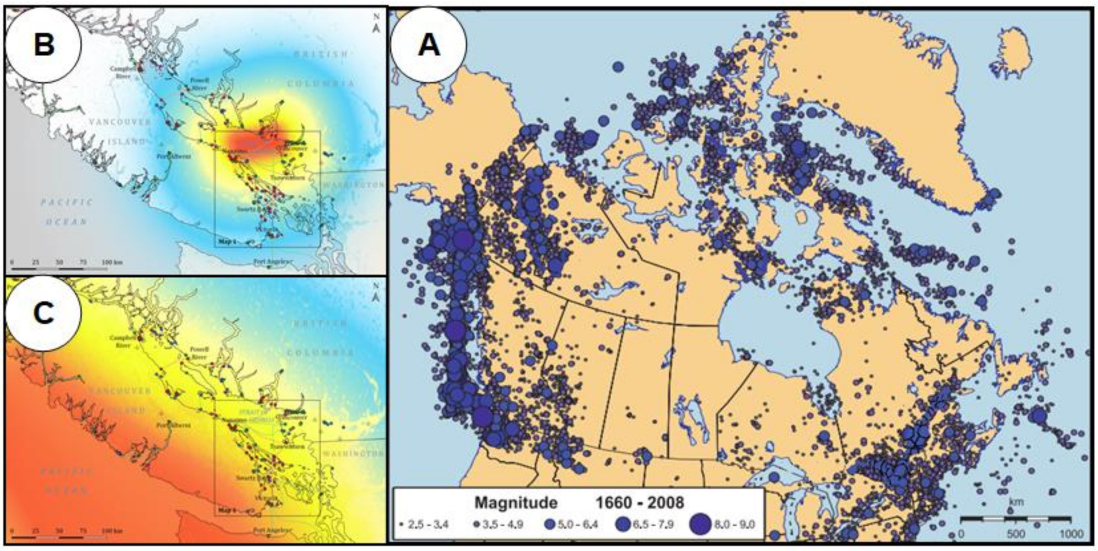

Figure 1: Map of historic earthquakes in Canada (A), maps of plausible peak ground accelerations for a shallow crustal M7.3 earthquake (B), and a Cascadia subduction zone M9.0 earthquake (C); based on [7] and [9]

Figure 1 (B) represents a shallow crustal M7.3 earthquake occurring as a local rupture along the Georgia Strait Fault Zone. Such an earthquake would have medium to high impacts on communities in the lower mainland area, and on multi-modal transportation assets, infrastructures, and operations in the affected area. Figure 1 (C) represents a Cascadia subduction zone M9.0 earthquake, a large-scale megathrust rupture along the Cascadia subduction interface. A similar earthquake occurred in January 1700, and research suggests that such an event has a return period of about 500 years [7].

Figure 2 illustrates the plausible impacts of a Cascadia subduction zone M9.0 earthquake as in Figure 1 (C) on critical infrastructures (A), communities (B), road infrastructure (C), and marine terminals for two of the major local operators, BC Ferries (D) and Seaspan (E). It is seen that such a disaster could have very high impacts on western and southern communities on Vancouver Island, and medium impacts on other coastal communities in the area. Power, water, and communications infrastructures would experience a complete outage on the entire Vancouver Island, with extreme outages in the lower mainland area, including Vancouver, and major to extreme outages in areas extending as far as Powell River and Abbotsford. Communities in these areas would be severely impacted and heavily dependent on external support for supply of essential goods and services, including delivery of fuel, food, and medicine, Search and Rescue, and medical evacuations. The disaster would also have high impacts on multi-modal transportation infrastructures, with many roads unpassable for logistics operations, and most BC Ferries and Seaspan terminals damaged, leading to severe disruptions to marine transportation.

Importantly, having an offshore epicenter, such a Cascadia subduction zone earthquake, would also result in a tsunami, which would reach the Pacific Coast, Salish Sea, and Southern Strait of Georgia, possibly with further devastating effects in coastal areas [21].

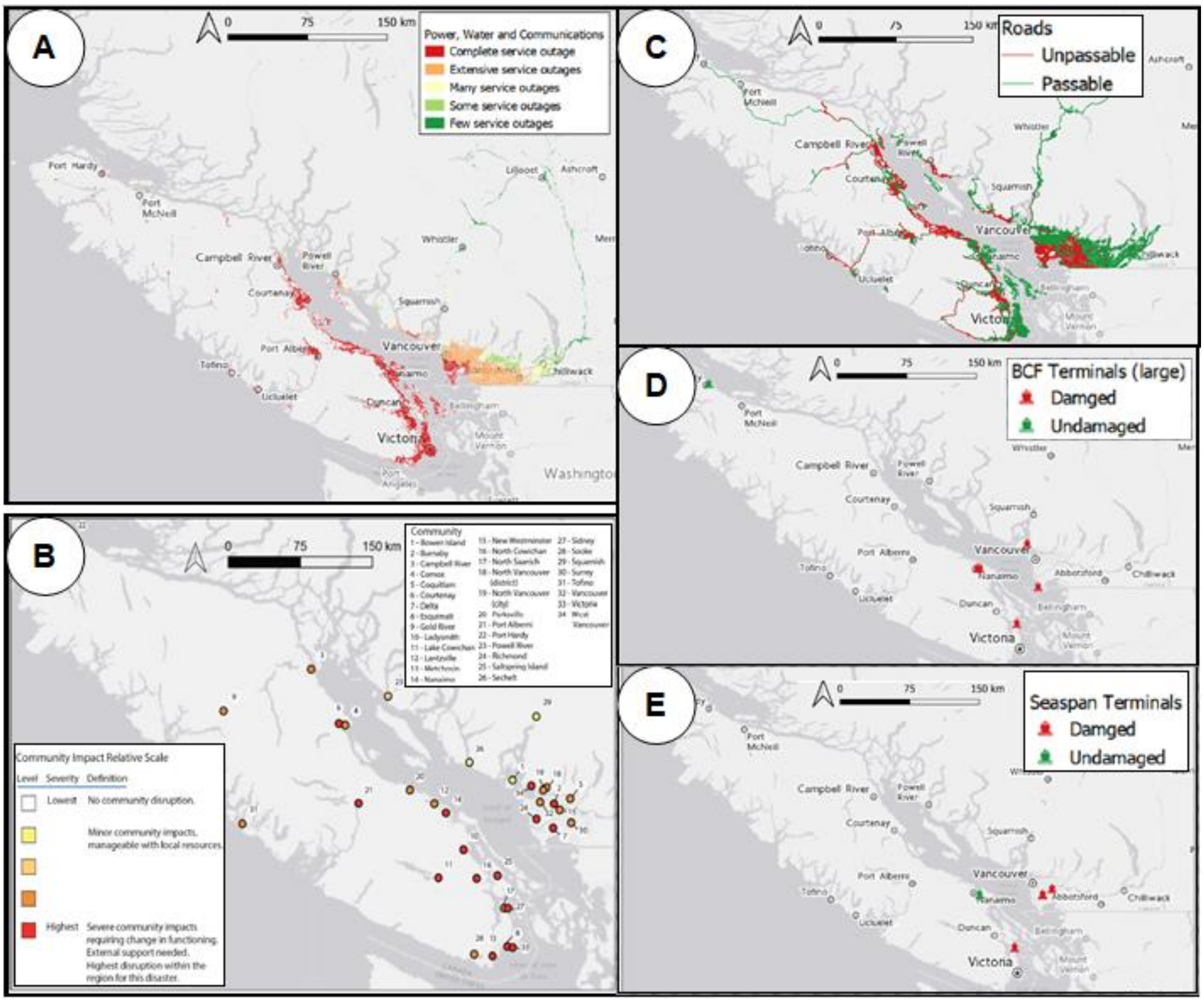

Figure 2: Impacts of a plausible Cascadia subduction zone M9.0 earthquake event: (A) disruptions to critical infrastructures (power, water, and communications), (B) relative impacts to communities, (C) passability of roads, (D) damage to BC Ferries terminals, (E) damage to Seaspan terminals; based on [9]

The Eastern Canadian provinces at the Atlantic Coast are vulnerable to hurricanes and post-tropical cyclones. The impacts of such disasters are caused by high winds, storm surge, rain, and ocean waves, and include power outages, damage to houses and other building types, flooding of especially low-lying coastal areas, extensive damage to roads, bridges, and dykes, and thousands or even millions of trees toppled, leading to debris which makes roads and railroads inaccessible [30]. An example of a historic Category 2 hurricane event is shown in Figure 3, showing the September 2010 Hurricane Igor's temporal path and intensity evolution (B), maximum sustained wind speeds and wind gusts (C), and rain, community impacts, and passability of roads (A). It is seen that this disaster led to large-scale regional impacts to communities and transportation networks. In a context of climate change, it is estimated that similar disasters will become more frequent and more intense in the future [6].

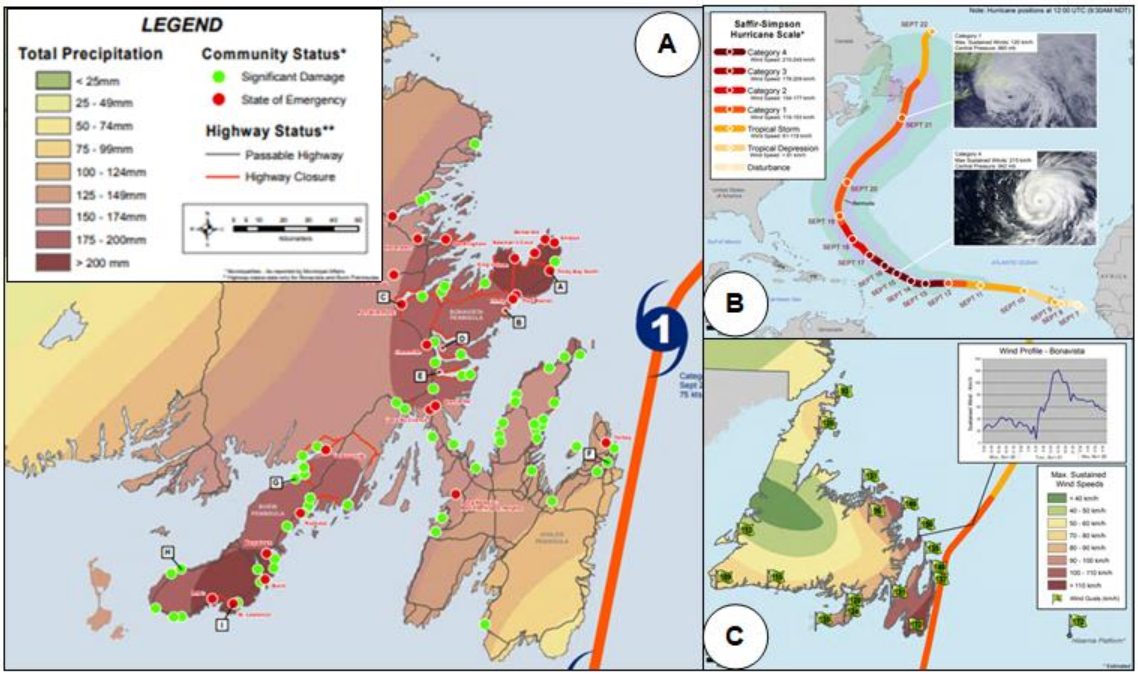

Figure 3: Hurricane Igor: (A) rain, community impacts, and passability of roads, (B) temporal path and intensity evolution, (C) maximum sustained wind speeds and wind gusts; based on [20]

3. A TOOLBOX FOR ASSESSING RISK TO MULTI-MODAL COMMUNITY SUPPLY IN NATURAL DISASTERS

3.1. Scope of and Requirements for the Toolbox

The modeling toolbox aims to support risk management and governance, focusing on multi-modal community supply in the context of natural disaster preparedness in Canada. The specific focus of the toolbox is the regional supply of emergency relief goods (fuel, food, medicine,…) to communities affected by the occurrence of a natural disaster, further considering the impacts on and disruptions to the physical assets of the multi-modal transportation system, including marine vessels, marine terminals, and road infrastructure. Given the prevalence of high-risk natural disasters near coastal areas (see Section 2) and the dependency on maritime transportation of coastal communities especially in British Columbia and Newfoundland, the models should be appropriately tailored to marine shipping. The toolbox aligns with the key requirements set forth in an elaborately justified modeling framework for transportation impact models for disruptions to regional supply chains [10]:

(i) consideration of physical vulnerability of key assets,
(ii) explicit attention to different modes through which hazards can cause system disruption,
(iii) accounting for the duration of disruption,
(iv) ability to measure the mitigating effects of planning and preparedness on system disruption.

One additional requirement for the toolbox is foreseen:

(v) systematic consideration of uncertainties through probabilistic analysis.

This additional requirement is based on insights from the risk management literature, in which the importance of uncertainty treatment is emphasized [3]. In its current implementation, the main models included in the toolbox are deterministic, i.e., they only enable the analysis of one specific set of conditions for a given natural disaster scenario. However, as outlined in the introduction, large-scale natural disasters can be characterized as complex, uncertain, and ambiguous risk problems, with many possible variations of, and large uncertainties about, the specific contextual conditions of the disasters to prepare for. Hence, the models should not only capture the essential complexities of the disruptions to the multi-modal supply system for deterministic scenarios, but also be practically useful for a more elaborate probabilistic analysis, to understand the implications of parameter and model uncertainties.

In terms of the foreseen use context of the toolbox, the models are intended to enable insights into the impacts of natural disasters in terms of hazards, risks, and vulnerabilities associated with the multi-modal supply to affected communities in the post-incident phase. Based on the conceptualization of the planning framework used by the Province of British Columbia [15], the models are applied to the disaster preparedness phase, to understand the effect of mitigation strategies to improve response in the immediate and sustained response phase, and to provide useful insights for the recovery phase. Hence, the models should support an analysis of the likely capability of the disrupted transportation system to supply communities, and to anticipate the effects of decisions and mitigation activities on this capability. The main end users of such analysis are regional emergency response managers and their associated stakeholders, in particular communities, transport service providers, and administrations responsible for the design, maintenance, and repair of critical transportation infrastructures.

3.2. Risk Management Questions (RMQ) Addressed by the Models in the Toolbox

While developing, it is useful to consider the risk management questions to which the models intend to provide insights. The following questions were set forth as particularly important by the regional emergency management organizations:

Q1. How are transportation assets (esp. vessels) and their operability affected by disasters?
Q2. How would a disaster affect maritime and multi-modal transportation routes?
Q3. What operational capacity would the disrupted multi-modal transportation system have to ship relief supplies to communities in the response phase?
Q4. What ports and other transportation infrastructure should be prioritized for repair and clearance to maximize the effectiveness of supply to the affected communities?

The proposed toolbox consists of four interrelated models. These are briefly summarized in Table 1, which lists their name, which of the questions they provide information for, the technique(s) underlying the models, the disaster type(s), and the geographical area to which these are tailored, as applicable. Listed references provide more detailed information about the models. The following subsections give a brief outline of the models and show some preliminary outputs to illustrate the types of results obtained.

Table 1: Overview of toolbox for multi-modal coastal community supply disruptions to support natural disaster preparedness in Canada

Model	**RMQ**	**Applied Technique(s)**	**Disaster Type(s)**	**Geographical Area**	**Ref.**
Road clearance and network reconnection model	Q2 Q3 Q4	- Multi-vehicle prize-collecting arc routing for connectivity problem (KPC-ARCP) - Metaheuristics (GRASP, ACO)	AV, EQ, FL, HU, LS, TO, TS, WF (*)	(†)	[2] [29] [33]
Multi-modal community disaster relief supply distribution model	Q2 Q3 Q4	- 2-echelon Split Delivery Vehicle Routing Problem with Time Windows (2E-SD-VRP-TW) - Metaheuristics (SA) - KPC-ARCP	AV, EQ, FL, HU, LS, TO, TS, WF (*)	(†)	[16] [31]
Model for damage to marine transport assets	Q1	- Data analysis - Qualitative expert model - GIS analytics	EQ, TS	V.I. and surrounding sea	[26]
Marine route disruption model	Q2	- Bayesian Network	EQ, TS	V.I. and surrounding sea	[13]

Notes: AV = avalanche | EQ = earthquake | FL = flood | HU = hurricane | LS = landslide | RMQ = risk management question (see text above table) | TO = tornado | TS = tsunami | V.I. = Vancouver Island | WF = wildfire | (*) = can be used for multiple disaster types, given appropriate inputs | (†) = can be used for any geographical area, given appropriate inputs

3.3. Road Clearance and Network Reconnection Model

As seen in Figure 2 and Figure 3, natural disasters can very severely impact road infrastructure, making it unpassable for vehicles such as trucks to deliver goods to communities. In the immediate and sustained response phases to a natural disaster, to facilitate land-based logistics operations, it is therefore important to clear roads and reconnect the road network as efficiently as possible to enable the supply to isolated communities. There is a growing literature focusing on models and solution approaches to address this problem (see [32] for a recent review).

It is reasonable to account for differences in demand levels between communities, for instance due to variations in population size and resilience levels to cope with the effects of a disaster [9, 27]. Therefore, the efficiency of reconnecting isolated communities can be understood as what roads to prioritize for clearing and repair. Within the toolbox, this is modeled using the multi-vehicle prize-collecting arc routing for connectivity problem (KPC-ARCP) [2], in which disconnected parts of the network are given distinct priorities. This state-of-the-art model, shown in Figure 4, groups communities into components which multiple road clearing and repair teams, all originating from one single depot, aim to reconnect. The model's objective is to maximize the "prize" of reconnected components within a given time window, where the prize can be considered as a function of factors such as population size and community resilience. Figure 4 (a) shows a road network with communities and the depot before the disaster occurs. Figure 4 (b) shows the intact and blocked roads, whereas Figure 4 (c) illustrates the nodes grouped in components, which are reconnected by the K teams in the depot.

An important issue to consider for applying the model to real-world regional transportation networks and natural disasters, is that such networks are very large, with an example road network for the 2010 earthquake in Port-au-Prince (Haiti) consisting of 16,657 vertices and 19,558 edges [27]. To solve the KPC-ARCP so that, according to requirement (v) of Section 3.1, multiple scenarios can be efficiently calculated, it is therefore important to devise solution algorithms which quickly provide accurate results. Originally, a matheuristic was applied to obtain solutions for the KPC-ARCP. However, later work found that an Ant Colony Optimization [29]or a Greedy Randomized Adaptive Search Procedure (GRASP) [33], can achieve accurate results much faster for larger network sizes.

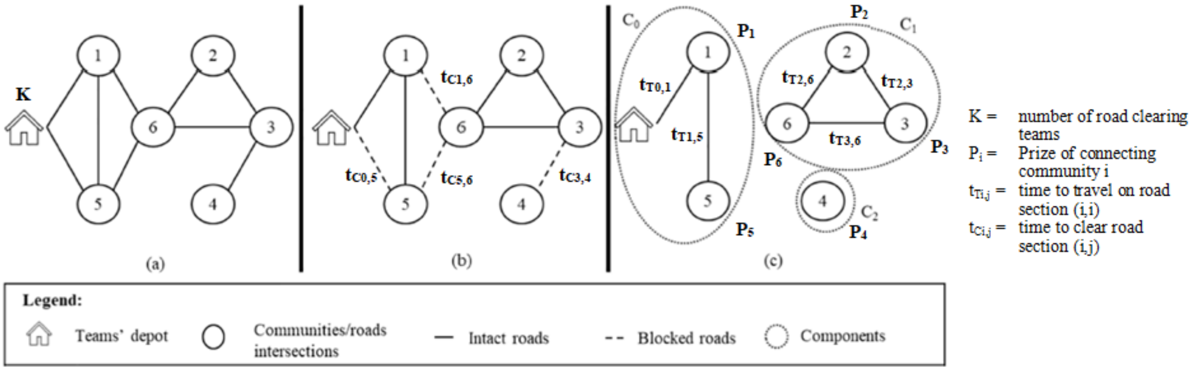

Figure 4: Schematic representation of the KPC-ARCP problem; based on [2, 33]

This model takes as inputs the road network, defined through the location of vertices and edges. Furthermore, the location of the depot with road clearing teams and the locations of communities in the network need to be specified. For each edge, a traversing speed t_T denotes how long it takes a road clearing team to cross the road segment between vertices i and j, whereas a clearing time t_C denotes how long it will take a road clearing team to clear the road segment between vertices I and j. The number of road clearing teams in the depot (K) and a time horizon over which the road reconnection operations are to be analyzed, needs to be specified. As outputs, the model gives the value of the total prize collected, and the routes taken by each repair team (combinations of positions and time for each team), including the status of the network at the end of the time horizon. Figure 5 shows an example of the results of the KPC-ARPC applied to a scenario for road clearance on Vancouver Island, subjected to a road damage similar to Figure 2 (c). More details about the scenario can be found in [9].

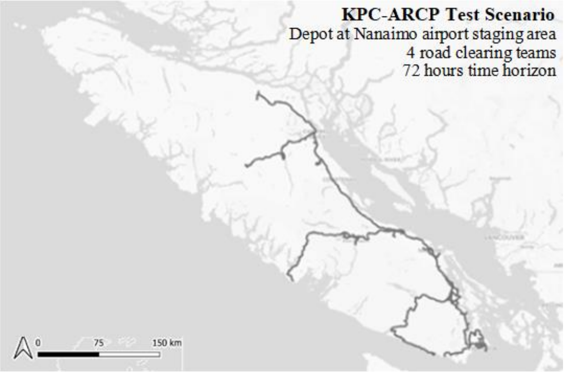

Figure 5: Illustrative output of KPC-ARCP for a case study on Vancouver Island, showing the route taken by all road clearing teams at the end of the time horizon; based on [9]

3.4. Multi-modal Community Disaster Relief Supply Distribution Model

The multi-modal community disaster relief supply distribution model integrates the road clearance and network reconnection model of Section 3.3 with an implementation of the 2-echelon Split Delivery Vehicle Routing Problem with Time Windows [16, 31]. This is applied sequentially for different transportation modes over a given time window and synchronized with the operability of the road and maritime routes, using results of the models of Section 3.3 and Section 3.6. The high-level structure, as well as model inputs and outputs, is shown in Figure 6. For illustrative model results, see [9].

The core of the model, the distribution of relief supplies, starts with the ferries. Routes are created, starting on the ports at the hub side of the marine logistics network (1st echelon), with as destinations the open ports on the spoke side of the logistics network (2nd echelon). The routes are characterized by the origin and destination ports, the vessels operating on that route, their speed and capacity, and the time at which the route becomes operable. The routes of trucks in the 2nd echelon are subsequently created considering the supplies available at each port, the demand level of the communities, and the state of the roads as obtained from the road clearing model. After ferries are assigned, the model identifies ports and coastal communities which did not receive all the needed supplies. Barges are sent to these locations, considering the ports and terminals which are open, the delay of the route operability of the tug-barge combinations, the capacities, and the demands. Similar as for trucks, the model then considers how many supplies arrived at what barge landing site (taken as points near coastal communities) and creates routes using the information about the state of the road network and the community demand levels. If the model results in a community not being supplied by sea or land, the available helicopters deliver relief supplies to these, prioritizing the most impacted communities.

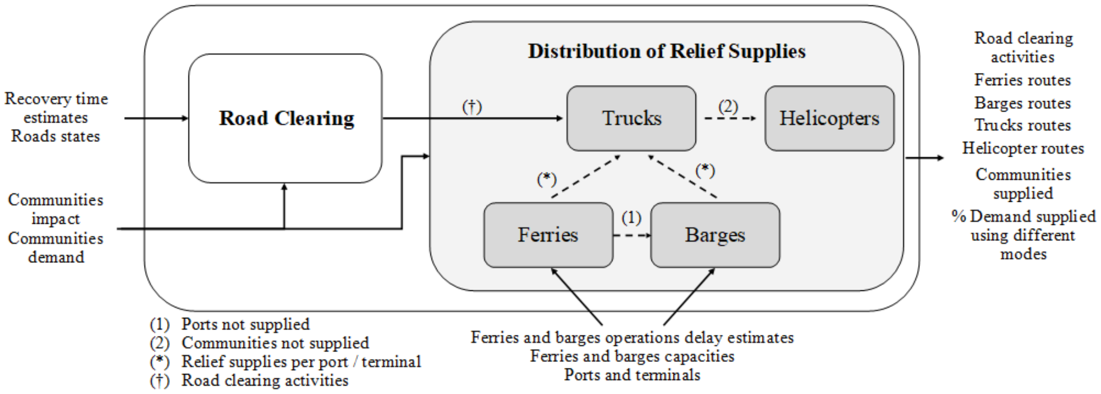

Figure 6: Structure, inputs, and outputs of the multi-modal community disaster relief supply model; based on [9]

3.5. A Model for Damage to Marine Transport Assets

In large-scale earthquake events, especially when a tsunami occurs, ships and barges can be damaged and rendered inoperable for logistics operations [19, 27]. Because of their importance for delivering goods to Vancouver Island, and the expectation that a M9.0 Cascadia subduction zone earthquake-tsunami event would cause significant damage to the fleet in the area, it is important to obtain better insights into the extent to which the fleet would retain the capability to provide logistics services.

To investigate the extent of damage, a spatial analysis is performed, as illustrated in Figure 7. A zonal vessel damage model is applied to estimate the probability of damage to a specific ship operating at a given time and location on a route in the area, given a specified earthquake and tsunami impact scenario (Figure 7 (a)). Given the available evidence of past experiences with earthquakes and tsunamis, the model is constructed based on the premise that an earthquake-tsunami event can occur at any given time, and that the location of a vessel will determine its susceptibility to damage. The model adopts a zonal approach, considering factors such as whether the vessel is located in a port area, the arrival time and intensity of the tsunami wave and current at the given location, the bathymetry in the area, the proximity to shore, and the vessel size. A spatial analysis is performed, by evaluating the damage model for each point on the routes of vessels operating in the study area, with routes derived from AIS data and data about ports and terminals in the area. Results of the calculations are aggregated over vessel routes and over the entire fleet, distinguishing vessel sizes and types, see Figure 7 (b) and (c).

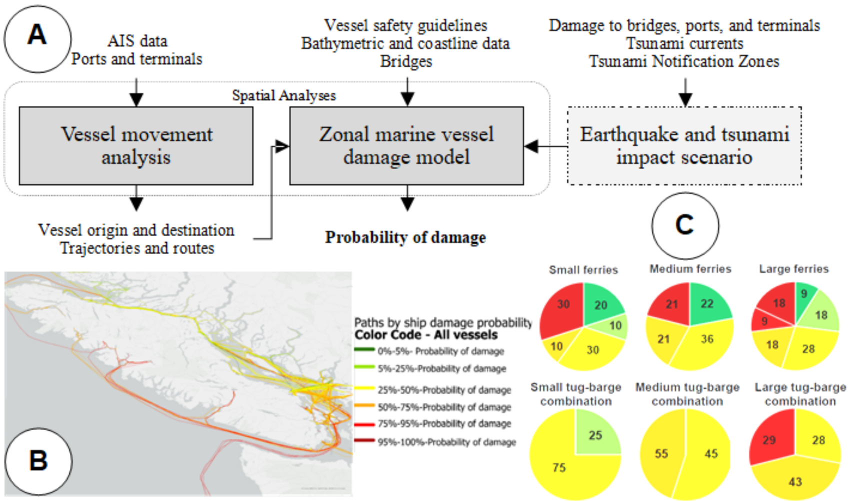

Figure 7: Schematic overview of the analysis process and results of damage to vessels operating to Vancouver Island due to a Cascadia subduction zone earthquake and tsunami; based on [26]

3.6. Marine route disruption model

In the multi-modal community supply model of Section 3.4, the operability of transportation routes, and the speeds at which the assets can traverse these, are important aspects. In the community supply model, this is represented as a time delay after which an edge becomes available (with t=0 the occurrence of the disaster), and a speed at which the transportation asset can transit that edge.

Given the importance of maritime assets as a mode of transportation to supply Vancouver Island with essential goods such as fuel, food, and medicine, a model is developed to estimate the operational delay following plausible earthquake scenarios, in which the possible occurrence of a tsunami is also considered. The model is developed as an expert-based Bayesian Network, with details given in [13]. The model accounts for contextual factors such as high-level characteristics of the earthquake (including the epicenter location, and the severity at the origin and destination of the shipping route), and the vessel type. The network further considers the damage to critical infrastructure on which maritime transport depends (including terminal, waterway, and communications infrastructure damage), and a series of operational considerations which influence decisions on operability of the vessel (including the need for completing a bathymetric survey, tsunami warning, restoration of communication systems, etc.). Finally, based on estimates of delays associated with these contextual factors, an overall probabilistic estimate is made for the delay of the operability on a given route.

Combining the information from the earthquake scenario in terms of earthquake severity (through the proxy variable ‘ground acceleration intensity’), an analysis of maritime routes based on data from the Automatic Identification System (AIS), results from the damage to critical infrastructures and operability of shipping terminals (see Figure 2), and a series of expert judgments, estimates of the route operability of various vessel types operating in the area are obtained. Indicative results of such an analysis are illustrated in Figure 8 for a Cascadia type earthquake as in Figure 1 (c). More details about the analysis can be found in [9] and [13].

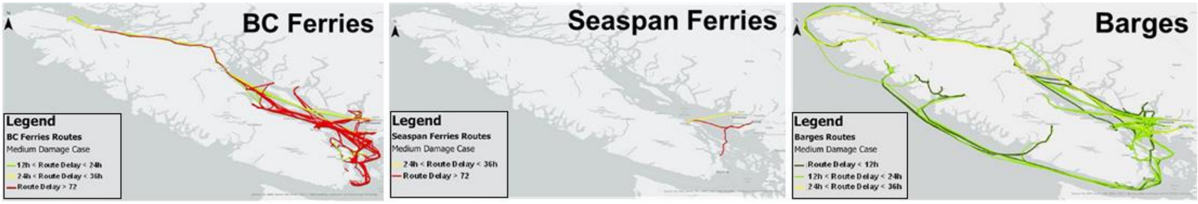

Figure 8: Illustrative output of the maritime route disruption model for a plausible M9.0 Cascadia subduction zone earthquake, applied to maritime shipping routes derived from AIS data; based on [9]

4. DISCUSSION

It is evident that future research and model refinement is desirable. Inspired by state-of-the-art reviews of models for road network repair [8, 32] and disaster logistics [4], the presented toolbox can be refined and extended in several areas. These include the characterization of the repair teams operation (e.g. availability of workforce and equipment over time, team expertise, productivity of multiple teams, multi-depot team location, etc.); the formulation of the objective(s) of the network restoration (e.g. time- or utility-based, or multiple objectives); the (dynamic) interdependence of the road network with other networks (e.g. critical infrastructure operability, logistics support systems, evacuations, etc.); the routing and delivery of relief supply assets (e.g. dynamic and adaptive vs static, fixed vs variable time window); scheduling of various disaster response activities (e.g. reconnaissance, resupply, and evacuation operations); uncertainty in demand; non-homogenous load and asset types; etc.

For handling uncertainty about the disaster scenario, the solution approaches for the deterministic models need to be investigated for a variety of network types, to ensure that accurate results are obtained computationally efficiently, thus enabling probabilistic analyses of vulnerabilities, risks, and mitigation measures associated with disaster impacts, and preparedness and response activities. Test instances need to be developed to facilitate this work, where both randomly generated networks as well as real-world case studies and associated datasets need to be compiled and made available [32]. Importantly, considering that natural disasters are often interdependent, models need to be developed to characterize plausible multi-hazard disaster conditions [12], along with models relating these disaster conditions with the impacts on multi-modal transportation infrastructures and assets, and communities. Finally, the presented models, once further developed along avenues outlined above, can be integrated to provide a holistic analysis of the impacts of natural disasters on multi-modal supply networks.

5. CONCLUSION

In this paper, the ongoing development of a risk modeling toolbox for multi-modal coastal community supply disruptions is outlined. The need for this development is positioned within a Canadian context and several outlined models are tailored to geographic, infrastructure, operational, and natural hazard conditions of Canadian regions prone to large-scale natural disasters with wide and severe regional impacts. Nevertheless, several models are generic and can be applied to any geographical area and for any natural disaster type, given a comparable multi-modal logistics setup and appropriate inputs.

After briefly describing the key types of natural disasters for which the models in the toolbox aim to provide insights, a high-level overview of the toolbox is given. Issues addressed include the scope and requirements for the toolbox; the risk management questions to which the models aim to provide insights; the model structure and key features, and their inputs and outputs. For some of the models, preliminary results are given as illustration of the kinds of results the models will deliver. Finally, a discussion is made on future research and development needs, to eventually obtain a more comprehensive toolbox to analyze the disruptions to multi-modal supply chains due to natural disasters.

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