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Modeling Multi Modal Supply Chain Vulnerability To Earthquakes: Case Study On Canada West Coast

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Abstract

Natural disasters such as earthquakes can cause extensive impacts on critical transportation infrastructure such as roads and bridges, railroads, and marine ports and terminals. In case these are rendered inaccessible or damaged, this can severely disrupt multi-modal supply chains, especially in the immediate aftermath of a large-scale disaster. While understanding supply chain vulnerabilities can inform disaster preparedness planning and supporting decisions on risk mitigation measures, the interdependent nature of humanitarian logistics operations makes this a complex risk problem. To support disaster risk management and related decision-making, this article outlines a model which synchronizes road clearing activities with multi-modal distribution of relief supplies, accounting for road, marine, and air assets. The model is based on earlier proposed problems, in particular the multi-vehicle prize collecting arc routing for connectivity problem (KPC-ARCP) and the multi-depot split delivery vehicle routing problem with time windows (MDSDVRP). A bi-level heuristic is applied to solve the problem. Apart from adumbrating the model and solution approach, the article presents abridged results of a case study on Canada's West Coast, illustrating the model's capabilities and applicability for disaster risk mitigation decision-making. A plausible Cascadia M9.0 Megathrust Earthquake scenario is considered in the area near Vancouver Island, British Columbia, which leads to regional impacts on roads and ports. A brief discussion on future research directions is given.

Keywords: natural hazards, multi-modal transportation, emergency preparedness, risk management, road clearing, maritime transportation

1. Introduction

Natural disasters are widely considered to be one of the most important global risks (World Economic Forum, 2020). They can lead to severe damage to critical infrastructures, commercial, industrial, and community facilities, as well as housing over large geographical areas, and often lead to significant loss of life and other negative impacts to human well-being and safety. Risk assessment has been recognized as an important process to obtain insights into hazards, vulnerabilities, and negative impacts, and to support disaster preparedness and mitigation decision making and risk management (Agrawal, 2018). In Canada, risk and vulnerability analysis are recognized as important tools for disaster risk management for instance by the Government of British Columbia (Government of British Columbia, 2016).

Following a natural disaster, multi-modal humanitarian operations are essential to evacuate victims, to support Search and Rescue activities, and for delivering essential goods and supplies to impacted communities. A growing academic field is dedicated to developing models and tools to support disaster preparedness and response planning. Key research themes include prepositioning of relief supplies and facility location, relief routing and delivery, and network restoration (Baxter et al., 2020, Souza Almeida et al. 2022a). In a Canadian context, work has been dedicated to understanding the impacts of natural disasters on communities (Chang and Tanner, 2022), disruptions and delays to regional road and maritime networks (Goerlandt and Islam, 2021, Souza Almeida et al. 2023), and restoration of road networks to port facilities (Souza Almeida et al. 2024a). Despite the significant progress made to develop models for road clearing activities to reconnect communities to supply depots, there has been little focus on combining such models with other operations in the immediate aftermath of a natural disaster, such as supply distribution models for humanitarian logistics (Souza Almeida et al. 2022a).

Given this, a first aim of this article is to outline a new model which synchronizes the activities of road clearing teams working out of one depot, with the multi-modal distribution of supplies using marine, road, and air assets. The model integrates and synchronizes previously proposed problems, namely the multi-vehicle prize collecting arc routing for connectivity problem (KPC-ARCP) (Akbari and Salman, 2017) and a version of the multi-depot split delivery vehicle routing problem with time windows (MDSDVRP) (Lim, 2007). It is tailored to the specific geographical area of Vancouver Island, British Columbia, where in normal transport operations supplies originate from a mainland area and are transported via vessels to ports or terminals on an island, from where trucks distribute goods by road to affected communities. The second and main aim of this article is to illustrate the capability of this model to provide insights into the vulnerability of the multi-modal supply chain in the case of an large-scale earthquake impact, to support disaster preparedness risk management. Section II briefly outlines the methods and data. Section III presents selected results. A brief discussion is provided in Section IV, which also concludes the article.

2. Methods and data

2.1. Model overview

The problem addressed in the model is represented in Figure 1, and briefly outlined next. The multi-modal distribution is situated between a mainland ("land α") and island ("land β") area. Marine transport occurs with a heterogenous fleet consisting of Ro-Ro ferries and barges (which can load varying numbers of trucks, and operate at specific speeds), where the former can dock in designated port terminals to unload the trucks, and the latter can do so directly in coastal communities. Due to the impacts of an earthquake, some vessel routes may be rendered inoperable or experience delays, e.g. for reasons related to ensuring navigational safety. A fleet of trucks, uniform in terms of loading capacity and speed, is transported by these vessels from ports of origin on land α to available ports on land β, noting that some ports may be rendered inoperable due to earthquake impacts. Helicopters, also assumed to have uniform characteristics in terms of loading capacity and speed, originate from land α and can land directly in any community on land β.

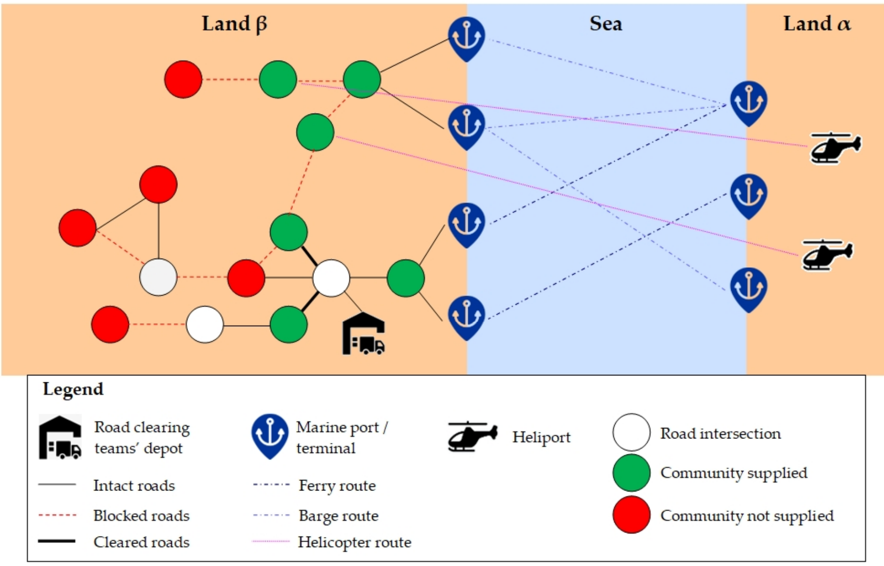

Fig. 1. Problem for synchronizing the multi-modal distribution of relief supplies with road clearing activities.

After being offloaded in one of the destination ports, trucks proceed using the presently available route network to deliver goods to affected communities, which can be prioritized based on their resilience level and demand level (which is assumed to be proportional to the population size). A split delivery is considered, i.e. multiple trucks may be needed to meet a community's demand, and the logistics operations are limited by a time horizon within which the deliveries must be completed. This is achieved by implementing a version of the multi-depot split delivery vehicle routing problem with time windows (MDSDVRP) (Lim, 2007). An unlimited number of trucks is assumed to be available on land α, and after these are transported by vessels to land β and have completed their delivery to communities on land β, trucks do not return to the port to load more goods. In contrast, maritime assets, after unloading trucks in the destination port, can return to their port of origin to resupply, if this operation can be completed within the time horizon. Helicopters can similarly return to their base on land α to resupply, and return to supply affected communities within the time horizon.

Given that, due to the earthquake impacts, several roads may be damaged or rendered inaccessible, there is a need for clearing these roads before they can be used by trucks. In the current model implementation, this is achieved by one or more road clearing teams, assumed to be homogenous, and which start from one depot. The objective of the teams is to reconnect clusters of isolated communities, i.e. those which due to the earthquake impacts on the road network no longer are accessible by land from ports and hence cannot receive supplies from these main maritime supply hubs. Road clearing teams prioritize clusters of communities with lower resilience levels, as these are more dependent on outside assistance for their supply of essential relief goods. To address the road clearing problem and reconnect communities to ports, the model incorporates the multi-vehicle prize collecting arc routing for connectivity problem (KPC-ARCP) (Akbari and Salman, 2017), which is illustrated in Figure 2. Figure 2(i) illustrates the situation before the disaster, whereas Figure 2(ii) shows the situation following the earthquake, leading to several roads being blocked. In the KPC-ARCP, the isolated communities are then grouped into clusters as shown in Figure 2(iii), which are given a relative 'prize' for reconnecting these to the road clearing depot. The KPC-ARCP results in a list of roads unblocked by the clearing teams, and the time since the start of the operations when the roads again become accessible for road transport.

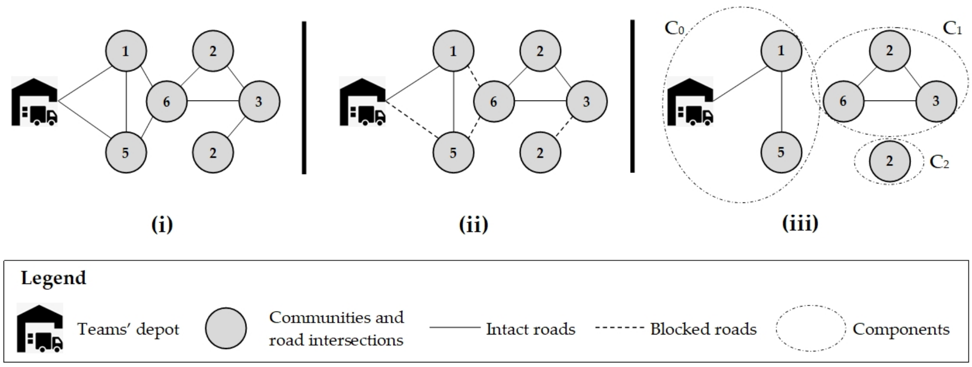

Fig. 2. Representation of the Multi-vehicle prize collecting arc routing for connectivity problem (KPC-ARCP).

The routing and scheduling of trucks is synchronized with the operations of the road clearing teams, so that trucks can only access roads which have been previously cleared by one of the road clearing teams. Furthermore, the logistics operations between vessels, trucks, and helicopters are synchronized, such that goods are delivered to communities by trucks only after these arrive at a port or terminal. The model implements this synchronization practically by first solving the road clearing problem on land β, i.e. it determines which roads can be made accessible by the clearing teams within the given time horizon. Thereafter, communities are clustered to their closest ports. The vessels serving each port are then clustered, and it is determined how many trucks can reach each port and unload goods within the time horizon, where vessels may make return trips to their origin port if they can do so within the time window. Subsequently, the algorithm implementing the multi-depot split delivery vehicle routing problem with time windows is applied, and the delivery of supplies to communities is performed, accounting for their priority (in terms of their demand and resilience level). Details about this procedure are provided in Souza Almeida et al. (2024b).

A high-level overview of the logic of the complete model to synchronize the multi-modal distribution of relief supplies to communities with road clearing activities to remove debris on roads impacted by an earthquake, is given in Figure 3, with further explanation of inputs and outputs in Table 1. The figure shows that inputs are first given to the road clearing model, which is solved first. Its results are used to update the availability of the road network at various time instances, indicated as (A) in Figure 3. Subsequently, the routes and schedules of ferries and barges are determined based on the clusters of communities and the ports these serve (B), accounting for the operational delays of vessel routes as appropriate. Vessel routes are determined sequentially, with the vessels with largest carrying capacity accounted for first. The results of this step (C) provide information about how many trucks can reach each port within the given time window, and at what times these arrive. Together with the road network information (A), this information is used to address the vehicle routing problem, where the ports are considered depots from which trucks deliver goods to affected communities within the predetermined time horizon, prioritizing communities with high demand and low resilience. Finally, the routes and schedules of helicopters are determined (D), so that communities which have not yet received their supply demand through vessels or trucks at the end of the time horizon receive relief supplies by air.

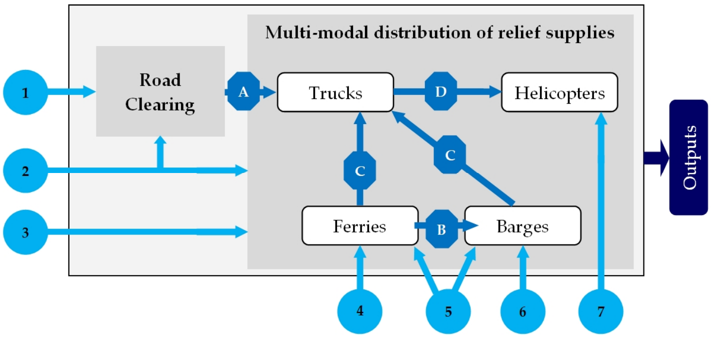

Fig. 3. Overview of model synchronizing the multi-modal distribution of relief supplies with road clearing activities, for explanation of number and letter symbols, see Table 1.

Table 1. Inputs, internal model information, and outputs associated with model of Figure 3.

Input		**Internal model information**		**Output**
Nr	*Explanation*	*ID*	*Explanation*	
1	Roads unblocking times	A	Road clearing schedule	Road clearing schedules and routes
	Roads state		Road clearing routes	Ferries schedules and routes
2	Communities resilience level	B	Ports and communities not supplied	Barges schedules and routes
3	Communities demand		by ferries	Trucks schedules and routes
4	Ferries operations delay	C	Supplies available per port	Helicopters schedules and routes
	Ferries capacity and speed	D	Communities not supplied by	Communities supplied
			trucks, ferries, or barges	
5	Ports/terminals list			% demand supplied using each transportation mode
	Communities list			
6	Barges operations delay			
	Barges capacity and speed			
7	Helicopters capacity and speed			

As shown in Table 1, through its construction, apart from providing insights into the system's capability to deliver goods to affected communities, the model also provides insights into the road clearing routes and schedules, routes and schedules of trucks, marine vessels, and helicopters, and the relative share of goods delivered to communities by different transportation modes. It is a deterministic model taking inputs for a specific natural disaster scenario, described by supply demands by communities and their resilience levels, the impacts to the road network in terms of the duration of clearing different road segments, and the delays of ferries and barges on different marine routes.

2.2. Solution approach

The model outlined in Section 2.1 is solved using a bi-level metaheuristic approach. As shown in Figure 3, the KPC-ARCP is solved first. The literature contains several solution approaches for this problem, including a matheuristic (Akbari and Salman, 2017), an Ant Colony Optimization (ACO) approach (Souza Almeida and Goerlandt, 2022), and a Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic (Souza Almeida et al. 2022b). GRASP is selected as it is the only one which can efficiently solve large network instances as in the case study of Section 2.3. Furthermore, it can provide accurate results compared to other solution approaches (Souza Almeida and Goerlandt, 2022). The reader is referred to Souza Almeida et al. (2022b) for details about the algorithm applied in this implementation.

The routes and schedules of ferries, barges, trucks, and helicopters are sequentially determined using a GRASP metaheuristic approach. The objective of this optimization problem is to maximize the volume of goods delivered to ports (for ferries and barges) or communities (for trucks and helicopters). For details about these procedures, the reader is referred to Souza Almeida et al. (2024b).

2.3. Case study: Cascadia M9.0 Subduction Zone Megathrust earthquake impacts

Earthquakes occur relatively frequently in British Columbia. These mostly have a relatively low intensity, but evidence suggests that a large-scale earthquake at the Cascadia subduction interface can lead to very high ground accelerations in a wide region, likely leading to extremely large-scale impacts (Cassidy et al., 2010). The scenario considered in this case study is a plausible Cascadia subduction zone M9.0 earthquake. Such a disaster would highly impact western and southern communities on Vancouver Island, and lead to medium impacts on other coastal and island communities. Critical infrastructures would be severely disrupted, and communities in these areas would be heavily dependent on external support for supply of essential goods. Figure 4 presents selected impacts from the plausible Cascadia M9.0 earthquake scenario, with further details given in Souza Almeida et al. (2023).

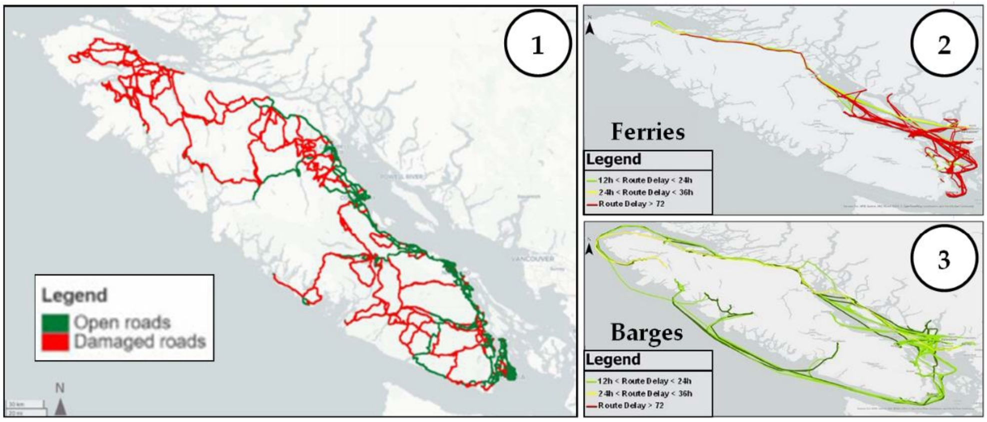

Fig. 4. Impacts of a plausible Cascadia subduction zone M9.0 earthquake: (1) passability of roads, (2) expected delays on ferry routes, (3) expected delays on barge routes; based on Souza Almeida et al. (2023).

In the baseline scenario, the demand is proportional to the communities' population size, and is based on a demand for one week of supplies. The road clearing depot is in the Nanaimo port staging area. Four clearing teams and four helicopters are available. All ferries and barges which normally operate between mainland British Columbia and Vancouver Island are considered to be available. These only operate on their normal routes as identified in Souza Almeida et al. (2023), i.e. there is no rerouting if ports are inoperable or if marine routes experience high delays. Table 2 contains further information about key parameters for the baseline scenario. A time horizon of 72 h is considered.

Table 2. Information about key model parameters in the M9.0 Cascadia subduction zone earthquake scenario.

Parameter	Value	Parameter	Value
Road clearing team traversing speed	50 km/h	Barge loading time	3 h
Truck traversing speed	50 km/h	Barge unloading time	3 h
Truck unloading time	2 h	Barge and ferry traversing speed	see (†)
Ferry loading time	2 h	Helicopter traversing speed	180 km/h
Ferry unloading time	2 h	Helicopter loading time	3 h
Ferry and barge capacity	see (†)	Helicopter unloading time	3 h

Note: (†) Souza Almeida et al. (2023)

2.4. Disaster scenario variations

To obtain insights into possible decisions made by emergency planners, representing measures to mitigate supply chain disruption risks, a selected number of variations of the baseline scenario are considered and applied to the synchronized model for multi-modal distribution of relief supplies and road clearing. These are outlined in Table 3, and consider decisions such as rerouting vessels, increasing the number of barges, prioritization of communities based on their resilience level, changing the location of the clearing teams' depot, and increasing the number of clearing teams. In all variations, all other conditions are as in the baseline scenario outlined in Section 2.3.

Table 3. Variations of baseline disaster scenario, representing different mitigation measures.

Identifier	Explanation of represented mitigation measure
M1	All available ferries and barges are rerouted to open ports if terminal configuration and capacity allows, minimizing delivery time.
M2	The number of barges is doubled, but all vessels operate only on their normal routes.
C	The community resilience scale is used to prioritize supplies to less resilient communities.
R1	Road clearing operations start from the Victoria airport staging area.
R2	The number of road clearing teams is doubled.

3. Results

Selected results of applying the model which synchronizes the multi-modal distribution of relief supplies with road clearing activities to the baseline M9.0 Cascadia subduction zone earthquake scenario, described in Section 2, are presented in Table 4 and Figure 5.

Table 4. Community supply/demand ratio by region of Vancouver Island and nearby islands, see Souza Almeida et al. (2023) for definition.

Region	Supplies delivered relative to community demands [%]				
	Ferries	Barges	Marine + truck	Helicopter	Total
North Island	0	0	18	14	32
Pacific Coast	0	19	20	3	42
Central Island	0	2	44	2	48
South Island	0	0	7	2	9
Sunshine Coast Island	73	0	0	27	100
Gulf Island	73	0	0	13	86

It is observed from the results that in the immediate response phase, i.e. in the first 72 hours after the earthquake, ferries are not very useful to resupply the island, so that barges have to be relied on to deliver supplies, with especially the Pacific Coast area heavily dependent on barges. The road clearing teams successfully reconnect various parts of the island, and trucks take routes in the central parts of Vancouver Island, and to the north of the island to deliver supplies. However, due to the remaining inaccessibility of areas within the time horizon, not all communities receive supplies, especially in the in the south and far north of Vancouver Island.

Table 5 shows the results of the model application to different variations of the scenario, representing different mitigation measures. It is seen that by rerouting maritime assets and by increasing the number of available barges, Vancouver Island can be much better resupplied. Prioritizing less resilient communities redistributes supplies more towards the Pacific Coast and South Island, which are more severely impacted. Significant effects can also be obtained by relocating the clearing teams, and by increasing their number.

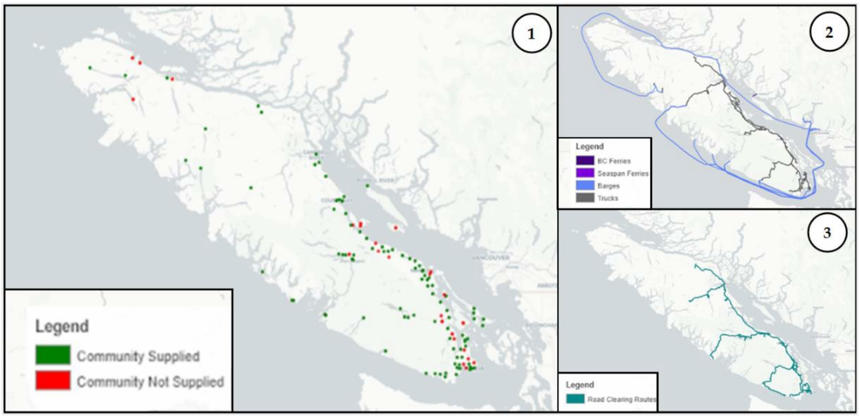

Fig. 5. Model results for a plausible Cascadia subduction zone M9.0 earthquake, baseline case: (1) communities supplied and not supplied, (2) routes by ferries, barges, and trucks, (3) routes by road clearing teams.

Table 5. Community supply/demand ratio for different scenario variations, see Table 3 for definitions.

Region	**Supplies delivered relative to community demands [%]**					
	Baseline	M1	M2	C	R1	R2
North Island	32	9	6	26	43	50
Pacific Coast	42	52	87	88	100	97
Central Island	48	22	50	57	28	84
South Island	9	20	62	21	36	50
Sunshine Coast Islands	100	73	79	100	73	100
Gulf Islands	86	25	6	83	87	100

4. Discussion and conclusion

This article has outlined a modeling approach to provide insights into the capability of the multi-modal transportation system to deliver goods to communities in the immediate disaster response phase, i.e. to provide insights into vulnerabilities associated with supply chain disruption. The model is set within a disaster preparedness and mitigation context, focusing on the impacts of the earthquake to the multi-modal transportation system. The model is not intended to be used predictively but as a basis for a reflective discourse between emergency managers and stakeholders to support disaster risk management. Such model use aligns well with recommended analytical-deliberative approaches for risk governance, actively engaging stakeholders (IRGC, 2017).

The model has several important simplifications: it only allows for one road clearing depot, offers little flexibility in adapting the maritime transportation to different routes, presupposes that the damage extent of roads and maritime routes is known a priori, and is fully deterministic. No explicit consideration is given to uncertainty treatment, even though this is considered essential in contemporary risk perspectives (Goerlandt and Reniers, 2018), especially because several aspects of the data underlying the earthquake scenario are relatively weakly evidenced (Souza Almeida et al. 2023). Future research directions hence can be directed to alleviate the above limitations and shortcomings. Additional work to develop a more user-friendly decision support tool to support the analysis, and to develop approaches to optimize the system response effectiveness depending on risk mitigation measures, is also recommended.

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