A Formulation And Solution Procedure For Optimal Evacuation Planning And Routing For Isolated Communities (ICEP)

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Introduction

General problem:

- Vulnerability to natural disasters
- No permanent/reliable road connection
- Limited possibility for self-evacuation
- Dependency on coordinated fleet of external resources
- Time sensitive
- Large set of potential approaches
- Uncertainty over affected population

Cases like this:

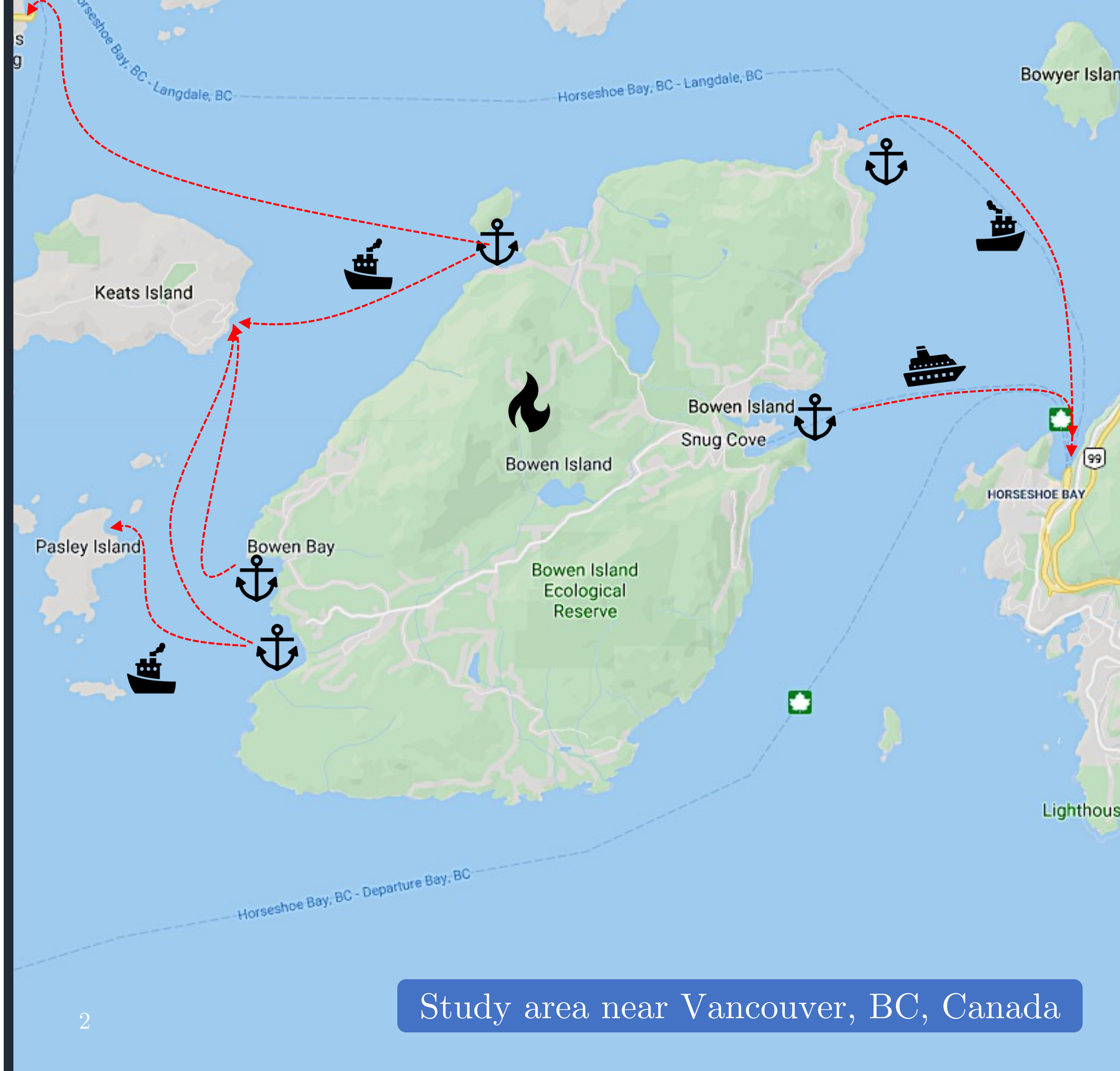
- 9 in Washington State alone
- 77 in the United States (not including isolated areas in Alaska)
- ~10,000 around the world

Currently no established evacuation procedure

Research Questions:

- How to find an optimal evacuation procedure?
- What resources are needed?

Source of map: Google, Inc., 2020



Study area near Vancouver, BC, Canada

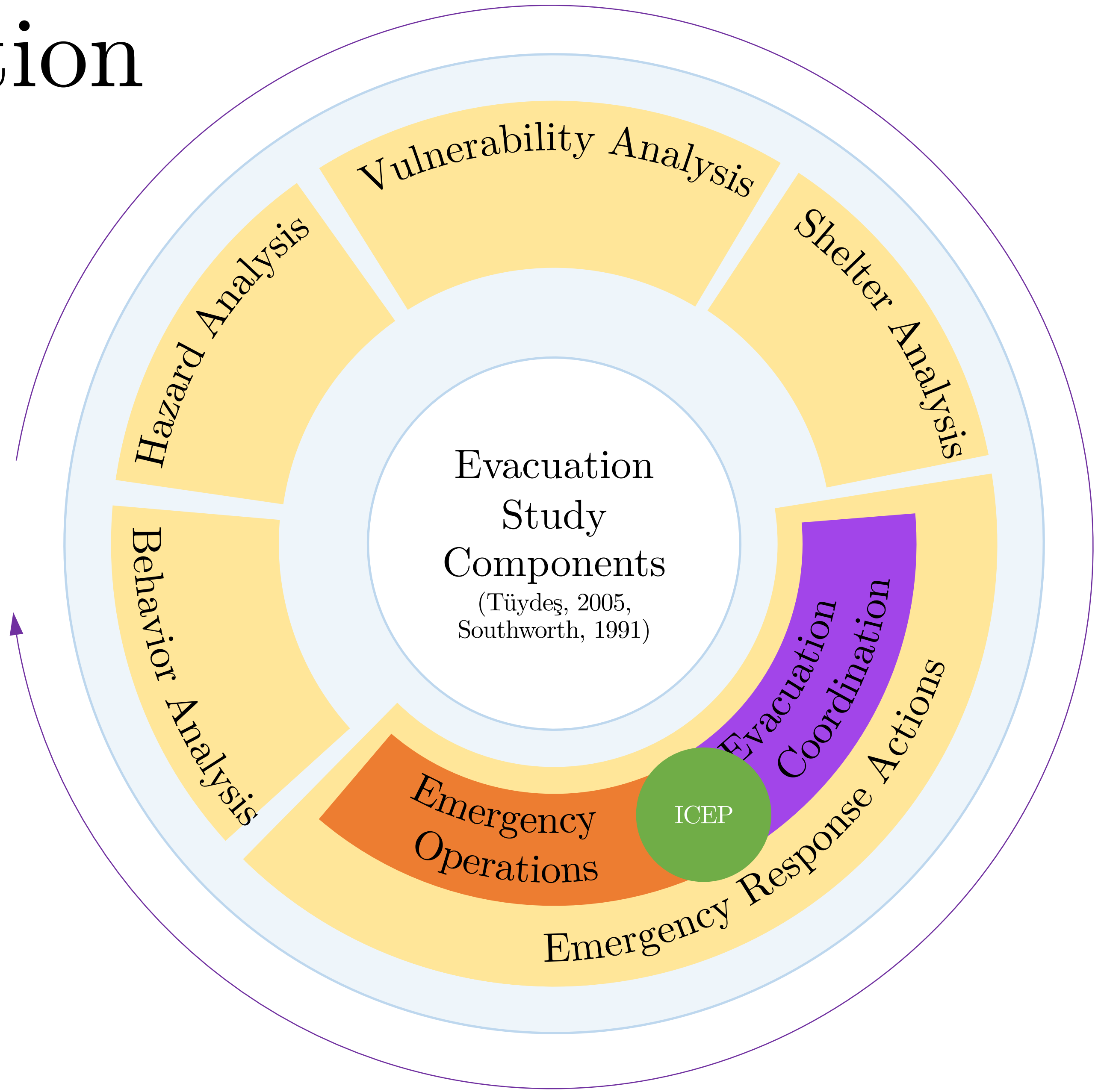
General Evacuation Framework

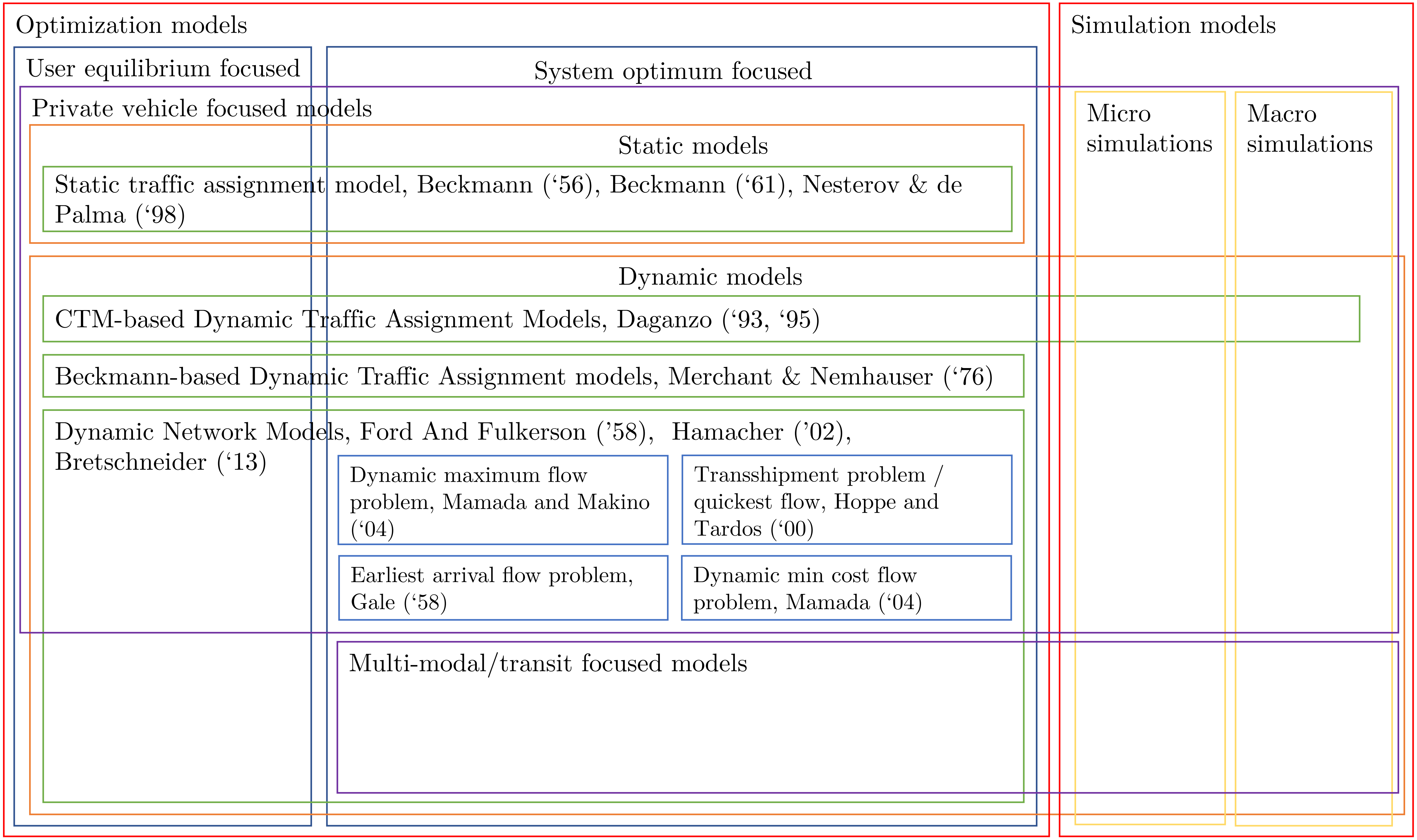
Isolated Community Evacuation Problem (ICEP)

ICEP falls into Evacuation Coordination and Emergency Operations stage

Considered modeling approaches:

- VRP with time windows (Scharge, 1981)
- Multi-modal evacuation VRP
- Bus Evacuation Problem (Bish, 2011)





Optimization models
User equilibrium focused
System optimum focused
Simulation models
Private vehicle focused models
Micro simulations
Macro simulations
Static models
Static traffic assignment model, Beckmann (‘56), Beckmann (‘61), Nesterov & de Palma (‘98)
Dynamic models
CTM-based Dynamic Traffic Assignment Models, Daganzo (‘93, ‘95)
Beckmann-based Dynamic Traffic Assignment models, Merchant & Nemhauser (‘76)
Dynamic Network Models, Ford And Fulkerson (’58), Hamacher (’02), Bretschneider (‘13)
Dynamic maximum flow problem, Mamada and Makino (‘04)
Transshipment problem / quickest flow, Hoppe and Tardos (‘00)
Earliest arrival flow problem, Gale (‘58)
Dynamic min cost flow problem, Mamada (‘04)
Multi-modal/transit focused models

Multimodal / transit focused optimization models

An, et al.: Location planning for transit-based evacuation under the risk of service disruptions (2013)

Rui, et al.: Optimum transit operations during the emergency evacuations (2009)

Abdelgawad and Abdulhai: Managing large-scale multimodal emergency evacuation (2010)

Abdelgawad et al.: Optimizing mass transit utilization in emergency evacuation of congested urban areas (2010)

Goerigk et al.: Combining bus evacuation with location decision: A branch-and-price approach (2014)

Bish: Planning for a bus-based evacuation (2011)

Kulshrestha et al.: Pick-up locations and bus allocation for transit-based evacuation planning with demand uncertainty (2014)

Goerigk et al.: Branch and bound algorithms for the bus evacuation problem (2013)

Goerigk et al.: Branch and bound algorithms for the bus evacuation problem (2013)

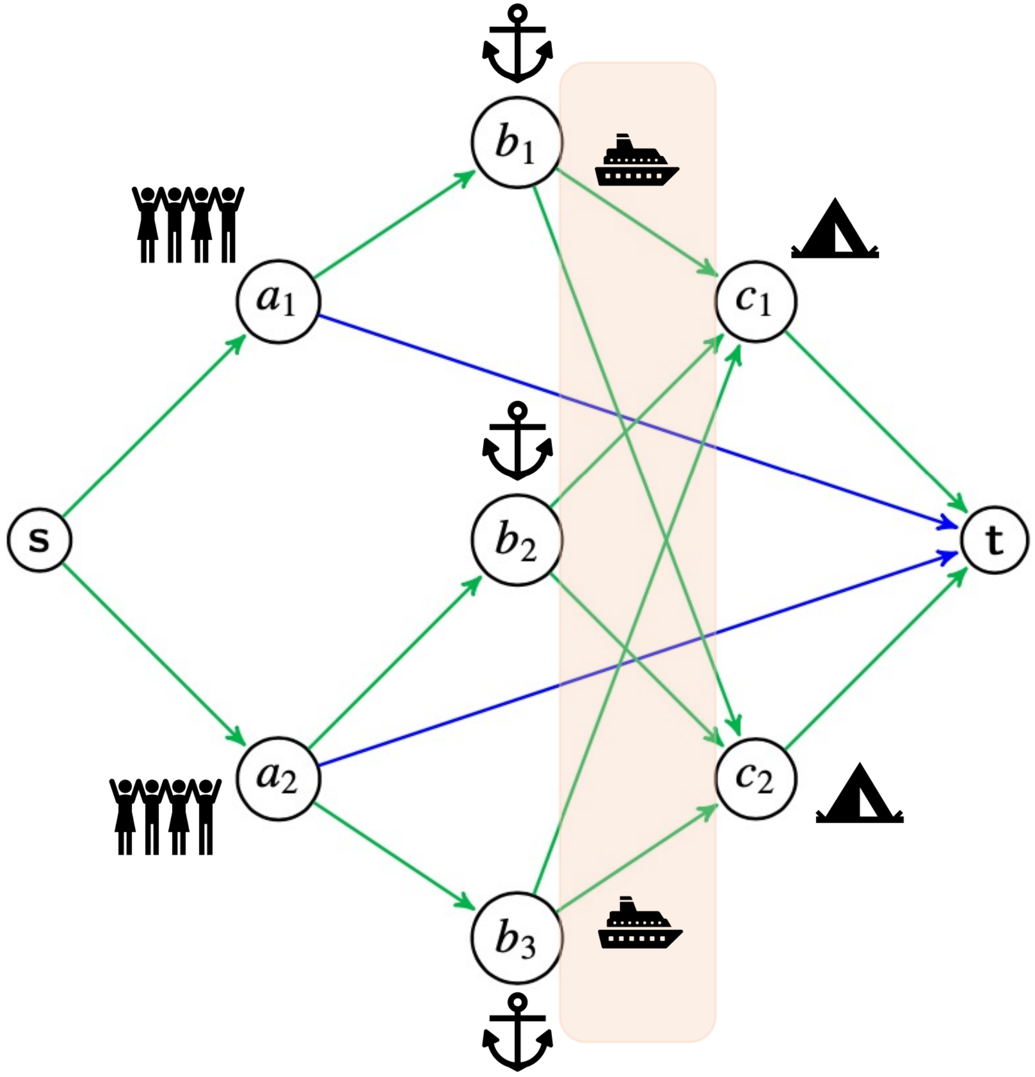
Goerigk et al.: A comprehensive evacuation planning model and genetic solution algorithm (2014)

Goerigk and Gruen: A robust bus evacuation model with delayed scenario information (2014)

Goerigk et al.: A two-stage robustness approach to evacuation planning with buses (2015)

Zheng: Optimization of bus routing strategies for evacuation (2014)

Network flow problem

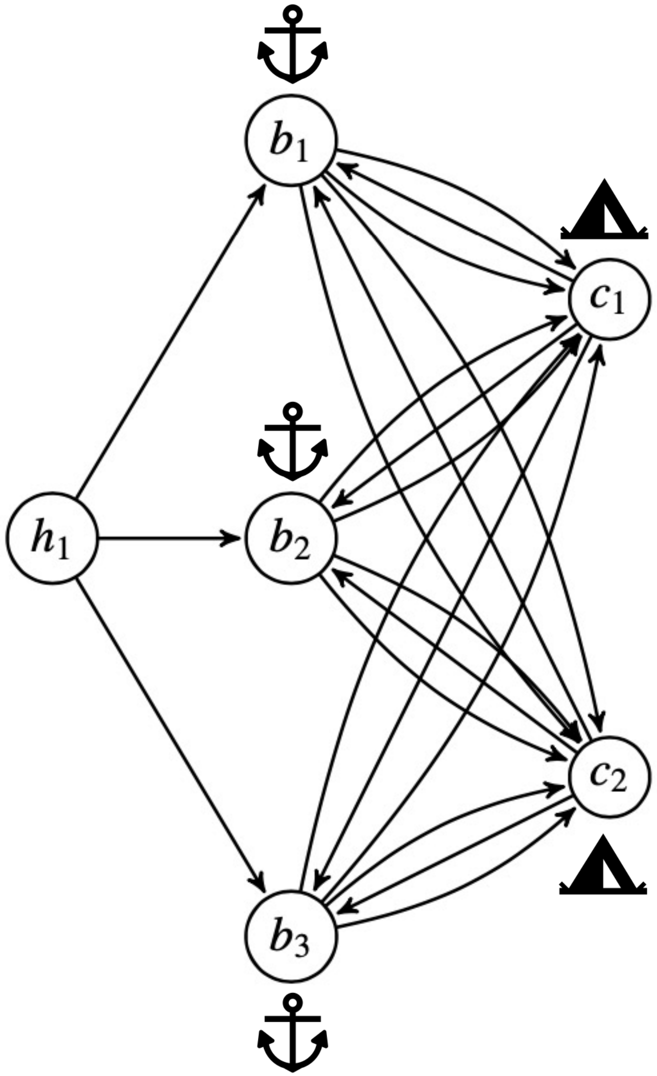


Evacuation area
Pick-up location (dock)
Drop-off location (shelter)
Evacuation resource

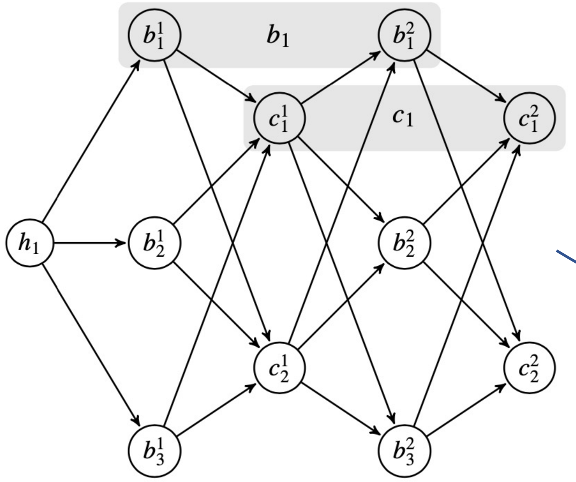
Non-linear
Multiple tours
Heterogeneous fleet

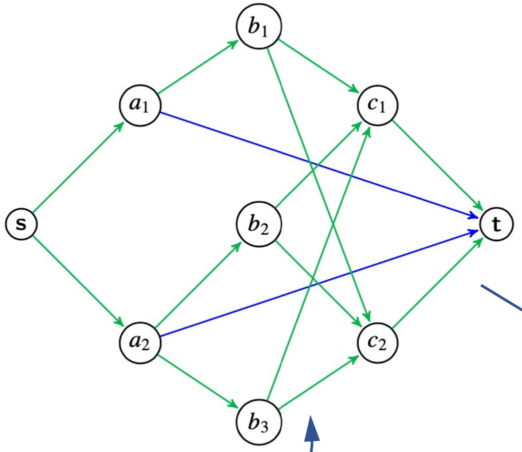
Routing problem

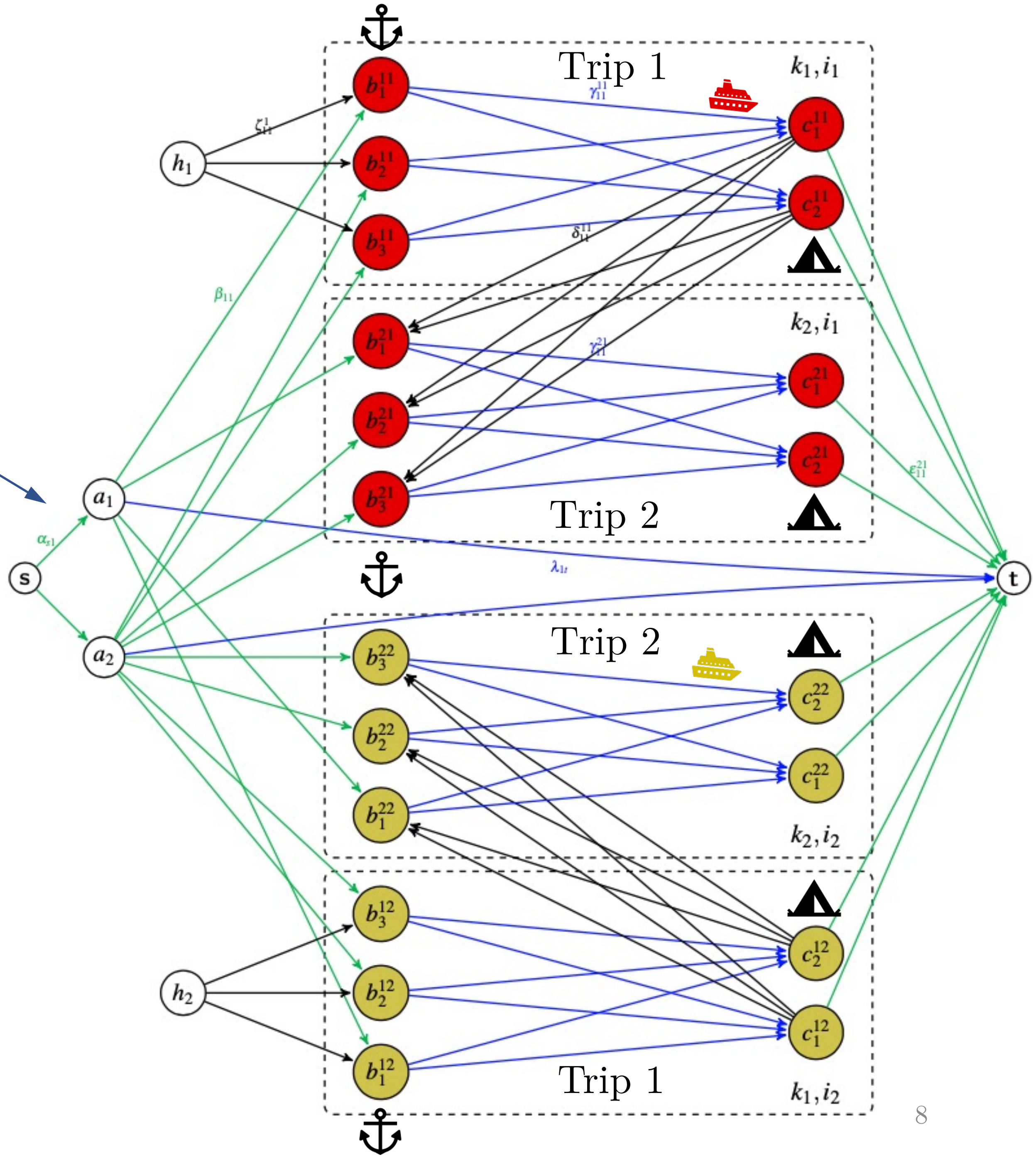
Evacuation area
Pick-up location (dock)
Drop-off location
Evacuation resource



Deterministic ICEP (D-ICEP)







Evacuation area

Pick-up location (dock)

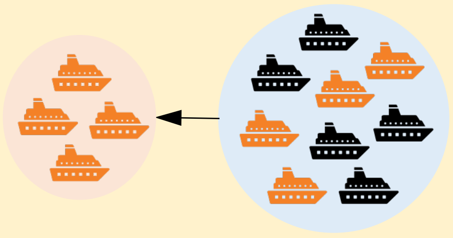
Drop-off location

Evacuation resource 1

Evacuation resource 2

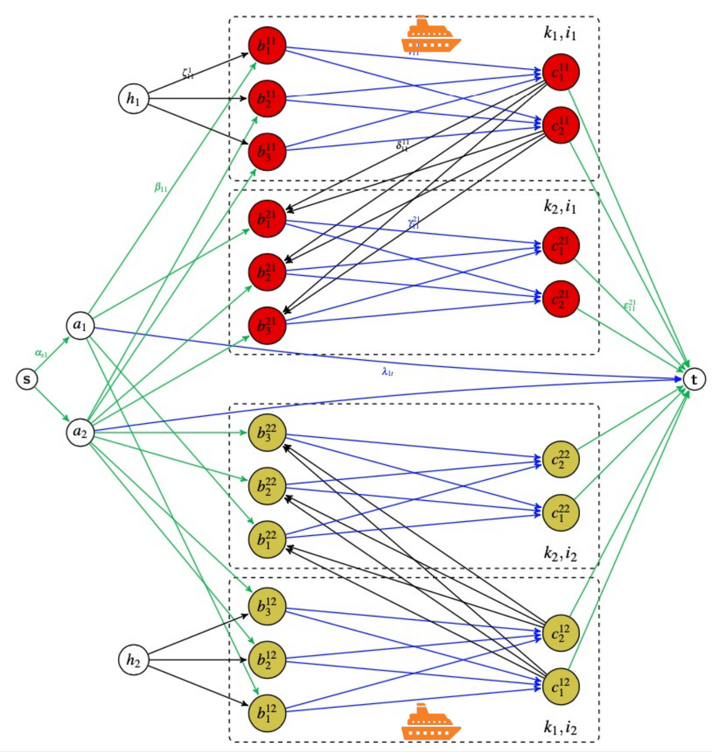
Stochastic two-stage ICEP formulation (S-ICEP)

Incorporate uncertainty for two-stage structure with scenarios



Determine scenario independent evacuation fleet based on expected cost and evacuation time

For each scenario, use pre-determined evacuation fleet to find shortest evacuation plan



Stochastic two-stage ICEP formulation (S-ICEP)

First stage problem

$$\min \quad \sum_{i \in I} cfix_i z_i + \mathbb{E}[C(z, \xi)] \tag{1}$$

$$s.t. \quad C(z, \xi) = \left(comp(\xi) + \frac{1}{K} \left(\sum_{i \in I} cvar_i S_i(\xi) \right) + P \left(\sum_{a \in A} fl_{an}(\xi) \right) \right) \quad \forall \xi \in \Xi \tag{2}$$

$$z_i \in \{0, 1\} \quad \forall i \in I \tag{3}$$

Stochastic two-stage ICEP formulation (S-ICEP)

Second stage problem

$$\min \quad comp + \frac{1}{K}\left(\sum_{i\in I} cvar_i S_i\right) + P\left(\sum_{a\in A} fl_{an}\right) \tag{4}$$

$s.t.$ **Time constraints**

$$t_{hb}^{ki}\left(\sum_{\zeta_{hb}^{ki}\in Z} w_{hb}^{ki}\right) + t_{bc}^{ki}\left(\sum_{\gamma_{bc}^{ki}\in\Gamma} x_{bc}^{ki}\right) + t_{cb}^{ki}\left(\sum_{\delta_{cb}^{ki}\in\Delta} y_{cb}^{ki}\right) +$$

$$t_{h}^{ki}\left(\sum_{\zeta_{hb}^{ki}\in Z} w_{hb}^{ki}\right) + t_{b}^{ki}\left(\sum_{\zeta_{hb}^{ki}\in Z} w_{hb}^{ki} + \sum_{\delta_{cb}^{ki}\in\Delta} y_{cb}^{ki}\right) + t_{c}^{ki}\left(\sum_{\gamma_{bc}^{ki}\in\Gamma} x_{bc}^{ki}\right) = S_i \quad \forall i\in I \tag{5}$$

$$S_i \leq comp \quad \forall i \in I \tag{6}$$

$$comp \leq T \tag{7}$$

Stochastic two-stage ICEP formulation (S-ICEP)

Capacity constraints

$$fl_{at} \leq cap_{at} \quad \forall \lambda_{at} \in \Lambda \tag{8}$$

$$fl_{bc}^{ki} \leq cap_{bc}^{ki}(x_{bc}^{ki}) \quad \forall \gamma_{bc}^{ki} \in \Gamma \tag{9}$$

$$fl_{bc}^{ki} \leq cap_{bc}^{ki}(z_i) \quad \forall \gamma_{bc}^{ki} \in \Gamma \tag{10}$$

Flow conservation constraints

$$fl_{sa} = fl_{at} + \sum_{b^{ki} \in B} fl_{ab}^{ki} + fl_{an} \quad \forall a \in A \tag{11}$$

$$\sum_{a \in A} fl_{ab}^{ki} = \sum_{c^{ki} \in C} fl_{bc}^{ki} \quad \forall b^{ki} \in B \tag{12}$$

$$\sum_{b^{ki} \in B} fl_{bc}^{ki} = fl_{ct}^{ki} \quad \forall c^{ki} \in C \tag{13}$$

Stochastic two-stage ICEP formulation (S-ICEP)

Select at most one connection per segment

$$\sum_{\zeta_{hb}^{ki} \in Z} w_{hb}^{ki} \leq z_i \quad \forall i \in I, \{k = 1\} \tag{14}$$

$$\sum_{\zeta_{hb}^{ki} \in Z} w_{hb}^{ki} = 0 \quad \forall i \in I, \forall k \in K \setminus \{k = 1\} \tag{15}$$

$$\sum_{\gamma_{bc}^{ki} \in \Gamma} x_{bc}^{ki} \leq z_i \quad \forall i \in I, k \in K \tag{16}$$

$$\sum_{\delta_{cb}^{ki} \in \Delta} y_{cb}^{ki} \leq z_i \quad \forall i \in I, k \in K \setminus \{k = K\} \tag{17}$$

$$\sum_{\delta_{cb}^{ki} \in \Delta} y_{cb}^{ki} = 0 \quad \forall i \in I, \{k = K\} \tag{18}$$

Stochastic two-stage ICEP formulation (S-ICEP)

Route adjacency constraints

$$\sum_{h \in H} w_{hb}^{ki} = \sum_{c^{ki} \in C} x_{bc}^{ki} \quad \forall b^{ki} \in B : \{k = 1\} \tag{19}$$

$$\sum_{c^{ki} \in C} y_{cb}^{(k-1)i} = \sum_{c^{ki} \in C} x_{bc}^{ki} \quad \forall b^{ki} \in B, k \in K, \setminus \{k = 1\} \tag{20}$$

$$\sum_{b^{ki} \in B} x_{bc}^{ki} \geq \sum_{b^{ki} \in C} y_{cb}^{ki} \quad \forall c^{ki} \in C, k \in K \tag{21}$$

Stochastic two-stage ICEP formulation (S-ICEP)

Variable definitions

$$fl_{at} \geq 0 \quad \forall \lambda_{at} \in A \tag{22}$$

$$fl_{ab} \geq 0 \quad \forall \beta_{ab} \in B \tag{23}$$

$$fl_{an} \geq 0 \quad \forall b^{ki} \in B \tag{24}$$

$$fl^{ki}_{bc} \geq 0 \quad \forall \gamma^{ki}_{bc} \in \Gamma \tag{25}$$

$$fl^{ki}_{ct} \geq 0 \quad \forall \varepsilon^{ki}_{ct} \in E \tag{26}$$

$$comp \geq 0 \tag{27}$$

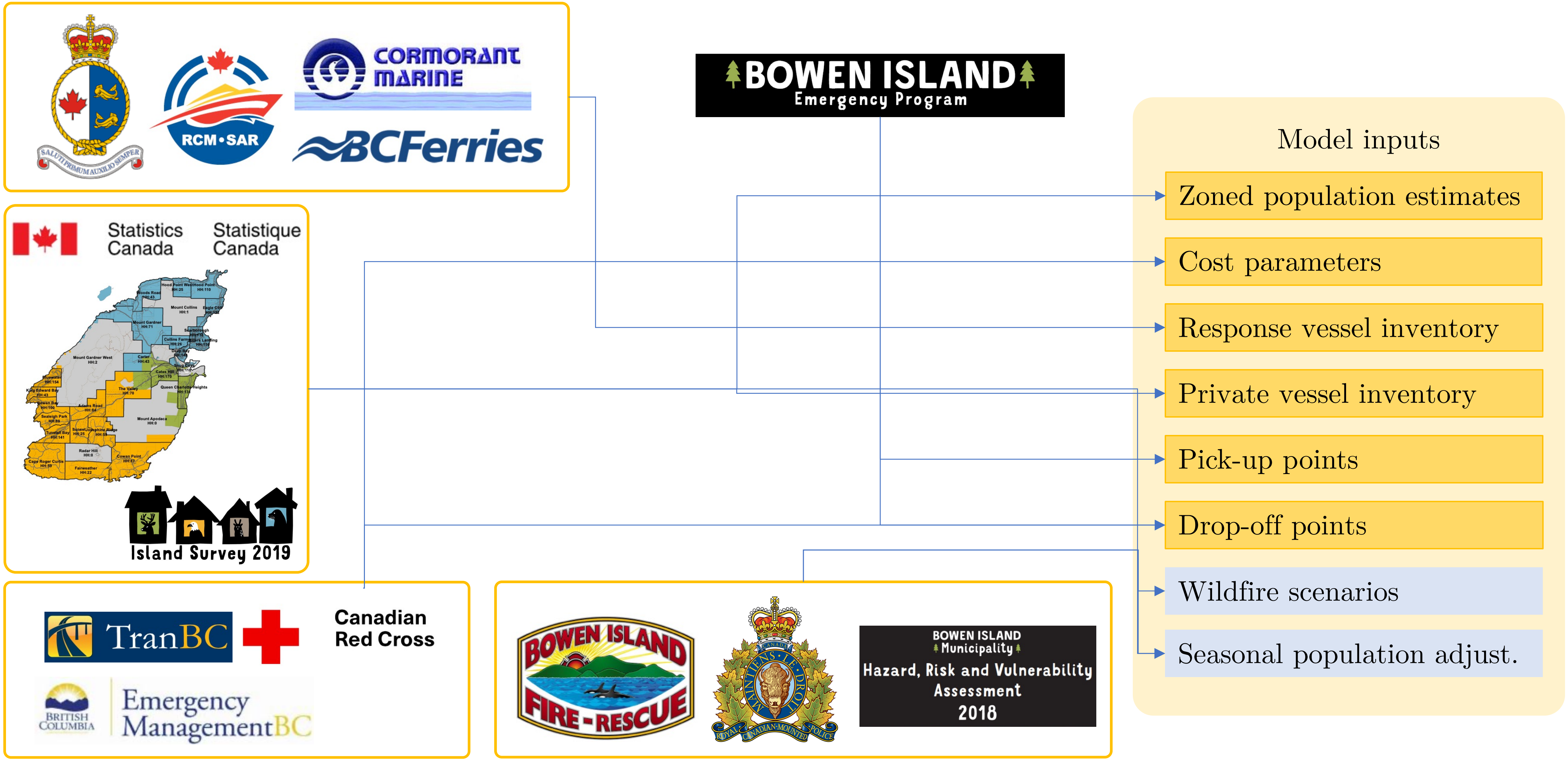
$$S_i \geq 0 \quad \forall i \in I \tag{28}$$

$$w^{ki}_{hb} \in \{0,1\} \quad \forall \zeta^{ki}_{hb} \in Z \tag{29}$$

$$x^{ki}_{bc} \in \{0,1\} \quad \forall \gamma^{ki}_{bc} \in \Gamma \tag{30}$$

$$y^{ki}_{cb} \in \{0,1\} \quad \forall \delta^{ki}_{cb} \in \Delta \tag{31}$$

Case Study – Data – Bowen Island, Canada



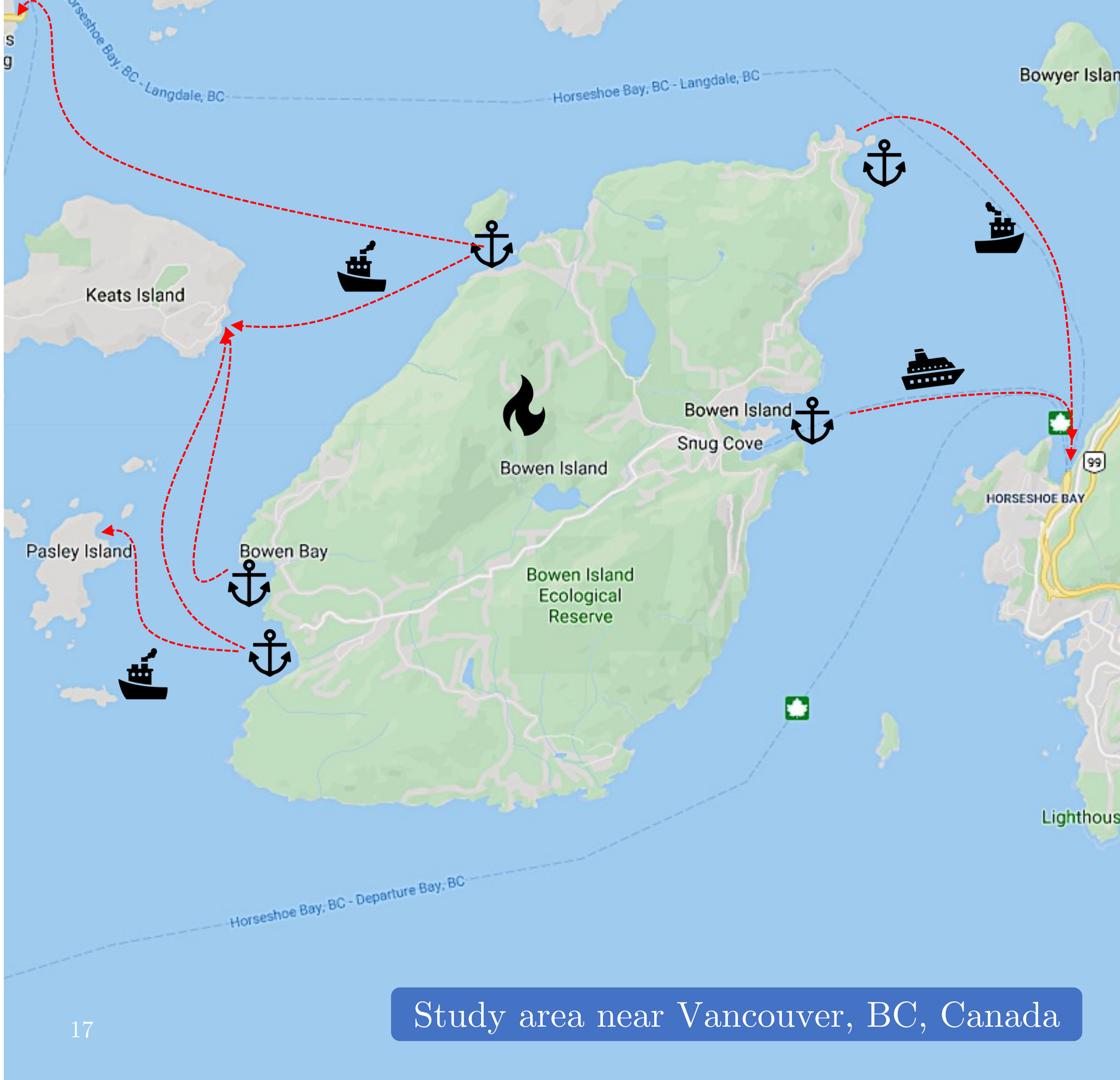
Source of images: Bowen Island Municipality, BCFerries, Cormorant Marine, RCM-SAR, CCG-GCC, Statistics Canada, Canadian Red Cross, BC Ministry of Transport and Infrastructure, Province of British Columbia, RCMP

Study Design Specifics

Two fleet size considerations
- primary (local) fleet
- entire (extended) fleet

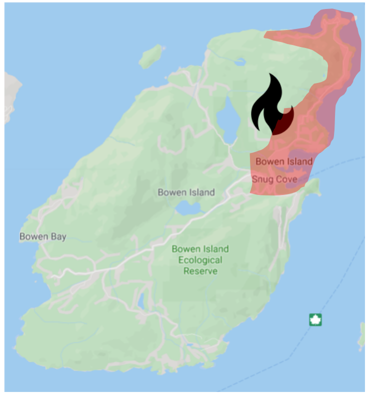
Three shelter location considerations
- Mainland only
- Temporary shelters on Keats Island
- Temporary shelters on Keats and Pasley Island

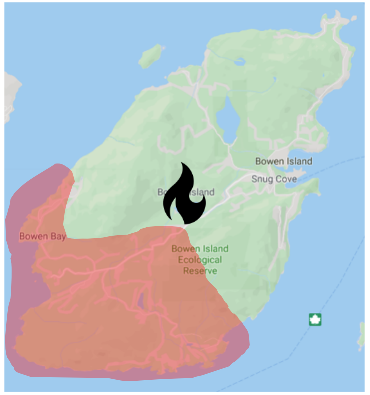
Source of map: Google, Inc., 2020

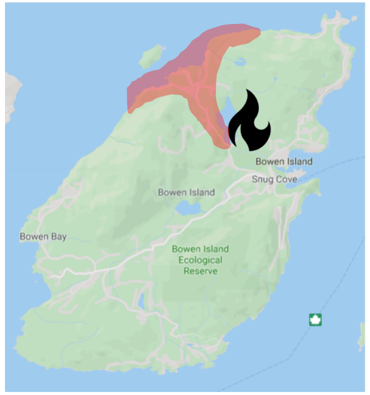


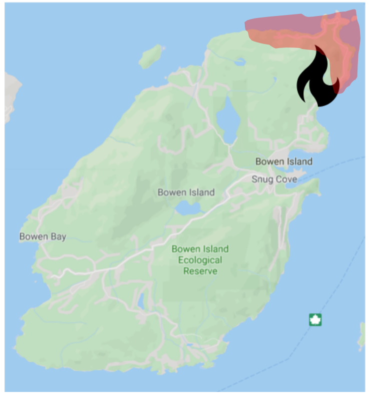
Study area near Vancouver, BC, Canada

Case Study – Scenarios





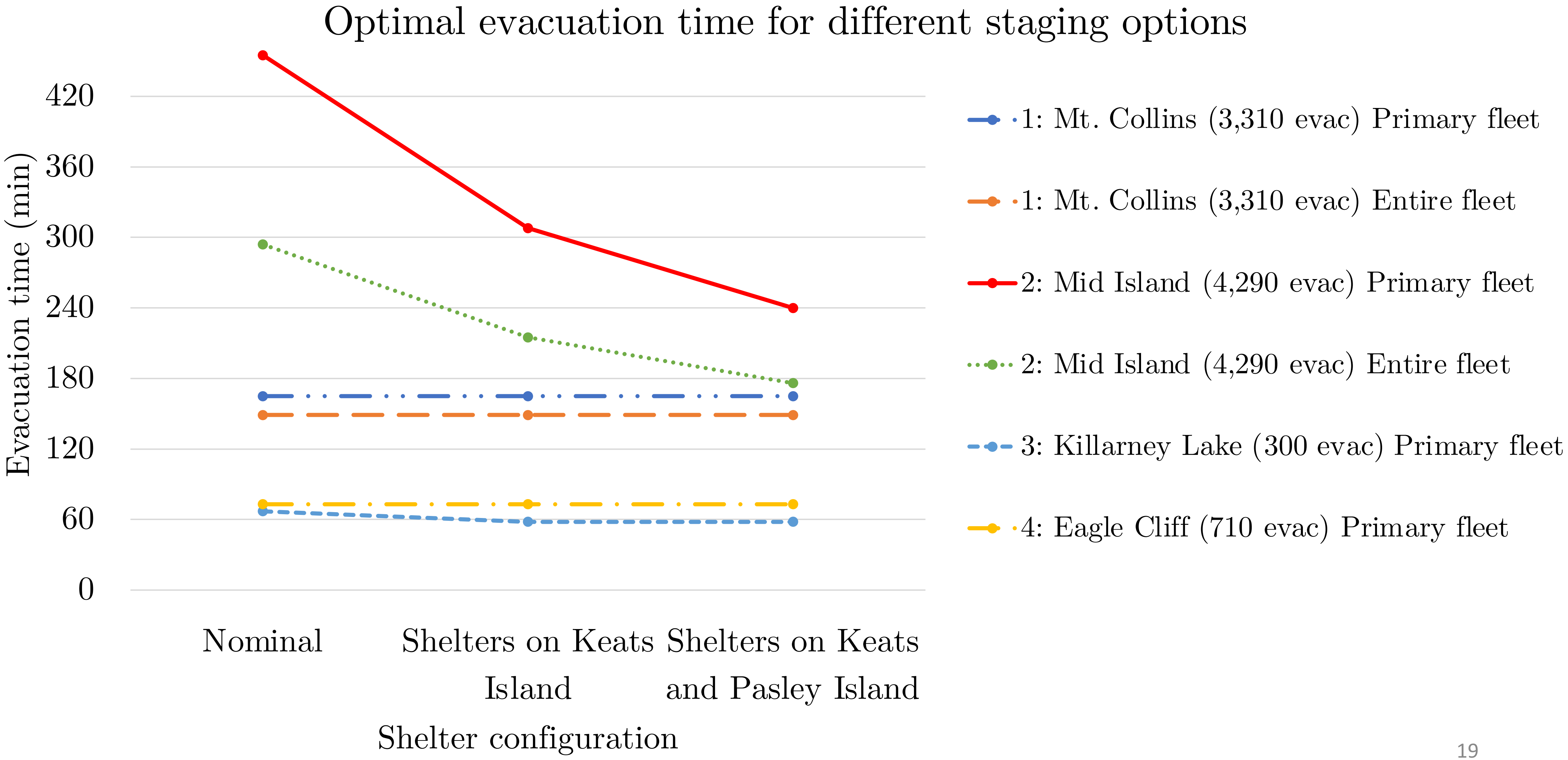




Scenario	**1**	**2**	**3**	**4**
Relative probability	40%	10%	15%	35%
Affected areas	2	2	2	1
Affected population	3,300	4,300	300	700
Usable docks/landing site	4	2	1	2

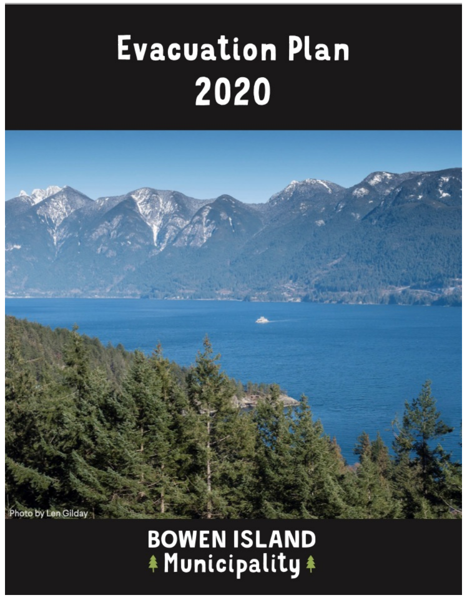
Source of maps: Google, Inc., 2020

Case Study – Bowen Island, BC, Canada



Conclusions

- New network formulation allows for heterogeneous resources and limited compatibility
- Two-stage formulation allows incorporating demand uncertainty
- Model applicable to evacuation studies of isolated communities of different types (e.g. valleys, mountains)
- Real-world case study has provided new insights on evacuation planning and response
- Results from case study are now part of official Bowen Island Evacuation Plan



Next Steps / Ongoing research

- Complete response tool development:
  - Finish heuristic solution method with local search component
  - Embedding into a meta-heuristic global search approach
- Exploration of alternative modelling approaches
- Simulations including on-land transportation component
- Expansion to other application areas

Questions & Answers

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