DEVELOPMENT OF A HYBRID SIMULATION MODEL FOR UNDERSTANDING COMMUNITY RESILIENCE TO FUEL DISRUPTION

by

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Abstract

Coastal and island communities in British Columbia are dependent on a multi-modal transportation network to support their basic needs, such as transportation of critical supplies. The network involves both land and marine transportation modes, various stakeholders and facilities. A broad range of potential disruptions, including natural disasters and human-induced events, threatens this system. Among all the critical supplies, fuel is of special importance. Fuel is required by not only the general consumers but also the emergency responses vehicles and facilities. The remote and semi-remote communities, which are at the end of the supply chain, will experience shortages of critical supplies if the regular transportation service is disrupted beyond the level that can be met using the local inventory. There is a critical need to understand fuel resilience and plan for potential fuel disruptions from the demand-side perspective.

In this thesis, a hybrid model for simulating the community fuel supply, demand and inventory is presented. The development of the model is preceded by a detailed study of consumer behaviors and community fuel inventory strategies. In the model, a hypothesized hoarding mechanism to describe and predict consumer behaviors is established. Four disruption scenarios are created. Several strategies that may enhance the community resilience are proposed. The hybrid model is applied to the case study area, Powell River. It contributes to evaluate current fuel system resilience and examine the effectiveness of the proposed strategies. The simulation results demonstrate the importance of restraining possible consumer hoarding behaviors and conducting efficient inventory management. The concerns and recommendations from this thesis may lay the foundation for further exploration fuel resilience from the demand side.
Lay Summary

The coastal and island communities in British Columbia use different transportation modes, facilities, and personnel, to transport fuel. The transportation network is threatened by various disruptions, such as natural disasters and human-induced events. What will the communities experience if disruption happens? How should the communities prepare for and respond to the disruption? We currently know little about these questions.

In this thesis, I create a model to simulate the situations possible to occur in different types of fuel disruptions. I also bring up some strategies that may be adopted to help the community survive the disruptions. The model is then used to test the effectiveness of these strategies. The modeling results develop new knowledge in the fuel supply and demand of coastal communities, thereby contributing to improving their resilience.
Preface

The introduction of the fuel system in BC in Chapter 1 is based on work conducted by Maritime Transportation Disruption: An Integrated Assessment for Coastal Community Resilience research team, including Stephanie Chang, Hadi Dowlatabadi, Terje Haukaas, Allanah Brown, Rodrigo Costa, Bethany Dobson, Alexa Tanner, and myself. I was responsible for gathering information from publicly available reports, websites and media accounts, and developing the fuel balance in the region. I am the lead investigator for the other part of the thesis where I was responsible for data collection, modeling, and analysis. The interviews with key stakeholders are mainly conducted by Stephanie Chang, Hadi Dowlatabadi, Allanah Brown, and Bethany Dobson.
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Dedication

To my beloved parents

父母深恩 春晖朝露

长我育我 辛劳旦暮

今赴七万里长途

别故国故土之邦

格物致知 上下求索 奋然无悔矣

惟愿学有所成 以报双亲万一
Chapter 1: Introduction

Fuel is necessary for a broad spectrum of societal functions, from the movement of people and goods to heating, power, industry and commerce, and social services such as hospitals. Furthermore, in extreme events such as natural disasters, fuel will be essential to emergency responders and restoration of normal activity. Coastal and island communities in British Columbia (BC) are highly dependent on maritime transportation to support their basic needs, such as the transportation of fuel. They receive and redistribute fuel resources through multi-modal transportation networks. The normal operation of the network, however, is constantly threatened by various natural and human-induced disruptions. It is noteworthy that Canada’s Pacific coastline is part of the Cascadia Subduction Zone and is susceptible to earthquakes, which can impact the community well-being. In BC, existing planning for fuel emergencies is limited while there is a critical need to plan for it.

Recognizing the vulnerabilities, we propose developing knowledge on the local fuel system and emergency fuel management to help enhance the community resilience to potential disruptions. Many literature related to this topic have been focusing on increasing the robustness of the supply chain. However, we propose enhancing the resilience from the demand side. It is necessary for the local public sector to identify available resources, understand the local fuel supply and demand, and plan for emergency resources management within their authorities. Improved fuel inventory strategies and post-disruption supply management can lead to significant enhancement in community resilience. In this thesis, a hybrid model of community fuel supply and demand is presented. The model is tested under several disruption scenarios to predict possible conditions and test strategies and policies that may enhance the community resilience.
1.1 Thesis Structure

The first chapter, which is this chapter, offers background information about the fuel transportation network in BC and the goal of this study.

Chapter 2 discusses the importance of critical resources, especially fuel resources, in emergency management. It then presents a literature review on previous cases of disruptions to the fuel supply. The third part of the chapter explores the consumer hoarding phenomenon, which is frequently observed in emergencies. It provides the theoretical basis for modeling consumer behavior in the following chapter.

Chapter 3 introduces the research methods used in this thesis, including modeling platform and three modeling approaches, System Dynamics (SD), Agent-based (AB), and Discrete-event (DE). It also describes the case study area and sources of data.

Chapter 4 and Chapter 5 present the two models developed to understand the community fuel supply and demand from different perspectives. The first bottom-up model integrates both Agent-based and Discrete-event approaches, and aims at simulating the consumer behaviors in different contexts. A mechanism to explain fuel hoarding is introduced and modeled in this chapter. Several strategies that can be applied to restrain hoarding is tested in the model. The model introduced in Chapter 4 establish a basis for further looking into the issue from a community perspective. Chapter 5 describes a highly aggregate SD model, which is used to describe the community fuel supply and inventory. The model is then tested under four disruption scenarios to evaluate the community fuel resilience.
Chapter 6, the last chapter, briefly summarizes the thesis and provides policy implications based on the findings. The limitations and future research directions are also discussed.

1.2 The Fuel System in British Columbia

1.2.1 Fuel Supply

The quantity of oil production within British Columbia is not enough to supply the local demand, making the Province dependent on imported fuel. The fuel distribution chain typically starts in distant sites and reaches BC by pipeline, rail, road, and maritime transportation. The approximate quantities of crude and refined oil movement within the Lower Mainland is depicted in Figure 1.1 (Maritime Transportation Disruption: An Integrated Assessment for Coastal Community Resilience research team, 2017).

![Figure 1.1 Sources and Conveyances of Fuel in the South Coast BC](Source: Maritime Transportation Disruption: An Integrated Assessment for Coastal Community Resilience research team)
This fuel flow diagram has been developed using publicly available data, averaged over a one-year period. The bulk of liquid fuels used in the province is imported from Alberta and Saskatchewan via pipeline and railcars. In addition, Washington State, USA, imports refined products to BC via marine barges and, at peak demand, tanker trucks. A small amount of conventional crude oil, approximately 11,000 bbl/d, is produced in BC and refined at the Huskey Energy, Prince George Refinery. BC also exports crude oil to Washington State, USA.

Alberta and Saskatchewan supply the majority of fuel to BC’s south coast. The Kinder Morgan Trans-Mountain Pipeline (TMPL) is the only pipeline crossing the Rocky Mountains. The pipeline begins near Edmonton, Alberta and stretches 1150 km to its endpoints on the Burrard Inlet and in Puget Sound, Washington State, USA. TMPL is capable of carrying crude and refined fuel in batches with the reported capacity to be 300,000 bbl/d.

Once in BC, the fuel products from the pipeline are delivered to the Kinder Morgan Burnaby Terminal for temporary storage and distribution (capacity 1,680,000 bbl). Local pipelines are used to transport the fuel to local fuel terminals or the Chevron refinery. Fuel destined for export is transported to the Westridge Marine Terminal (capacity 395,000 bbl). In addition, significant quantities of crude oil and semi-refined products are exported to refineries in Puget Sound, Washington State (Kinder Morgan, 2015a).

The increasing demand for oil products and the closure of smaller, local, refineries has led the demand of fuel in BC to exceed the local production capacity vastly. This puts reliance on TMPL to operate at capacity and an increasing dependence on external forms of fuel transportation to meet local demand. For example, in 2009, 52,000 bbl/d of oil products were transported to BC by
rail. By 2013, this volume increased to 80,000 bbl/d (Pynn, 2015). Today, rail provides approximately 35% of all BC’s petroleum products, coming from Alberta, Saskatchewan, and Washington State. Rail transportation of fuel is expected to continue to grow in relation to demand in the coming years (Canadian Association of Petroleum Products, 2016).

While pipeline and rail supply most fuel imported to the Lower Mainland, some of the refined products - notably Jet A - are exported from Puget Sound via tanker or barge and arrive in BC at the Westridge Marine Terminal in the Burrard Inlet. Truck transportation from Puget Sound is also used to deliver fuel to the Lower Mainland, particularly the YVR airport.

Once the petroleum products arrive in BC, the fuel is destined to either the local refinery, one of three fuel terminals, or the YVR airport for domestic consumption. Semi-refined and crude products arriving in the province via TMPL are delivered to the only local refinery still in operation, the Chevron Stanovan, in Burnaby. Chevron Stanovan has a refining capacity of 57,000 bbl/d and is responsible for nearly 30% of the province’s gasoline (Moreau, 2012) and supplies about 40% of the fuel consumed by YVR airport using the Trans-Mountain Jet Fuel pipeline (Vancouver Airport Fuel Facilities Corporation, n.d.). The Chevron Stanovan terminal is also directly connected to the CN railway (Pynn, 2015) and receives approximately 8,000 bbl/d from the rail (Pynn, 2013).

The three fuel terminals in the Lower Mainland are owned and operated by independent providers. Refined products delivered via TMPL are destined to Suncor Oil, on the Burnaby-Port Coquitlam border, and for domestic fuel needs (Moreau, 2012). Imperial Oil (IOCO) Esso, in Port Moody, is supplied mostly by rail from Edmonton with a focus on Marine Gas Oil (used by tugs and ferries), diesel flux, intermediate, and bunker fuel (City of Port Moody, n.d.). Finally, Shell owns and
operates the Shellburn Terminal located in Burnaby and focuses on local demand. The Shellburn Terminal receives fuel from barges or ships coming from the U.S. and rail from Alberta and does not use TMPL (Moreau, 2012).

The YVR Airport receives fuel from trucks and barges coming from the U.S. An average of 25 truck deliveries are received at YVR daily, with up to 35 deliveries being made during peak periods, such as summer and holiday periods (Vancouver Airport Fuel Facilities Corporation, n.d.). In addition, barges deliver fuel to the Westridge Marine Terminal where it is combined with fuel from the Chevron Stanovan fuel terminal and sent via the Trans-Mountain Jet Fuel pipeline to YVR.

By using publicly available data, Figure 1.1 provides an overview of BC’s dependence on refined product deliveries from Alberta and displays the different levels of dependency by product type. There is a significant part of regional fuel flow remains unknown. This is labeled as ‘unknown’ and shaded in black in Figure 1.1. There is no publicly available data about volume, origins, destination, and transportation modes, a critical gap.

1.2.2 Fuel Distribution

Once the fuel is delivered to BC, it is distributed across the Southern Coast using both land and marine transportation. Fuel destined for the Lower Mainland is transported directly from the distribution centers by land delivery. Fuel for coastal communities is first transported from distribution centers to nearby marine docks by pipe or truck and then shipped to the destined ports for local distribution.
1.2.2.1 Land

Transportation from distribution centers to end users is accomplished through similar modes as wellhead transportation. Typically, refined fuel is either collected from racks at the refinery by truck or pumped directly through pipelines to tanks or port facilities.

Multiple companies truck fuel from storage facilities to the docks for marine transport to coastal distribution points and ultimately, end-users. Pipelines are also prevalent in the transfer of oil from storage facilities to barges, marine tankers, and from dockside ships to nearby tank farms. For example, the Vancouver International Airport is served via Kinder Morgan Trans-Mountain Jet Fuel (TMJ), a dedicated 41 km pipeline between Chevron Burnaby, Westridge Marine Terminal, and Vancouver International Airport (Kinder Morgan, 2015b). Chevron provides close to 50% of the aviation fuel transported via TMJ to the airport. A similar volume is delivered by tanker or barge to Westridge Marine Terminal. However, during peak times, additional supply is provided to the airport by up to 35 tanker trucks per day (over 8000 bbl/d) from Cherry Point refinery in Washington State. Aside from these services, there are additional trucking services between Cherry Point, Washington State, and prominent locations in BC.

Once the fuel arrives at coastal communities by marine transportation, trucks are the last link in fuel delivery. In the case of tanker vessels, trucks deliver fuel from local storage tanks to fuel retailers, and end-users. Moreover, in the case of roll-on roll-off ships, tanker trucks are key at both ends of the supply chain; trailers can also be used directly from barges. Trucks transport fuel to petrol stations and local businesses, dispensing fuels to the capacity of the recipient’s onsite tanks.
1.2.2.2 Marine transportation

Fuel barges and marine tankers are both utilized to serve BC coastal communities. The larger corporations use marine tankers which are loaded and unloaded at a dock by pipeline. Service to medium and smaller communities, which have a local road network, uses roll-on-roll-off inventory, and their barges carry fuel in trailers. This portfolio of marine vessels provides flexible transportation options to meet the needs of end-users. They require far less fixed infrastructure but require cleared shipping lanes, safe harbors, docks and mechanisms to deliver cargo to shore. The density of marine fuel delivery is displayed in Figure 1.2.

Figure 1.2 Density of Fuel Vessel Tracks (AIS Shipping Data) (Sources: Maritime Transportation Disruption: An Integrated Assessment for Coastal Community Resilience research team)*

* This publication draws on Satellite AIS data which are provided by exactEarth Ltd. 2016, and processed courtesy of MEOPAR.
The density map contains the movement of 81 vessels during 2015, making 381 tracks. Due to the nature of the data, most vessels included are tugboats, all of which have AIS receivers installed. This data provides an estimate of fuel deliveries, though some discrepancies may exist if deliveries are made by boats without the AIS receiver activated.

The figure highlights the major distribution centers on Vancouver Island, namely, ESSO Nanaimo, Suncor Nanaimo, Shell Chemainus and Chevron Cobble Hill. These distribution centers are frequently visited by various marine vessels to support the nearby communities. While fuel deliveries are made in more rural locations, the frequency of such visits is substantially lower.

1.2.3 Communities

Coastal and island communities in southern BC rely heavily on the maritime transportation system to support their basic needs. These communities vary in size, connectivity, and frequency of delivery (from daily to monthly). On-site storage facilities provide fuel supply security and are managed in accord with the frequency of delivery. Each tank owner-operator has their own fuel inventory management strategy – some keep their tanks as close to full as the supply-demand dynamic permits, others keep a smaller inventory to minimize costs.

Different modes of vulnerability exist depending upon such factors as population size, location, connectivity, frequency of delivery, local storage capacity, and the inventory management strategy used. These factors influence the susceptibility to a fuel supply disruption and the effect a disruption would have on the community. Here we describe the fuel delivery system in place and the related vulnerabilities associated with four representative communities.
Large population centers on Vancouver Island, such as Nanaimo, have several tank farms which are replenished daily. These communities are vulnerable to interruptions in the supply chain as they are prone to experiencing fuel shortages shortly after a disruption. However, these communities possess more resources and have a fuel demand high enough to allow them to negotiate fuel deliveries from alternative suppliers independently.

Powell River and smaller Gulf Island communities are supplied by secondary services from Vancouver Island. Most fuel deliveries originate in the Lower Mainland and are transported through Nanaimo and other leading ports before local distribution. Many of these medium-sized semi-remote communities are only accessible by air or boat, making them dependent on maritime fuel deliveries. Powell River requests new fuel shipments when there is available space in the tank farms. With no regularly scheduled fuel supply from the Island, the community places a fuel delivery order when needed, approximately two to three times per week.

In remote communities on the Mid Coast and North Coast, diesel power generation is supported through monthly fuel shipments. For this reason, these communities tend to keep large fuel inventory. However, this is changing as BC Hydro is taking over their operations. In Hartley Bay, for example, when the community operated their generation facility, they kept fuel inventory of two months, while now significantly lower inventory is kept on-hand.

1.3 Problem Statement

The above description demonstrates the complexity of the fuel transportation network in BC. It involves different communities, transportation modes, personnel, and public and private sectors. BC has little direct experience with fuel shortages the resilience of the system is relatively untested. The broad range of disruptions threatening the region reminds us not to treat the issue lightly.
Some public institutions, such as emergency management committee, have initiated measures and plans to enhance the regional resilience in a macro level. However, no government entity has engaged with the entire fuel supply chain. Moreover, the information gap described before has impeded further understanding of the local fuel system. There is still a long way to go before a comprehensive emergency management is achieved.

Moreover, the coastal and island communities in BC remains relatively “invisible” in this system. Most of them are at the end of the fuel supply chain. Unlike the fuel distribution center or the population hub, they receive much less attention. These communities have little access to the operation of the fuel supply chain and the deployment of critical resources. They are geographically isolated and have less connectivity in the transportation network. How these communities should plan for and respond to disruptions to fuel supply remains unclear.

1.4 Objective of the Study

Considering the gaps mentioned above, the focus of this thesis lies on exploring how coastal and island community can build up fuel resilience from the demand side. We believe that the understanding of enhancing regional fuel resilience can be more multifaceted. Focusing on establishing the robustness of supply chain may result in overlooking the demand side. The strategies that local communities can adopt within their authorities are not fully studied yet. Coastal and island communities have the ability to increase their resilience with the use of improved emergency planning and management.

The main objective of the research is to understand the fuel resilience from the community perspective. To achieve this goal, a fuel supply and demand model for modeling the fuel dynamics
under different disruption scenarios is created. The model is supported by the knowledge on consumer behavior and inventory management. The specific objectives of this research include:

- Understanding how disruptions may affect the local fuel system. The influences of disruptions are not limited to interrupting the fuel supply. The fuel storage facilities may be damaged. The consumers may change their consuming habits accordingly. The goal is to propose a mechanism to describe the consumer decision-making process. The mechanism can be used to predict the consumer behaviors in different contexts.

- Developing a model for simulating both macroscopic and microscopic activities of community fuel supply and demand. The model should utilize different modeling approaches to simulate different actions, objects, and structures. The model should also incorporate both detailed consumer behavior and abstract community strategies. It is also necessary to develop possible disruption scenarios and test the model with them.

- Proposing possible strategies that can be adopted by coastal and island communities to enhance their resilience to fuel shortage and other related emergencies. Test the effectiveness of the strategies in different disruption scenarios. Provide policy implications based on the simulation results.
Chapter 2: Literature Review

2.1 Critical Resources in Emergency Management

Previous literature on emergency management (McLoughlin, 1985; Petak, 1985) has identified four key components of emergency management: mitigation, preparedness, response, and recovery. In recent years, there has been increasing attention to other phases of the disaster cycle, besides response (Abrahams, 2001; Federal Emergency Managment Agency, n.d.; Ministers Responsible for Emergency Management, 2011). When describing the four components, resources management is frequently mentioned. Resources management is an operational process for identifying, categorizing, mobilizing, tracking and recovering resources (ASTM International, 2010). In emergency preparedness, it is important to identify the available critical resources, develop knowledge of resources at risk to damage, and make resource management plans in order to improve operational capabilities for responding to an emergency. In emergency response, whether the local authorities can make maximum efficient use of existing resources can make great differences. In the recovery period, the resources are mobilized and deployed to restore the vital support systems for the community to return to normal.

Critical resources in emergency management vary by kind and type and may be used in different operational aid in emergency context (ASTM International, 2010). Examples are material resources, such as food, water, clothing, shelter, fuel and medical supplies, personnel resources, such as physicians, volunteers, and service resources, such as transportation services and medical services. In some cases, an emergency can result in resources shortage by disrupting the supply chain or damaging the inventory. In some other cases, resource shortage is the origin of the emergency. Examples are the energy crisis (Gardner, 2015) and food crisis (Berry, 1984; Burki,
1986). In either case, it is common to suffer from different types of resource scarcities in an emergency (Chang, Wilkinson, Brunsdon, & Seville, 2011; Hick, Hanfling, & Cantrill, 2012; Sheu, 2010). Thus, resources management becomes one of the key steps in emergency management as discussed by scholars developing new approaches in the emergency resources management (Arora, Raghu, & Vinze, 2010; Cai, Zhao, & Xu, 2012; Caunhye, Nie, & Pokharel, 2012; Li, Jin, & Zhang, 2011).

Compared with other critical material resources, fuel is of particular importance. First, it is hard to acquire if the fuel supply is disrupted. Many residents have food and clothing inventory at their home. It is also relatively straightforward to develop the capacity to produce potable water as needed. However, medicine and liquid fuels have to be cached or supplied. Furthermore, medicines are usually compact and lightweight and can be airtifted to areas in need. However, only small quantities of liquid fuel can be delivered by air. In addition to that, fuel is the basis of many critical services resources. Police vehicles, fire trucks, and ambulances are all dependent on fuel. Critical infrastructures, such as hospitals and police stations, predominantly use diesel-fueled emergency generators to maintain operation. In this vein, the focus of this study is on how to manage the vulnerability of communities to fuel shortages in an emergency.

2.2 Previous Cases

Previous occurrences of fuel shortages in Canada and around the world can be explored to learn how fuel shortage can be triggered by extreme weather, such as hurricanes (Gaouette et al., 2005; Kumins & Bamberger, 2005; Smythe, 2013; Takeda & Helms, 2006), earthquakes (American Red Cross, 2011; Kawahara & Koca, 2013), and human-induced events (BBC News, 2016; Price, 2016).
Natural disasters can damage pipelines and refineries, and shut down ports and fuel terminals. They may also obstruct shipping channels from above (falling bridges) and below (slumping mud banks). During Hurricane Katrina, the Capline pipeline system between Louisiana and Illinois was shut down for several weeks (Kumins & Bamberger, 2005).

Many communities choose to keep a substantial fuel inventory in the local fuel tanks. Although the fuel inventory is a crucial reserve, it is costly and may threaten nearby areas with oil spills if the tank facilities are themselves damaged. Comprehensive studies of storage tank subjected to earthquake actions have shown that there is a correlation between the tank fill level and its damaged state: full or near full storage tanks of conventional design are far more susceptible to severe damage and collapse (American Lifelines Alliance (ALA), 2001; Cooper, 1997; O’Rourke & So, 2000). In the emergency response to Hurricane Sandy, fuel shortages became both a logistical as well as a public relations concern (Smythe, 2013). In Japan’s 2011 earthquake, tsunami, and nuclear disaster, fuel shortages compounded emergency response difficulties. The survivors suffered from the lack of emergency supplies, because of both the lack of emergency supplies and the lack of fuel, which hampered the supply because of both the lack of emergency supplies and the lack of fuel, which hampered the supply deliveries (The New York Times, 2011). The fuel shortage, together with electricity outage, caused problems varying from lack of mobility, communication, heating to reduced health conditions (Holguín-Veras et al., 2014; Koca & Kawahara, 2013; Suzuki, 2012).

Human-induced events can also be influential in fuel supply system. Though not many studies cover this topic, sufficient information can be found in news reports. In the summer of 2015, Nova Scotia experienced a temporary fuel shortage when the main marine fuel terminal shut down
unexpectedly for three days; an investigation found that public health could have been affected had the outage lasted a day longer (MacNeil & Keefe, 2015). A more recent case happened in 2016 when hundreds of gas stations in France run dry or low in supplies as workers blocked fuel depots and shut down refineries to protest an unpopular labor law (BBC News, 2016). The gasoline spill in Birmingham, Alabama in 2016 forced a pipeline shutdown that created various levels of fuel shortages in Alabama, Georgia, North Carolina, South Carolina, Tennessee and Virginia (Price, 2016).

These cases have demonstrated how fuel transportation systems can be disrupted in extreme events, the consequences of the ensuing fuel shortages, and the importance of planning for such fuel emergencies. The availability of fuel is limited in the affected areas because: (1) fuel deliveries are down, (2) local gas stations and refinery facilities themselves are damaged, and (3) people in the affected area, as well as those nearby, tend to hoard the remaining fuel inventory immediately after the disasters. A literature review of consumer hoarding is presented in section 2.3.

While facing various hazards that could disrupt fuel supply and distribution, BC has little experience with fuel shortages. Indeed, the only experience was a 2007 flood in northern BC, in which a highway closure halted fuel deliveries by truck and threatened a fuel shortage in Prince Rupert. In this event, the Province arranged an emergency diesel fuel delivery by a Canadian Coast Guard vessel, and the city arranged for a barge delivery from a major fuel company. However, it is noted that the region is not adequately prepared for a fuel disruption that is of a greater scale (AIR Worldwide, 2013; Auditor General of British Columbia, 2014). Recognizing the importance of fuel system vulnerabilities, numerous states and local governments in the U.S. have been planning for fuel disruptions through energy assurance and emergency planning. In BC, there is a
critical need to plan for potential fuel disruptions. However, to date, planning for fuel emergencies has been limited.

### 2.3 Consumer Behavior in Emergency

The consumer hoarding, or panic buying, has frequently been observed in actual or anticipated emergencies. Human-induced events, such as protests, price changes, are likely to cause hoarding. The fuel hoarding behaviors among the population make the issue not only an emergency response problem but also a public relations problem. In this vein, how to allocate the inventory and maintain social order becomes a critical challenge facing local authorities. In the wake of the 1973 oil crisis, widespread panic triggered motorists to hoard fuel. Six years later, due to memories of oil shortages, long lines appeared again at gas stations (J. D. Sterman, 2015). In the 2000s, a series of fuel protests struck the UK. At least two major fuel hoarding, one in 2005 and the other in 2007, were observed. The hoarding soon closed gas stations. At their heights, around 3,000 gas stations were left empty (Knight, 2005; Polak, Noland, & Bell, 2001). Natural disasters, such as storms and earthquakes, can also lead to hoarding. Examples are the panic buying of fuel during the Hurricanes Katrina and Sandy (Chow & Elkind, 2005). The disruptions can even trigger population in the other area to hoard. When the droughts in Australia reduced local rice production, consumers in Vietnam and India rushed to stores to build up their own inventory of rice (Shou, Xiong, & Shen, 2011). During the 2011 nuclear crisis in Japan, panic buying of salt swept all over China. The worried population hoarded bags of salt in the false belief that the iodized salt can guard against radiation exposure (Lin, Wei, & Jie-yiing, 2011; Zhang, 2012).

The hoarding behaviors of consumers not only put unnecessary pressure on the supply chain, but also have significant negative impacts in the emergency contexts. The crowds and the long wait-
lines are likely to further exacerbate the situation by spreading the anxiety. The pace to depleting a scarce resource is accelerated by the hoarding of consumers, which results in poor performance in the emergency response and post-event relief. It is important to understand the conditions, causes and the implications of hoarding behavior and how to mitigate it.

2.3.1 Definition of Hoarding

Many studies have defined the hoarding behaviors (Helsloot & Ruitenberg, 2004; Shou et al., 2011; J. D. Sterman, 2015; Stiff, Keith, & Tourk, 1975; Strahle & Bonfield, 1989; Zarrel, 1970). In general, these definitions focus on three factors: the external stimulus, the coherent purchasing behavior, and the unusual purchase volume.

In previous observations (Helbing, Ammoser, & Kühnert, 2006), hoarding usually follows disruptions, such as disasters, price increases, supply shortages, and civil unrests. The disruption can be actual or perceived. Consumers may misinterpret signals and rush to hoard even when everything is normal (Costantini, Gracceva, Markandya, & Vicini, 2007). In 1973, Americans once went out to hoard toilet papers only because Johnny Carson, the famous talk show host, made a joke about the shortage of toilet paper in his show. The stocks of the supermarket were soon sold out, which only served to reinforce the rumor. The hoarding finally created an actual scarcity of toilet papers (Hughes, 1988; McKinnon, Smith, & Keith Hunt, 1985). In short, the consumers first receive or perceive a sign of danger from the external stimulus, a precondition of hoarding. The external stimulus then triggers consumers to accumulate an unusually large amount of goods to avoid the future shortage. In some cases, the consumers increase the purchase frequency if the volume of single purchase is restricted. Fuel hoarding at the gas station is a typical example.
Some scholars consider hoarding as a type of inventory accumulation of consumers (McKinnon et al., 1985). In most supply chain studies, consumers are usually the last link, which means that they are supposed to consume, rather than to stock. However, in an emergency context, the consumers’ inventory exceeds their historical inventory. They may also change their consumption rates if the expectation of the duration of scarcity is long. In other words, hoarding is how the consumers cope with a real or perceived scarcity.

2.3.2 Theories of Hoarding
The previous discussion of definitions explains the precondition and the features of hoarding. However, how do consumers make the decision? Why does hoarding become group behavior? Are people making rational decisions or are they imitating other people’s behaviors? Economist, psychologist, and sociologists have studied the underlying mechanism of hoarding. To study the hoarding is meaningful in both business and public policy context. For instance, if hoarding is a rational decision of consumers, the consumers will no longer hoard when the system is redesigned and the hoarding is not the optimal solution. If hoarding is a type of social trap or herd behavior, an effective solution requires more psychological and social interventions.

2.3.2.1 The Standard Economic Explanations
Some economist believes that the disruption can be interpreted as the “distortion of demand curve” (Armony & Plambeck, 2005; Dong, Zhou, & Li, 2013; Stiff et al., 1975). They find that hoarding usually happens in goods that have low income elasticity and low price elasticity of demand. In other words, the goods are widely consumed by consumers with different incomes, and the demand remains relatively unaffected when price changes. The goods generally have few substitutes and are easy to store. Some scholars (Weitzman, 1991) consider the disruption as “price distortion”
because the cost of searching, waiting or other “effort-cost” is added to the price. No matter how these economists interpret the disruption, in these theories, hoarding is a rational response to the disruption. The consumers make the decision by comparing the loss and gain and finally achieve the optimal utility. When the consumers perceive the disruption, they start to value the supply higher and become less elastic to price. They perceive signals from the environment and subjectively calculate the cost of acquiring goods now and later. They also take into account the probability that the good may be sold out in the market. It is noteworthy that what the consumers value is to secure their own supplies of the goods rather than financial profits. This is the difference between hoarding and speculation. The economists also suggest that the hoarding behavior can be rational for individuals while being costly to the supply chain and the society.

Hallsworth and Tolley (2000) use Game theory to explain the hoarding behavior. They make an analogy with the Prisoners’ Dilemma, pointing out that the inability to make the optimal decision results from the uncertainty of other ‘players’. The effect of any decision the individual makes is bound up with the decisions made simultaneously by others. In the Prisoner’s Dilemma, the two rational individuals may not cooperate. Instead, they may rush to confess because they cannot trust the other. In the hoarding scenario, the chances that thousands of consumers will cooperate seems slim. So, the consumers will rush to hoard just as the prisoners rush to confess. This is how the consumer pursues self-interest instead of acting for public good.

Another model being used is the Tragedy of the Commons. In the Tragedy of the Commons (Hardin, 2009), the future/long-term results are shared by the whole community and individuals are more likely to act according to their own self-interest in the short term. Similarly, in the hoarding context, the results of supply depletion are suffered by the whole community. To
maximize the individual gain by consuming/purchasing the best of what is left becomes the rational choices, at least in the short term. When there are no authorities to organize and regulate, we can hardly rely on the voluntarism and self-regulation of the prudent consumers.

2.3.2.2 The Bounded Rationality and the Sociological Explanations

Other scholars, however, tend to view consumers as bounded rational individuals with imperfect information and limited cognitive ability and time to make the decision. Some even bring views from psychiatry and neuroscience literature, saying that hoarding is a highly adaptive behavior and the propensity to hoard is an evolutionary trait (Bartness & Day, 2003; Grisham & Barlow, 2005). They suggest that many animals, including human, evolved in an environment filled with scarcity, uncertainty, and competition. In such environment, individuals who store resources are more likely to survive. Brain studies (Anderson, Damasio, & Damasio, 2005) also show that the subcortex, which is a brain region that emerged early in the evolution, is responsible for the drive to hoard, while the rational decision-making region, the frontal cortex, emerged later. One theory is that the hoarding propensity is distributed among the population randomly and the behavior is inevitable. However, Sterman and Dogan (2015) conducted an experimental study and disproved the theory. Their study indicates that the external stressors, such as scarcity and demand spikes, trigger consumer to hoard. In other words, every consumer may choose to hoard to some extent. But individuals who have experienced stressors before are more likely to hoard than those who have not.

The conclusion conforms with the behavior explanation of hoarding, in which the consumers act with bounded rationality. The decision-making process is not only cognitive but also affected by emotions. The external stressors and previous experience cause stress, anxiety, fear, which leads
people to use heuristics to make the decision. They then start to build up their inventory even when it is irrational. Apart from previous experience, researchers also suggest that people’s poor understanding of dynamics, such as feedback processes, time delays and stock and flow, may also make the irrational behavior more likely (Sterman, 2000).

Sociologists think the theories of economics has centered on individual decision makers making decisions in “relative social isolation” (Strahle & Bonfield, 1989). They also provide some possible explanation of hoarding behavior. For example, the herd behavior, which has been studied in stock markets (Cont & Bouchaud, 1997; Hirshleifer & Hong Teoh, 2003; Rook, 2006), may be used to explain the hoarding phenomenon. The sociologists believe that the consumers’ buying behaviors are influenced by the others’ behaviors. People tend to imitate others and join the line of panic buying (Miao, Yu, Bao, & Tang, 2011). Sociologists also pay attention to the role of media and the rumors spreading among the people (Chen, Shen, Ye, Chen, & Kerr, 2013; Kasperon, 2012; Lin et al., 2011; McCartney, 2011). They even describe the media and information sharing as the “Greek choruses”, suggesting that the media play a role in reinforcing the hoarding behavior and accelerating the speed of resource depletion.

While there are many proposed theories for consumer hoarding behavior, none are free from strong detractions. The standard economic theories have long been criticized for the assumption of rationality. The Game Theory and the Tragedy of the Commons point out the importance of the uncertainty from other “players” and the results being shared among “the whole community”. However, they fail to involve the external stimulus into the explanations. The dispositional hypothesis, which suggests that hoarding propensity is distributed among the population, is disproved by the study of Sterman and Dogan (2015). They support the situational hypothesis,
which believes that people who have experienced stresses are more likely to hoard. However, there remain questions to be answered. For example, does the situational experience have universality? Will people who have suffered from food scarcity rush to hoard gasoline in a fuel shortage? Also, for those individuals who do not have any relevant experience, how do they decide to hoard or not?

The Sterman and Dogan’s experiment sheds new lights on hoarding behavior, though it is far from a full explanation. Similarly, theories of sociologists offer new perspectives. However, more work is needed to arrive at a complete theory.

Apart from the mechanisms of hoarding, the impacts of hoarding are also understudied. Some news provides information about the impacts of the hoarding. More research, especially studies exploring empirical evidence of hoarding, is needed.
Chapter 3: Methodology

As described before, coastal communities in BC have a very low self-sufficiency rate in fuel supply. The complex fuel transportation network is constantly threatened by potential disruptions. This study aims at enhancing fuel resilience of coastal communities in B.C in an emergency context. Interventions to enhance resilience varies from capital investments in transportation facilities, fuel storage, and warehousing. By taking a demand-side perspective, the study mainly focuses on strategies that local communities can adopt within their authorities. The study uses a hybrid modeling approach to simulate the fuel supply and demand of coastal communities. The model is used to evaluate the performances of the pre- and post- event strategies and test the adequacy of local fuel inventory.

3.1 Modeling Platform and Approaches

3.1.1 The AnyLogic® Simulation Software

The model is implemented on AnyLogic®, which is a popular software for modeling and simulation. AnyLogic® supports discrete events, system dynamics, and agent-based simulation, which are the three major paradigms in simulation modeling (Borshchev & Filippov, 2004). The first two were developed in the 1950s and 1960s, and both employ a system-level (top-down) view of things. The agent-based approach, a more recent development, is a bottom-up approach where the modeler focuses on the behavior of the individual objects. In general, the system dynamics method assumes a high abstraction level and is primarily used for strategic level problems, the discrete event modeling is mainly used on operational and tactical levels, and the agent-based models are used at all levels: agents can be competing companies, consumers, projects, ideas, vehicles, pedestrians, or robots.
AnyLogic® allows the modeler to combine these modeling approaches in the same model. The flexibility of modeling approaches makes AnyLogic® a widely used tool in the simulation of complex systems. It is used in modeling supply chains, transportation, strategic planning and management, and marketing and competition. The platform also has access to the online map and geospatial data, which is very convenient for simulating real-world cases.

3.1.2  Modeling Approaches

No single approach can fully describe the complex systems of interest. In total, three modeling approaches are used to simulate different part of the complex system and test policies to support the decision-making and implementation. The contrasts between the three modeling approaches, including scope, fundamental theories, and aggregation level, make the applications of them more appropriate for different situations. By combining these approaches, components of the system can be modeled discretely or continuously based on the system characteristics. A hybrid model can provide strategic insights from System Dynamics models while still describing individual heterogeneity of entities and processes from the Agent-based and Discrete-event model (Macal & North, 2010; Phelan, 1999). The hybrid paradigm has been adopted by a myriad of research. It is implemented in studying the diffusion of technological innovation (Swinerd & McNaught, 2014), intercity transportation(Lewe, Hivin, & Mavris, 2014), supply chains (Onggo, 2014).

3.1.2.1  System Dynamics Modeling (SD)

System Dynamics modeling, originally developed in the 1950s, is used to describe non-linear systems and originates from the system theory (Phelan, 1999). The theory suggests that the aggregate-level variables affect each other through feedback loops. The SD model describes the system behavior by stocks and flows, interacting feedback loops, balancing and reinforcing, and
delay structures (Forrester, 1997; Guerrero, Schwarz, & Slinger, 2016). It is typically used in long-term, strategic simulation models and assumes a high level of aggregation of the objects being modeled. People, products, events, and other discrete items are represented in SD models by their quantities. In this vein, they lose any individual properties, histories or dynamics. The high-level abstraction may render some problems when individual details are important. Then part of the model may need to be re-conceptualized using Agent-Based or Discrete Event (process-centric) methods.

3.1.2.2 Agent-based Modeling (AB)

Agent-based modeling is used for simulating the actions and interactions of autonomous agents. The method defines the individual behavior and predicts the appearance of aggregate phenomena (Bonabeau, 2002). The theory behind the modeling approach is the theory of Complex Adaptive Systems (CAS). The approach model the system as a result of decentralized decisions of entities and agents (Macal & North, 2010; Phelan, 1999). Basic steps of agent-based modeling include identifying the active entities, the agents, defining their behavior, putting them in a certain environment, establishing connections, and running the simulation. The agents in the model can be people, companies, projects, assets, vehicles, cities, animals, ships, and any other objects. The behaviors of the agents can be reactions, memory, states and so on. The global behavior then emerges as a result of interactions of many individual behaviors.

3.1.2.3 Discrete-event Modeling (DE)

Discrete Events (DE) models describe a discrete sequence of events in time (Gordon, 1961). The approach models entities (people, messages, tasks) travel through event flowcharts, where they can stay in queues, seize and release resources. Discrete Event Modeling techniques approximate
continuous real-world processes with non-continuous events. The approach works when the continuity is not the major concern in the problem. Examples of such events can be a customer arriving at a shop, a truck finishing unloading, a conveyor stopping, a new product launching, or an inventory level reaching a certain threshold.

Table 3.1 shows approaches used to model different elements of the system. Agent-based modeling is used to simulate the actions and interactions of the consumers. System Dynamics approach is used to simulate the fuel tanks of each consumer. The core function of the gas station, gas service, is realized by Discrete-event modeling. It also adopts the Agent-based approach to provide the refueling environment for the consumer community, and the System Dynamics approach to connect with the fuel inventory module. Disruptions are modeled by Discrete-event to act on the other elements. Fuel supply chain is modeled by the Discrete-event method. It also interacts with the fuel inventory by the System Dynamics approach.
### Table 3.1 Approaches Used to Model Different Elements of the System

<table>
<thead>
<tr>
<th>System elements</th>
<th>Modeling approach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System Dynamics</td>
</tr>
<tr>
<td>Consumer behavior</td>
<td>✓</td>
</tr>
<tr>
<td>Gas station operation</td>
<td>✓</td>
</tr>
<tr>
<td>Disruption</td>
<td></td>
</tr>
<tr>
<td>Fuel supply chain</td>
<td>✓</td>
</tr>
<tr>
<td>Fuel inventory</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.2 Case Study Site: Powell River

Powell River is a semi-remote community located on the Sunshine Coast of southwestern British Columbia. With an area of 28.91 km², the city had a population of 13,157 in 2016 (Statistics Canada, 2017a). The income of residents in Powell River is relatively lower than the average income in BC. In 2012, people in Powell River who filed tax returns earned an average of $35,494, while the BC average is $42,453 (Powell River Community Foundation, 2015). The main industries are a local paper-mill, support for resource extraction, and tourism. With no scheduled fuel supply from the Island, they are almost exclusively supplied by City Transfer, a local company that provides general freight transportation (Figure 3.1).
Figure 3.1 The Fuel Distribution of the Case Study Area: Powell River

City Transfer offers truck and barge shipping between many of the smaller, coastal communities, such as Powell River. Their barges collect fuel in Richmond and deliver to Powell River. The barges do not have a set schedule but are dispatched on order. In general, they arrive two to three times per week. Upon arrival, the fuel is stored in a number of independently owned tank farms near the docking facilities awaiting local distribution. The fuel is predominantly used for commercial business demands throughout the district.

Powell River has built in additional resilience by having large storage tanks at their local fuel stations. The community requests new fuel shipments when there is available space in the tank farms. The local tank farms continuously hold additional fuels on premises. As a semi-remote community in BC, Powell River has a relatively strong sense of being isolated in a crisis and the need to be self-reliant.
The local public sector has started the Powell River Regional Emergency Program (PRREP), which coordinates emergency planning, preparedness, training, response, and recovery (Powell River Emergency Services, 2013; Powell River Regional District, n.d.). The emergency plan takes fuel resources, possible collapsed fuel storage tanks and fueling of critical vehicles into account and develops different emergency scenarios.

Many of the coastal communities in BC receives fuel from multiple sources through land and marine transportation. The condition of Powell River makes it an ideal case for our research: it is a coastal community that relies completely on marine transportation for fuel supply; it has fuel storage facilities and has developed their own refilling strategies; the local authorities have realized the importance of fuel resilience and have been generous in support this study.

3.3 Data Description

To collect sufficient data and information about the fuel supply and demand at Powell River, we conducted interviews with key stakeholders including municipal representatives, emergency response organizations, shipping and transportation companies, and other individuals involved in the system. Publically available data from the internet was also gathered through an extensive review of the web pages for leading fuel facilities and transport agencies providing information about fuel facilities, capacities, and locations. Publicly available reports on community operations, past events, or previous studies were used. Reviews, concerns, and conclusions made in these reports were often confirmed or elaborated through the interviews.
Chapter 4: Modeling the Fuel Hoarding – A Consumer Perspective

4.1 Model Description

While the hoarding phenomenon is common in an emergency, the mechanism and the impacts of hoarding is relatively under-studied. A semi-remote community like Powell River can only temporarily rely on the local fuel inventory if the supply chain is cut. In this case, if severe hoarding happens, the local inventory will likely be depleted rapidly – under normal circumstances, the local inventory is sufficient for meeting 7-10 days of demand. This agent-based model aims to simulate the decision-making process of the consumers and the impacts of the hoarding behavior on local fuel inventory. Several measures to alleviate the hoarding are tested to provide insights into the public management of such event.

4.1.1 The Hoarding Mechanism

In Section 2.3, we introduced several theories of hoarding. Though many of them present innovative insights on the hoarding mechanism, none of them establish a complete explanation. In this model, we integrate some existing theories and propose a new mechanism to explain the formation and evolution of hoarding.

The decision-making process

The decision-making of refueling is related to many factors, including quantity remaining in the tank, the location of the gas station, vehicle attributes, price and services associated with refueling. In some instances, refueling is coordinated with other outdoor activities. That complex process is not the focus of this study. Instead, we focus on what determines the hoarding behavior. We borrow the theory from standard economics, assuming that all consumers rationally decide to refuel their
car by evaluating the cost and benefit of doing so. The ultimate goal is to achieve the optimal utility. The cost of refueling covers both monetary cost and time cost. The benefit of refueling far exceeds the price of the fuel (this is why price-elasticity of fuel is very low). The value of fuel service reflects utility derived from what it enables. In a crisis, the value of the fuel is amplified because it can be used for emergency power generation or mobility in response to the crisis. The cost of refueling is the price of the fuel, plus time spent searching for and waiting to refuel. The benefit of refueling is positively related to the tank space available. The fuller the tank, the less fuel can be gained by refueling. Consumers accept this cost when the benefit from having fuel exceeds their perceived cost.

*The three states of consumers*

The above assumption provides a basic description of the consumer decision-making process. Under normal conditions, gas stations have adequate serving capacity for consumers to refuel without waiting in queues. However, consumers behave abnormally in the hoarding condition. Our working assumption is that each consumer has three states: *calm*, *primed*, and *hoarding*. Under normal circumstances, consumers are assumed to be in the *calm* state. When consumers receive an external trigger signal, they can enter the *primed* state, which may lead to entering the *hoarding* state.

Whichever state the consumer is in, he/she is assumed to remain an economically rational decision-maker, making choices by evaluating the cost and benefit of refueling. The only difference is that the consumers start to value the fuel services higher when they are in the *hoarding* state. For those consumers who are unaffected (the *primed* state), their value of fuel services remains the same as that in the *calm* state, which triggers consumers to refuel even when there is still fuel in the tank.
These assumptions help explain the tank-topping behaviors in the hoarding context. In other words, the consumers accelerate the refuel frequency. In any unit time, the amount of consumer who decides to refuel increases, which builds up to the formation of hoarding. Though scholars have brought up theories of emergency decision-making, here we choose the easiest way to model and test its verisimilitude. We embody the principle of Occam’s razor, which believes that “entities should not be assumed without necessity”. The goal of this modeling is work is to choose the simplest model that best describes the phenomenon.

The three types of consumer

The three states of consumers explain the seemingly “irrational” behaviors of consumers. The next step is to characterize the consumers’ motivation to hoard. In Section 2.3, the dispositional hypothesis and the situational hypothesis explore two possible way to explain why some people are more sensitive to the external stimulus. Also, the sociologists suggest that some consumers engage in hoarding by imitating the other consumers’ behaviors. Based on these theories, we propose three consumer types in this model: pioneer, follower, and rational.

Figure 4.1 shows how different types of consumers transit between states. When receiving the external stimulus, all consumers transit to the primed state from the calm state. The pioneers have the propensity to hoard, because of either previous experience in scarcity or the biological instincts emerged during the evolution. Once primed, they are the first to move to the hoarding state. The pioneers’ behaviors will stimulate the followers to transit to the hoarding state. The rate of transition is positively related to current hoarding population. The larger the hoarding population is, the quicker the followers engage in hoarding. The process resembles the snowball effect, where the situation starts from an initial state of small significance and builds upon itself at a faster and
faster rate – positive feedback. The last type of consumer is more rational compared to the former two. Unlike the *pioneers* and *followers*, they never move to the *hoarding* state or engage in hoarding.

![Figure 4.1 Consumer’s Transition between States](image)

In the model, the three types of consumer are evenly distributed among the population. The distribution of *pioneer* and that of the *follower* are independent of each other. This is an oversimplification that we revisit in the sensitivity analysis. The following diagram (Figure 4.2) is the simulation result of the dynamics of the hoarding population when 35% of the consumer population are *pioneers*, and 60% of them are *followers*. The diagram shows that at the beginning of the disruption, the hoarding consumers only account for a small portion of the total population. However, the hoarding population soon becomes large because of the positive feedback. After a while, the growth rate slows down, and the hoarding population finally levels off.

The three states are simulated by the AnyLogic® Statechart. *Statechart* module has states and transitions. The state represents a location of control with pre-defined reactions to conditions and
events. Transitions between states may be triggered by user-defined conditions, such as timeouts, rates, Boolean conditions, and messages received.

![Graph](image.png)

**Figure 4.2 The Dynamics of Hoarding Population**

*35% pioneers and 60% followers. The disruption occurs at hour 0.*

### 4.1.2 Characterizing the Consumers and Vehicles

The census data from Statistics Canada shows that the city of Powell River has a population of 13,157 in 2016 (Statistics Canada, 2017a). No available public data about the number of the registered vehicle in Powell River was found. We use other available secondary data to estimate the number of the registered vehicle in the study area.

Data from Statistics Canada shows that total vehicle registration in BC reaches 3,615,373 in 2016 (Statistics Canada, 2017b). Moreover, the population of BC is about 4,751,600 in 2016 (Statistics Canada, 2017c). The vehicle per capita in BC is about 0.76. Within BC, people in Metro
Vancouver are less likely to have a car compared with people who live in the remote and semi-remote area. The convenient public transit in the Metropolitan provides transportation services for the citizen. The population of the Metro Vancouver is 2,463,431 (The Canadian Press, 2017). And the total vehicle registrations in the area is 1,632,402 in January 2016 (Insurance Corporation of British Columbia, 2017). The vehicle per capita in the Metro Vancouver area is about 0.66. Based on these data, we can also calculate the vehicle per capita in the other area of BC The results are presented in the following table (Table 4.1).

<table>
<thead>
<tr>
<th></th>
<th>Vehicle registration</th>
<th>Population</th>
<th>Vehicle per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>3,615,373</td>
<td>4,751,600</td>
<td>0.76</td>
</tr>
<tr>
<td>Metro Vancouver</td>
<td>1,632,402</td>
<td>2,463,431</td>
<td>0.66</td>
</tr>
<tr>
<td>Other areas in BC</td>
<td>1,982,971</td>
<td>2,288,169</td>
<td>0.87</td>
</tr>
</tbody>
</table>

We can assume that the vehicle per capita in the Powell River Community is about 0.87. Considering the population, we estimate that the total number of vehicles in Powell River is about 11,400. However, due to the constraint of the simulation tool AnyLogic®, we can only create 10,000 vehicle agents in the model. We believe this is an acceptable approximation as it preserves the order of magnitude with the actual system and we are seeking insights that are likely to be qualitatively the same even when the actual vehicle count is 11.4% higher. More importantly, we
assume all vehicles have similar properties. This is a far greater approximation when one considers the wide range of vehicles sizes, duty cycles and rates of fuel consumption.

Based on the description of the hoarding mechanism, the next step is to characterize the consumer’s value of time and fuel services, and vehicle specifications to support the decision-making process and further simulate the refueling and hoarding behaviors of the local consumers.

_The value of time_

In this model, we assume that how the individual values time is positively related to their income. The higher the income is, the more precious the time is. In Section 3.2, it is mentioned that the average income of Powell River residents is relatively lower compared with the mean income of BC, In other words, the consumers in Powell River are assumed to value their time less. In a hoarding context, they are more likely to join the queue even if the waiting time is long. However, the income distribution within the study area remains unclear. The Statistics Canada provides data on the income distribution of the BC in 2014 (Figure 4.3).

The AnyLogic® platform comes a large set of the probability distribution. It also supports the user to define the custom distribution, which can be continuous, discrete, or options. In this model, we assume that the income distribution in Powell River resembles that in the BC province. Considering the gap of average income, we proportionally scale down the horizontal axis by the ratio of the two average income. The number of working day in a year is about 260. People work for about 8 hours per day. Based on the above assumptions, the monetary value of time can be calculated.
The value of fuel services

The value of fuel services is hard to define as there is no survey data about how consumers perceived the functional value of the fuel. There are some examples of the changing pricing strategy of electricity suppliers. Some electricity suppliers in The Netherlands start to adopt value-based pricing strategy rather than the traditional cost-based pricing and the competition-based pricing (Energy Outlook, 2015). The price of gas, however, is much complex. The U.S. Energy Information Administration provides an explanation of gas pricing. Factors that affecting gas price includes the cost of crude oil, refining costs and profits, distribution and marketing costs and profits, and taxes (EIA, 2017). Apparently, the gas price reflects the cost of production, not the consumer perceived value of fuel directly.
In reality, the gasoline prices tend to have little effect on the demand (EIA, 2014). The very fact that fuel is relatively price-inelastic is a strong indicator that the utility derived from fuels is far greater than its price. However, few consumers refuel their vehicles as soon as there is space in the tanks. The reason behind it may be that when the fuel services operate normally, consumers do not need to worry about fuel scarcity. And refueling their vehicles when the tanks are almost empty acquire more utility than refueling when the tanks are almost full. In this model, we try to simplify this process by assuming that in the normal condition, consumers only initiate the decision-making process when the remaining fuel drops below a warning line (similar to the low-fuel warning light in the vehicles). However, they will start the process as soon as they enter the hoarding state no matter how much fuel is left. We make a conservative estimation of the value of fuel, assuming that in the normal condition, the cost and benefit analysis makes consumers accept refueling a half-full tank but refuse to visit gas station for fuel less than 10 L. The cost of refueling is related to the individual income. To make sure that all the consumers can refuel their vehicle, we use a piecewise function to define the value of unit fuel for consumers in different income levels. The assumption enables us to calculate the value of fuel services of each consumer. When the consumer starts to hoard, his/her value of fuel services increases by 50% and thus raises the chances of refueling.

**The vehicle**

The consumers can only purchase fuel with their vehicles. The other containers, such as jerry can, are not allowed to be used. To simplify the model, we further assume that each consumer owns only one vehicle. Moreover, all vehicles are identical. The vehicle tank has a capacity of 50 Liters. The fuel consumption rate of the vehicle is calculated based on information we gathered from the interviews. Powell River receives two or three fuel deliveries every week. The volume of fuel
being delivered is about 90,000L, which contains 50,000L diesel and 40,000 gasoline. In this model, we further assume that there is only one type of fuel. In total, Powell River consumes about 240,000L of fuel every week.

We then divide the total consumption by the total number of vehicles to calculate the consumption rate. In real life, most consumers refuel their car before the fuel tank runs empty. The vehicle we create will alert the owner to refuel when the remaining fuel decrease to 8L. The consumer will then execute the logic process to decide whether to fuel or not. At the beginning of the simulation, the model initialization will assign a remaining fuel volume to each car. The parameter obeys a uniform distribution between 8 to 50.

A summary of the key assumptions about characteristics of the consumer used in the study is presented in Table 4.2.

<table>
<thead>
<tr>
<th>Table 4.2 Specifications of Consumer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>State</td>
</tr>
<tr>
<td>Value</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
### 4.1.3 Characterizing the Gas Station

There are five major gas stations in the City of Powell River. The stations belong to Vanderkemp, Petro-Canada, Chevron, Shell and Top of the Hill, respectively. The five gas stations differ in business hours, locations, facilities, and gas prices. For example, Petro-Canada and Chevron stations open 24 hours a day while the others close at night. The Shell, Chevron, and Petro-Canada stations are located in the city center of Powell River. The other two, Vanderkemp and Top of the Hill, are on the edge of the town. These factors, including geospatial, price, and facility, are not the focus of this study. The focus is to create an abstract environment to interact with the consumers, allowing them to perform the act of refueling. We create five identical gas stations (Figure 4.4). Each station is the default choice of one-fifth of the consumer population.

![Figure 4.4 A Sample Gas Station in the Model](image-url)
The fuel tank of the gas station has a capacity of 65,000 L. The input pipe can receive fuel delivery. The output pipe is split into four pipelines, connecting with the four fuel dispensers. The design of the gas station is adapted from an exemplary model provided by the AnyLogic® (AnyLogic, n.d.). The gas station can serve at most four vehicles to refuel simultaneously. The entry and exit path are designed as the blue dash lines. For each car entering the station, it will choose an unoccupied fuel dispenser, refuel the tank, pay for the fuel, and leave. If none of the fuel dispensers are available, the cars will start to queue at the Queue point. It will take about 5~7 minutes to refuel a car if there’s no queue. The above refuel process is modeled using the discrete event (DE) approach. The gas station operates for 16 hours per day in the simulation.

4.1.4 Responses to Consumer Behaviors

As the validity of the model is limited by the assumptions and simplifications, the model works best for exploring relative magnitudes of changes hoarding in response to the possible strategies. We explore three possible strategies to alleviate the impacts of consumer hoarding.

Purchase ceiling

The objective of interventions to limit hoarding is to conserve the inventory and allow its allocation more equitable or to tasks critical to recovery. Imposing a purchase ceiling is a common approach to serve more clients using available inventory. The queueing theory suggests that the purchase ceiling is an effective way to increase the lengths of queues and waiting times, as it significantly reduces the average purchase size (Daskin, Shladover, & Sobel, 1976). The purchase ceiling is a form of rationing that in practice may also impose longer wait times, which itself can have a negative feedback on hoarding. Considering the value of time settings in our model, we believe
that the strategy may be good for lower-income consumers. However, the considerable amount of time is wasted in the queueing process, which results in a productivity loss.

*Purchase floor*

Purchase floor imposes a minimum purchase requirement, which helps eliminate the arrivals of irrational consumers. Tank-topping is common in previous hoarding cases. The purchase floor increases the mean purchase size and prohibits the tank-topping behavior. It rules some potential consumer out. However, the impacts on conserving fuel inventory may be limited.

*Limited Operating Hours*

In some cases, the gas stations are operated for limited hours to avoid further depletion of fuel. This drives the consumers to the other open gas stations and the consequent longer queues at open stations can discourage the other consumers from hoarding. How much this saves fuel is a function of how strongly long queues discourage consumers who are in a state of *hoarding*.

These three response strategies are simulated in the model enabling the modeler to explore system responses interactively.

### 4.1.5 Sensitivity Analysis

We conduct two types of sensitivity analysis by modifying the proportion of the *pioneer* and the *follower*. As mentioned before, there are few empirical data to support our assumptions on the hoarding mechanism. The sensitivity analysis helps confirm the robustness of the model and may also be used to explore the roles that *pioneers* and *followers* play in the hoarding. All the
simulations in this chapter assume no fuel inventory constraint so that we can focus on the changes in fuel sale.

The baseline assumption is that 35% of the whole consumer population has the propensity to hoard, either because of previous experience in scarcity or evolutionary biological instincts. This assumption is based on the results of a previous study (J. D. Sterman, 2015). And 60% of the consumers are followers. Figure 4.5 shows the fluctuation of fuel sale in 6 days. By applying the data, eventually, 75% of the consumers reach the state of hoarding. The fuel sale rushes to nearly 300% of the normal volume in the first day and remains above it until the third day. An explanation of the result is that most consumers have filled up their tanks by the third day, so the fuel sale drops down to the normal level after that. Even though the amount of fuel sale is about the same as normal, the gas stations still serve much more consumers, and the average refuel amount of each consumer is relatively lower than that in the normal scenario. The modeling results of the number of consumers being served also confirm with the explanation. In the hoarding scenario, the gas stations serve nearly 20,000 consumers, which is about five times of the normal scenario. The six-day fuel sales raise to 157% of the normal volume. The average waiting time in queues is 32 minutes in the first three days (we only focus on the first three days because the simulation shows that there is few queue problem after that).
In addition to that, the income distribution of the consumers who visit the gas station also changes (Figure 4.6). It can be observed that in the hoarding scenarios, low-income consumers take up more proportion. This is because the long queue in front of the gas stations drives away consumers who have a higher value of time, i.e., the high-income consumers.
Figure 4.6 Income Distributions of Refueling Consumers in Normal (Left) and Hoarding (Right) Scenarios

Table 4.3 shows the simulation results by assuming the different proportions of pioneer consumers. Delving deeper into the simulation results, we found that the pioneer proportion does affect the total fuel sale, the number of people who hoard, the speed of consumers’ transitions to hoarding state and the average waiting time. Sensitivity analysis of the follower proportion also shows similar trends (Table 4.4). The larger the proportion of follower, the more people engage in hoarding, the higher the fuel sales, and the longer average waiting times at the pump.
Table 4.3 Sensitivity Analysis of the Proportion of Pioneer Consumer

<table>
<thead>
<tr>
<th>Baseline % pioneers (60% followers)</th>
<th>Change (%) in total fuel sale*</th>
<th>Hoarding population (%)</th>
<th>Time when half of the population is hoarding (hour)</th>
<th>Average waiting time (minute)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>35%</td>
<td>157%</td>
<td>74%</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>10%</td>
<td>151%</td>
<td>65%</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>20%</td>
<td>153%</td>
<td>67%</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>30%</td>
<td>155%</td>
<td>72%</td>
<td>3</td>
<td>31</td>
</tr>
<tr>
<td>40%</td>
<td>159%</td>
<td>76%</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>50%</td>
<td>160%</td>
<td>80%</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>60%</td>
<td>164%</td>
<td>85%</td>
<td>1</td>
<td>35</td>
</tr>
<tr>
<td>70%</td>
<td>168%</td>
<td>88%</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>80%</td>
<td>171%</td>
<td>92%</td>
<td>1</td>
<td>38</td>
</tr>
<tr>
<td>90%</td>
<td>173%</td>
<td>96%</td>
<td>1</td>
<td>39</td>
</tr>
</tbody>
</table>

*The total fuel sale compared to the normal scenario volume.

**The average waiting time in the first three days. It is calculated by assuming the average refueling time of a car is 6 minutes.
Table 4.4 Sensitivity Analysis of the Proportion of Follower Consumer

<table>
<thead>
<tr>
<th>Baseline % followers (35% pioneers)</th>
<th>Change (%) in total fuel sale*</th>
<th>Hoarding population (%)</th>
<th>Time when half of the population is hoarding (hour)</th>
<th>Average waiting time (minute)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>157%</td>
<td>74%</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>10%</td>
<td>132%</td>
<td>41%</td>
<td>N/A</td>
<td>20</td>
</tr>
<tr>
<td>20%</td>
<td>139%</td>
<td>47%</td>
<td>N/A</td>
<td>22</td>
</tr>
<tr>
<td>30%</td>
<td>145%</td>
<td>55%</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>40%</td>
<td>148%</td>
<td>62%</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>50%</td>
<td>150%</td>
<td>67%</td>
<td>3</td>
<td>29</td>
</tr>
<tr>
<td>70%</td>
<td>164%</td>
<td>81%</td>
<td>2</td>
<td>33</td>
</tr>
<tr>
<td>80%</td>
<td>168%</td>
<td>87%</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>90%</td>
<td>170%</td>
<td>94%</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td>100%</td>
<td>173%</td>
<td>100%</td>
<td>1</td>
<td>37</td>
</tr>
</tbody>
</table>

*The total fuel sale compared to the normal scenario volume.

**The average waiting time in the first three days. It is calculated by assuming the average refueling time of a car is 6 minutes.
4.1.6 Responses to Hoarding

*Purchase ceiling*

The performance of the purchase ceiling strategy is presented in the following table (Table 4.5). We tested the model with different ceiling amount and compare the results with the normal scenario and the baseline.

The results show the purchase ceiling strategy can restrict the total fuel sale from overgrowth. The lower the ceiling is, the more fuel is preserved because the average refuel amount per capita decreases. In addition, the low purchase ceiling drives away those consumers who are not willing to queue for a small amount of fuel. For example, the gas stations serve about 20,000 consumers during the 6-day process. But when the ceiling amount is 5L, the total number of consumer served is about half of that in other scenarios. However, implementing a strategy with such small amount may not be practical in the real world. The strategy also implicitly discriminate consumers with high income. When purchase limit is set below 10L, more than half of the consumers who visit gas station has an income lower than CAN $25,000.

The results also indicated that purchase ceiling higher than 20L could hardly alleviate the hoarding problem. In the hoarding scenario where no intervention is implemented, the average refuel amount for every consumer who successfully refuels their vehicle is about 17 liters. When the purchase ceiling is too high (e.g., 40L, 35L, 30L), the changes in the average refuel amount per capita is tiny. In these scenarios, the gas stations are basically running at full capacity in the hoarding context, and the total number of consumers who are served is relatively stable. Thus, the limited changes in the refuel amount per capita finally result in limited changes in the total sale.
### Table 4.5 Influences of Purchase Ceiling on Hoarding

<table>
<thead>
<tr>
<th>Fuel sale (% of normal scenario)</th>
<th>Average waiting time (minute)</th>
<th>Total consumers served</th>
<th>Average refuel amount per capita (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal scenario</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(No hoarding)</td>
<td>100%</td>
<td>0</td>
<td>4926</td>
</tr>
<tr>
<td><strong>Baseline hoarding</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Hoarding, no intervention)</td>
<td>157%</td>
<td>32</td>
<td>19432</td>
</tr>
<tr>
<td><strong>Purchase ceiling scenarios</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40L</td>
<td>157%</td>
<td>31</td>
<td>19501</td>
</tr>
<tr>
<td>35L</td>
<td>152%</td>
<td>30</td>
<td>19601</td>
</tr>
<tr>
<td>30L</td>
<td>150%</td>
<td>28</td>
<td>19499</td>
</tr>
<tr>
<td>25L</td>
<td>144%</td>
<td>27</td>
<td>19514</td>
</tr>
<tr>
<td>20L</td>
<td>129%</td>
<td>24</td>
<td>19608</td>
</tr>
<tr>
<td>15L</td>
<td>106%</td>
<td>20</td>
<td>19753</td>
</tr>
<tr>
<td>10L</td>
<td>71%</td>
<td>13</td>
<td>19570</td>
</tr>
<tr>
<td>5L</td>
<td>21%</td>
<td>8</td>
<td>10852</td>
</tr>
</tbody>
</table>
An example of purchase ceiling is presented in Figure 4.7. The strategy effectively constrains the sale surge and thus conserve the fuel inventory.

![Figure 4.7 Fluctuation of Fuel Sale under Purchase Ceiling Strategy](image)

**Figure 4.7 Fluctuation of Fuel Sale under Purchase Ceiling Strategy**

*Purchase floor*

The second strategy, purchase floor, sets a minimum purchase requirement, which aims at reducing tank-topping and excluding “irrational” consumers. The simulation results (Table 4.6) shows that the strategy can decrease the number of consumers visiting the gas stations. The queuing problem is also alleviated. However, the strategy has limited influences on fuel sale. For example, when the minimum purchase requirement is 40L, the gas stations serve much fewer consumers. The total number of consumers visiting the gas stations is about 1/4 of that in the baseline hoarding scenario. As shown in Figure 4.8, the strategy constrains the fuel sale surge significantly in the first few
days. However, the fuel sale only decreases by about 50% because of the increasing average refuel amount per capita.

Table 4.6 Influences of Purchase Floor on Hoarding

<table>
<thead>
<tr>
<th>Purchase floor scenarios</th>
<th>Fuel sale (% of normal scenario)</th>
<th>Average waiting time (minute)</th>
<th>Total consumers served</th>
<th>Average refuel amount per capita (L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal scenario (No hoarding)</td>
<td>100%</td>
<td>0</td>
<td>4926</td>
<td>42</td>
</tr>
<tr>
<td>Baseline hoarding (No intervention)</td>
<td>157%</td>
<td>32</td>
<td>19432</td>
<td>17</td>
</tr>
<tr>
<td>5L</td>
<td>160%</td>
<td>31</td>
<td>18174</td>
<td>18</td>
</tr>
<tr>
<td>10L</td>
<td>156%</td>
<td>28</td>
<td>16015</td>
<td>20</td>
</tr>
<tr>
<td>15L</td>
<td>154%</td>
<td>28</td>
<td>13210</td>
<td>24</td>
</tr>
<tr>
<td>20L</td>
<td>131%</td>
<td>26</td>
<td>9319</td>
<td>29</td>
</tr>
<tr>
<td>25L</td>
<td>124%</td>
<td>21</td>
<td>8077</td>
<td>32</td>
</tr>
<tr>
<td>30L</td>
<td>115%</td>
<td>10</td>
<td>6976</td>
<td>34</td>
</tr>
<tr>
<td>35L</td>
<td>108%</td>
<td>8</td>
<td>6005</td>
<td>37</td>
</tr>
<tr>
<td>40L</td>
<td>101%</td>
<td>5</td>
<td>5124</td>
<td>41</td>
</tr>
</tbody>
</table>
When the minimum purchase requirement is low (e.g., 5L, 10L, 15L), its ability to reduce tank-topping is not apparent. This is because the requirement is easy to meet for most of the consumers. Another explanation is that the consumers whose tanks are relatively full may decide not to refuel the vehicles in the standard economic decision-making process. Refueling a nearly full tank can bring little benefit while the cost of joining the long queue is high. These consumers will not decide to refuel even without the minimum purchase requirement. Thus, the low requirement is much less efficient.

The income distribution of this strategy is more close to that of normal scenario. The reason behind is that available space left in the vehicle tank is the main factor that decides whether a consumer can refuel or not in this scenario. In the model, the initial amount of fuel left in the tank and the fuel consumption rate are independent of the consumer’s income. So unlike the purchase ceiling strategy, the high-income consumers are not discriminated in this scenario.
Limited operating hours

In the existing hoarding cases, many gas stations were forced to close when the fuel inventory went dry. Limited operating hours, however, cut down the service capacity of the gas station proactively to avoid the sale of too much fuel. The results summarized in Table 4.7 show that the strategy is an effective response to hoarding. Unlike the purchase ceiling strategy, which conserves fuel inventory by reducing the average refuel amount of each consumer, limiting operating hours strategy reduces the number of consumers served. As the strategy is implemented, the waiting line at the open gas station gets longer, which further discourage consumers to join hoarding. Though the average refuel amount increases, the overall fuel sale still decreases significantly.

<table>
<thead>
<tr>
<th>Table 4.7 Influences of Limited Operating Hours on Hoarding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel sale (% of normal scenario)</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>Normal scenario (No hoarding)</td>
</tr>
<tr>
<td>Baseline hoarding (No intervention)</td>
</tr>
<tr>
<td>Limited operating hours scenarios</td>
</tr>
<tr>
<td>10 hours</td>
</tr>
<tr>
<td>5 hours</td>
</tr>
<tr>
<td>2 hours</td>
</tr>
</tbody>
</table>
As shown in Figure 4.9, the gas stations are running at full capacity in the 6-day process.

![Fluctuation of Fuel Sale under Limited Operating Hours Strategy](image)

**Figure 4.9 Fluctuation of Fuel Sale under Limited Operating Hours Strategy**

### 4.2 Discussion

#### 4.2.1 The Impacts of the Consumer Group Behavior

The model simulated a hoarding scenario where thousands of people hoard and try to refuel their cars. The simulation results show that the group hoarding can result in a significant surge in demand for fuel. Comparing with the base scenario, the consumers bring the refueling ahead of the regular schedule. The long lines at the gas stations lead stations to run at a full capacity. At peak time, there are more than 55 cars waiting at each gas station. The queue may block the traffic, resulting in chaos and spread the stressful stimulus among the wider population. The fuel inventory in Powell River can support the community for about a week in the normal scenario if the fuel
tanks are full. The simulation results indicate that if no intervention is enforced, the hoarding will likely lead to fuel shortage. Besides the higher fuel sales, the hoarding also leads to wasted fuel. The fuel is expended by consumers idling in lines (if permitted) and cruising in search of available gas stations. In the simulation, the consumers spent on average 32 minutes waiting in the queue. They also visited on average two gas stations to find stations with shorter lines. This unnecessary waste of fuel deteriorates the condition.

4.2.2 The Interventions to Consumer Behaviors

Among the three proposed interventions, the purchase ceiling and the limited operating hours can significantly help alleviate in the conservation of fuel, either by reducing the average purchase amount or by reducing the number of consumers being served. The performance of the purchase floor strategy, however, is not satisfactory. While the strategy contributes to reducing tank-topping, it is not as effective in reducing total fuel sale. The results imply that the tank-topping may not be the major concern in the hoarding context. People with a relatively full tank are less likely to join hoarding, and they are not the main force of hoarding. In addition to that, the purchase floor strategy may be much more difficult to impose in a real-world setting where cars have very different tank capacities.

Combining the two effective strategies can be a better choice in responding to hoarding. Limiting the operating hours of gas stations, which leads to longer queue, can reduce the number of consumers being served. Only those consumers who need fuel most will join the line. The purchase ceiling, limit the amount of fuel each consumer can get and allow more consumers to acquire fuel. If we believe that the marginal benefit of fuel is diminishing, we achieve higher utility by serving
more consumers, though each of them gets less fuel. Figure 4.10 presents an example of combining the two strategies, where the purchase ceiling is 10 liters, and gas stations only operate for 5 hours per day. The combining strategy reduces the sale to about 26% of the normal sale. The parameters of the strategy can be adapted depending on the situation. If better fuel conservation is needed, we can further limit the operating hours or lower the ceiling.

Figure 4.10 The Performance of the Combination Strategy

4.2.3 Assumptions and Limitations

This chapter describes a multi-method model of consumer fuel hoarding. We caution the reader of the many assumptions and limitations of the model:
1) The hoarding mechanism: We proposed a mechanism to explain hoarding, assuming that there are three types of consumers and three states of consumers. The consumers may move to different states when receiving external stimulus. This mechanism remains unconfirmed. Further studies of hoarding are needed. In addition to that, the mechanism assumes that the consumers have no other concern or constraints on their time and activity. However, in a more realistic setting, the general public will have multiple triggers for hoarding (e.g., water, food) and they may have many constraints in terms of having to wait in many queues. This may accelerate how quickly they enter the hoarding state. It may also constrain how many of their requisite supplies that could actually be procured if each has a lengthy queue.

2) The assumption about Pioneers: We think pioneers may have experienced scarcity, shortage, or civil unrest before. This situational hypothesis believes that the unpleasant experience motivates them to engage in hoarding. However, the universality of the hypothesis is questionable. For instance, people who suffered from food shortage may not choose to join fuel hoarding. Experience in a shortage of one item may not lead to hoarding of another item. This assumption may overestimate consumers’ willingness to hoard certain type of supply.

3) The decision-making process of refueling: We design the process as a tradeoff between cost and benefit, which are dependent on the consumers’ value of fuel services and time. The consumers will refuel their vehicles when the value of fuel services exceeds the time cost. And in the hoarding context, the queues provide a negative feedback to discourage more consumers to hoard. This simplification fails to include many factors that may be important in the refueling decision, such as the location of the gas station, the habits or patterns of using cars, age, and education level of the consumer.
4) **Rationality assumption**: No matter which states the consumer is in, he/she behave rationally by implementing the decision-making process to decide whether or not to refuel the vehicle. The only difference is that the consumers value the fuel higher when they hoard. Many psychological studies have argued that people exhibit bounded rationality in the emergency decision-making (Gigerenzer & Goldstein, 1996; Pan, Han, Dauber, & Law, 2007). The limited time and information restrain people’s rationality. The assumption in this model may underestimate the severity of hoarding. Also, if hoarding is not a rational decision of consumers, whether the response strategies will be effective remains uncertain.

5) **The characterization of vehicles**: All the vehicles in the model are identical. They share the same tank capacity and fuel consumption rate. At the beginning of the simulation, the remaining fuel in the tanks follows the uniform distribution between 8 to 50. In the more realistic setting, the vehicle and its characteristics can affect the consumers’ decision-making of refueling. Also, strategies like purchase floor may be much more difficult to impose because cars have very different tank capacities.

6) **One fuel type**: There is only one fuel type in the model. However, this is not true in reality. For example, gasoline is the most common fuel used in the automobile of the general public. Diesel fuel is widely used in transport vehicles and electricity generators. The demand for diesel may rise higher in an emergency because critical services need more diesel to operate their vehicles and generators. It is true that some engine can still work with the inappropriate type of fuel. With more advanced engines which are fitted with sophisticated fuel metering, injection and pollution controls, they are likely to be damaged if putting in another type of fuel.

7) **The interdependence of the factors**: in this hoarding model, the settings of the consumers, including the consumer type (*pioneer*, *follower*, and *rational*), the income, the value of fuel
services, are all independent of each other. In reality, this may not be true. First, a consumer with less income is more likely to be a pioneer. For example, the retiree has less annual income. Considering their age, they may also have experienced shortage and scarcity before. Also, the vehicle tank capacity, fuel consumption rate correlates with the consumer’s income.

8) *The price elasticity of demand:* the model assumes that the price of fuel is not changed by the fuel supply disruption. In reality, gas stations usually raise fuel prices to respond to capture rent from hoarding. This may not be a good tactic since it will place a heavy burden on lower-income consumers. Also, the effectiveness of such measure is unknown.

9) *The unaffected consumption rate:* The fuel consumption rate in the hoarding scenario is the same as that in the base scenario. However, consumers may adapt their car usage based on their expectation of the future fuel supply or availability. Also, if the disruption that causes fuel supply interruption also results in other problems, such as road damage, the consumer’s use of the car will surely be affected.

10) *The unaffected gas station and refueling time:* The model focus on the impacts of disruption, on the consumers’ decision-making. In some emergency, the disruption may also affect gas station. For example, gas pumps are powered by electricity, so they are knocked out of service if there is a power blackout. In addition, the disruption may also extend the time spent on refueling. On average, each car spends about 6 minutes in refueling (not including the waiting time if there is a queue). It may take longer if the internet is not available and the consumers have to pay with cash. As the paying time gets longer, the vehicles in the queue have to wait longer.
Chapter 5: Modeling the Fuel Supply and Demand under Emergency – A Community Perspective

5.1 Model Description

Chapter 4 introduced a bottom-up model of consumers’ hoarding behavior in an emergency. It provides insights into how the demand for the fuel may change. In order to understand the fuel resilience of the community, we also need to understand the supply and the inventory. In this Chapter, we introduce a model to simulate the dynamics of the fuel inventory at the community level. The model is tested under several disruption scenarios and is used to evaluate the cost-effectiveness of current community fuel inventory strategy.

5.1.1 Disruption Scenarios

Coastal communities are under threat of myriads disruptions from various sources. Rather than where the disruption comes from or what type of disruption it is, it is which parts of the system are affected that matters. Though the whole fuel transportation system is complicated, the upstream supply chain is not under the jurisdiction of the local community. Thus, we divide the whole system into two parts: the supply chain and the demand side (the community). For the purpose of the study, we propose four scenarios:

1) BAU (Business as usual: neither the supply chain nor the demand side is disrupted;

2) Local disruption: only the demand side is disrupted while the supply chain is unaffected;

3) Supply disruption: only the supply chain is disrupted while the demand side is unaffected;

and,
4) Global disruption: both the supply chain and the demand side are disrupted.

Due to the geography of supply and demand locations and geology of the region, events impacting both the supply-side and demand-side (Global scenario) have a very low probability of occurrence. Examples of such event are a large-scale earthquake, tsunamis. The disruption can result in serious consequences although the possibility remains relatively low. The description of the four scenarios is presented in Table 5.1.

In this model, the focus is on the impacts of the disruption, on fuel supply and inventory. Fuel supply can be delayed, curtailed or interrupted by the disruption to the supply chain, such as Supply and Global disruption scenarios. The local fuel facilities, such as tank farms and pipelines, may be physically damaged if the disruption strikes the demand side (Local and Global disruption scenarios). The difference between these two scenarios is whether the fuel supply is intact. The fuel availability will be largely reduced if the supply is cut down. The community can only rely on its remaining fuel inventory until the supply is recovered or they find other sources of supply.
### Table 5.1 Description of the Four Disruption Scenarios

<table>
<thead>
<tr>
<th>Disruption</th>
<th>Supply chain</th>
<th>Demand side (Community)</th>
<th>Fuel supply</th>
<th>Fuel demand</th>
<th>Damage to local storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>No</td>
<td>No</td>
<td>Normal</td>
<td>Normal</td>
<td>No</td>
</tr>
<tr>
<td>Local disruption</td>
<td>No</td>
<td>Yes</td>
<td>Normal</td>
<td>Higher demand from local critical services and consumer hoarding.</td>
<td>Yes</td>
</tr>
<tr>
<td>Supply disruption</td>
<td>Yes</td>
<td>No</td>
<td>Interrupted</td>
<td>Higher demand from consumer hoarding.</td>
<td>No</td>
</tr>
<tr>
<td>Global disruption</td>
<td>Yes</td>
<td>Yes</td>
<td>Interrupted</td>
<td>Higher demand from local critical services and consumer hoarding.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The disruption also leads to changes in fuel demand. From the community perspective, we divide the fuel demand into two parts, one is from the individual consumers, and the other is from the critical service providers, such as police, fire brigade, and hospital. Consumer hoarding, which is modeled in Chapter 4, usually occurs when the fuel supply is interrupted. The supply failure is perceived as a signal of possible scarcity. They may engage in hoarding even if there is no shortage. The consumer hoarding may also occur in the Local Disruption scenario. But given the fuel supply remains unaffected, the probability of occurrence is lower, and the impacts are mild. The
increasing fuel demand from critical service providers usually occurs when the community is disrupted. These service providers play a vital role in emergency response and disaster relief.

5.1.2 Fuel Inventory and Inventory Strategy

A System Dynamics (SD) model was built to simulate the dynamics of local fuel inventory. Using stock, flow, and feedback loop, the model aggregates information about the fuel inventory, supply, demand and possible fuel loss due to disruptions. Unlike the Agent-based (AB) or the Discrete Event (DE) model, the SD model works only with aggregates. However, it interacts with the other models to acquire quantitative data. The interactions between parameters, agents, networks, and state charts, bridge the different modeling approaches and make the model integrated.

The SD model is shown in Figure 5.1, and the variables used are illustrated in Table 5.2. The fuel inventory is represented by stock, whose value is dependent on the supply flow, the demand flow, and the loss flow. In SD models, the stock defines the static part of the system while flow defines how stock value change in time and thus define the dynamics part of the system. The supply flow represents the fuel delivered by marine transportation. The demand flow represents the fuel demand from critical service providers and consumers. The loss flow is used to describe the fuel loss due to the damage to fuel tanks. The fuel demand from consumers is generated by the model introduced in Chapter 4. The fuel loss occurs only when the community is disrupted (Local disruption and Global disruption scenarios).
Powell River has not formed a community level decision or regulation on the fuel supply. During our interviews with Vanderkemp, one of the local gas stations, we learned that they have been building up their resilience by requesting new fuel shipments when there is available space in the tank farm. When we talked to the franchised gasoline vendors, we noted that they do not control when the fuel is ordered – it is done by headquarters and is based on fuel sales. To simplify the problem, we assume that all the retailers in the community follow the inventory management strategy of Vanderkemp. To realize the strategy in this model, we set a parameter, InventoryTarget, to represent the target value of fuel inventory. Once the fuel inventory drops below the target level, an Order message is sent out. The behaviors related to fuel supply, including order, process order, and fuel delivery, are modeled by DE approaches.
### Table 5.2 Definitions of the Objects and Parameters in the System Dynamics Model

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>FuelInventory</td>
<td>Stock</td>
<td>The fuel inventory of Powell River</td>
</tr>
<tr>
<td>FuelDelivery</td>
<td>Stock</td>
<td>The fuel delivered to Powell River</td>
</tr>
<tr>
<td>FuelLoss</td>
<td>Stock</td>
<td>The fuel loss in the disruption</td>
</tr>
<tr>
<td>FuelSupply</td>
<td>Flow</td>
<td>The fuel supply of Powell River</td>
</tr>
<tr>
<td>FuelDemand</td>
<td>Flow</td>
<td>The fuel consumption of Powell River</td>
</tr>
<tr>
<td>InventoryLoss</td>
<td>Flow</td>
<td>The fuel loss due to damage to facilities</td>
</tr>
<tr>
<td>DemandDisruption</td>
<td>Event</td>
<td>Schedule the demand disruption and apply it to the model</td>
</tr>
<tr>
<td>SupplyDisruption</td>
<td>Event</td>
<td>Schedule the supply disruption and apply it to the model</td>
</tr>
<tr>
<td>GlobalDisruption</td>
<td>Event</td>
<td>Schedule the global disruption and apply it to the model</td>
</tr>
<tr>
<td>InventoryTarget</td>
<td>Parameter</td>
<td>The inventory target of Powell River</td>
</tr>
<tr>
<td>CriticalServices</td>
<td>Parameter</td>
<td>The fuel demand of critical service providers</td>
</tr>
<tr>
<td>Consumers</td>
<td>Parameter</td>
<td>The fuel demand of consumers</td>
</tr>
<tr>
<td>Scenario</td>
<td>Dynamic Variable</td>
<td>The type of scenario defined by disruption</td>
</tr>
<tr>
<td>PStockGap</td>
<td>Dynamic Variable</td>
<td>The gap between the FuelInventory and the InventoryTarget</td>
</tr>
</tbody>
</table>
An example of the DE model is the behavior of the transportation company, City Transfer. The behaviors of City Transfer is described using the AnyLogic® Process Modeling Library. The Order sent from the Powell River will trigger the action of the flow chart (Figure 5.2). The Order is first stored in the Queue and then move the next step TakeShip. After that, a ship is seized from the Fleet and sent to deliver fuel. This action changes the value of the FuelDelivery variable in the SD model. After the delivery, the value of the FuelDelivery is set to be 0 again, and the Ship is released. The whole process is ready to start again as triggered by an order for supply.

![Figure 5.2 Discrete-event (DE) Model of Fuel Supply](image)

**5.1.3 Model’s Key Parameters and Settings**

The aggregate model simulates the community-level fuel supply and demand. The model is then tested under the four scenarios we proposed. In the model, the disruption is modeled by the Event function, which can schedule certain actions. The actions can be triggered by timeout, condition or rate. We set a random timeout ranging from 0 to 7 for the disruption. As the model time unit is the day, the disruption will occur within seven days when the model start to run.

When the disruption Event is triggered, it will impact the other parts of the model. The fuel delivery may be cut down. The consumers may engage in hoarding. In Chapter 4, we simulate the Normal Scenario, where no disruption happens, and the Baseline hoarding Scenario, where the disruption
results in hoarding while no intervention is implemented. The data generated is incorporated into this model as part of the fuel demand. Besides the above aspects, the disruption will also affect:

*Fuel demand from critical services*

In this study, we define critical services as fire, police, and medical services. They play a major role in emergency management and disaster relief. And it is necessary to ensure their access to fuel. Few existing literature looks into the fuel consumption from critical services in an emergency. Without empirical data, we can only adopt a maximum estimation based on the number of vehicles and facilities. By assuming the services operate 24/7, we can calculate the approximate fuel demand in the Emergency. In the model, it is estimated that critical service providers will consume approximately 15% of the normal community fuel consumption.

*Inventory loss*

Studies on storage tanks fragility to earthquake have shown that the tank failure probability and damage state is related to its fill level (American Lifelines Alliance (ALA), 2001; Cooper, 1997; O’Rourke & So, 2000). A recent study (Costa, Haukaas, Chang, & Dowlatabadi, 2017) develops the fragility curves for tanks with different fill levels. Storage tanks with higher fill level are more likely to suffer from severe damage, which is associated with collapse or loss of contents. The damage to storage tank may result in fuel leakage, which is not only a loss of inventory but also a threat to the surrounding environments. In our study, the disruption is an abstract concept. It represents any events that can impact the supply chain or the community, including earthquakes, hurricanes, or human-induced events. Thus, it is difficult to define the failure probabilities and damage states of the fuel tanks in different scenarios. However, we still want to reflect this feature in our model. Based on the literature on tank analysis in the seismic context (Costa et al., 2017;
Fabbrocino, Iervolino, Orlando, & Salzano, 2005; Salzano, Iervolino, & Fabbrocino, 2003), we set a range of failure probabilities for tanks with different fill levels.

**Recovery time**

We assume that the recovery of the system takes 5~7 days in the Local disruption and Supply disruption scenarios while it takes 7~10 days in the Global disruption. The reason behinds the assumption is that the affected area can get support from other areas if only part of the region is disrupted. However, in the case of large-scale disruption that affects both the supply chain and the demand side, a semi-remote community like Powell River is less likely to get enough help and resources from nearby. And it takes longer to resume in such scenario.

The following table (Table 5.3) summarizes how the model is affected in different scenarios.
<table>
<thead>
<tr>
<th>Table 5.3 Key Settings and Parameters in the Model</th>
<th>BAU</th>
<th>Local disruption</th>
<th>Supply disruption</th>
<th>Global disruption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel delivery</td>
<td>Normal</td>
<td>Normal</td>
<td>Interrupted</td>
<td>Interrupted</td>
</tr>
<tr>
<td>Consumer</td>
<td>Normal</td>
<td>Hoarding probability: 30%</td>
<td>Hoarding probability: 60%</td>
<td>Hoarding probability: 80%</td>
</tr>
<tr>
<td>Critical service providers</td>
<td>0</td>
<td>Emergency response</td>
<td>0</td>
<td>Emergency response</td>
</tr>
<tr>
<td>Fill level</td>
<td>&gt;90% No fuel loss</td>
<td>Failure probability: 40~60%</td>
<td>No fuel loss</td>
<td>Loss amount: 40~90%</td>
</tr>
<tr>
<td>Fill level</td>
<td>50%~90% No fuel loss</td>
<td>Failure probability: 10~40%</td>
<td>No fuel loss</td>
<td>Loss amount: 10~50%</td>
</tr>
<tr>
<td>Fill level</td>
<td>&lt;50% No fuel loss</td>
<td>Failure probability: 0~10%</td>
<td>No fuel loss</td>
<td>Loss amount: 0~10%</td>
</tr>
<tr>
<td>Recovery time</td>
<td>N/A</td>
<td>5~7 days</td>
<td>5~7 days</td>
<td>7~10 days</td>
</tr>
</tbody>
</table>
5.2 Simulation and Results

5.2.1 The Fuel Resilience of Powell River Community

While the model is built upon a real-world case, we do not have access to the fuel inventory data in Powell River. While several scenarios have been developed, there is no available record about previous disruptions in the study area. In order to test whether the model can reflect the real case to some extent, we run the model under the BAU scenario and examine whether the output data matches the phenomena observed in the real world.

From interviews with the local emergency management committee and the transportation company, we learn about the local storage capacity, fuel delivery frequency, and volume. The result presented in Figure 5.3 reflects the fuel consumption rate in BAU scenario and the fuel delivery. It can be seen that the fuel inventory is replenished two or three times every seven days. Moreover, the resupply volume is roughly 25% of the maximum storage capacity. Thus, the inventory management strategy is to keep a relatively high volume at hand, fully utilizing available local storage capacity. These features match with the observed facts: Powell River community fuel vendors trigger refueling orders as soon as there is room for new supply in their storage tanks. The local storage capacity is about 325,000 Liter. On average, Powell River order for a delivery every two or three days. We thus believe that this abstract model can reflect the real case at least to some extent.
Figure 5.3 Fluctuations of Fuel Inventory in the BAU Scenario

The model is then tested in other scenarios to explore the fuel resilience of the community. We run the model multiple times and count the “survival” rate of the community. Here the “survival” means the fuel inventory is not run out and the community does not suffer from a fuel shortage.

As shown in Figure 5.4, local disruption scenario, in which the disruption strikes the demand side, not the supply chain, has a very high survival rate. It is understandable since the community can always order for fuel delivery if it is short of fuel. The only chance to suffer from fuel shortage in this scenario is when the fuel delivery is still on the way, and the fuel tank collapses, and the remaining fuel cannot meet the requirements from consumer and emergency service providers. However, the shortage usually will not last long. Once the fuel is delivered, the crisis is solved.
However, the performances in Supply disruption and Global disruption scenarios are not satisfying. Hoarding is the biggest problem in Supply disruption scenario. The lack of interventions to constrain the hoarding behaviors and comfort the hoarding population leads to fuel shortage. The simulation results show that the inventory in Powell River can support the community on average about five days. As the resumption time in this model is randomly distributed among 5~7 days, the survival rate of the Supply disruption scenario is 41%. If the fuel delivery is interrupted even longer, the chances that the community suffering from shortage will increase. The last scenario, which is the hardest one, has the lowest survival rate. The hoarding and tank failure together worsen the situation. It is noteworthy that the probability of the Global disruption happening is much lower compared with the other scenarios. However, the low survival rate still alarms us of the possible catastrophic condition.
5.2.2 Proposed Strategies

Powell River community maintains a high inventory target. Once the fuel inventory drops below the target, Powell River will send out an order to replenish the fuel inventory. The original intention of keeping high inventory is to ensure adequate fuel supply within the community in case of emergency or disruption. However, the above simulations indicate that without proper emergency management measures, the seemingly abundant inventory cannot help the community through a case of emergency.

The causes of failure are consumer hoarding and the fuel loss due to tank failures. Based on the simulation results in Chapter 4, implementing purchase ceiling and limiting gas stations operating hours can effectively restrain hoarding. Also, the fragility levels introduced in the related literature show that tanks are less likely to be severely damaged if the fill level is less than 50%. In this vein, lowering the inventory target may reduce the probability of tank failure.

We rerun the model under different scenarios. We set a new inventory target, which is 40% of the storage capacity and compare the results with the original target, which is about 70%. This time we also impose strategies, including limiting the operating time to 5 hours and setting a purchase ceiling of 10 liters, on both the tests (Figure 5.5).
It can be observed that the hoarding-response strategies significantly enhance the community resilience to disruption, especially in Supply disruption and Global disruption. Comparing the results with that in Figure 5.4, with the same inventory target (about 70% of the storage capacity), the survival rate increases from 41% to 98% in the Supply disruption, from 1% to 68% in the Global disruption. The results show that responding to hoarding is a critical component of emergency management. It contributes to the fuel conservation, which ensures that the critical services can operate normally.

Looking back to Figure 5.5, the performance of the lower inventory target is also interesting. The survival rate of low inventory target in the Supply disruption is slightly below the survival rate of high inventory target. However, the low inventory strategy performs much better in the Global disruption. This is because that the lower inventory target reduce the probability of tank failures. Also, the damage states are less severe compared with the tanks with higher fill levels.
5.3 Discussion

This Chapter describes a hybrid model of the community fuel supply, demand, and inventory. We abstract four scenarios from the real world and test the model under them to evaluate the community fuel resilience to potential disruptions. Although the community has been keeping a considerable amount of fuel inventory, hoping to increase the community resilience, the strategy may not work well if consumer hoarding and tank failure occur. We propose integrating hoarding-response strategies into the emergency management. The other option, setting a lower inventory target to reduce the fill level of tank facilities and avoid tank failures, may also be effective in certain cases. The model results show that the option can increase the survival rate, especially in the Global disruption. However, the simulation performances of this option are bounded by several limitations and assumptions:

1) The assumptions on the probability of tank failure and the fuel loss amount in different tank fill level need further exploration. The probability used in this model is an estimation based on available literature. Also, the probability of failure is dependent on the specific tank structures and parameters and the type and severity of the disruption. This abstract model only provides a preliminary research on this topic.

2) We can conclude that responding to hoarding in a timely manner is beneficial to the community. However, it remains unclear whether the low inventory target strategy is better than the high target strategy or not. And it is likely that the conclusion is dependent on circumstances. The low inventory target performs better in the Global disruption and a slightly worse in the Supply disruption. However, considering the fact that the Global disruption is a small probability event, we cannot make the conclusion that the low inventory target is better than the high target. The
low inventory target strategy has another advantage that is not discussed in the model: keeping less inventory is more economical. The effectiveness of the two strategies may change as the recovery time varies. If it takes longer to resume from the disruption, it is likely that the high inventory target strategy will win.

3) The survival rate of Global disruption may be underestimated. If the disruption results in damage to tank facilities, other facilities including road and houses may also be ruined. In that case, the fuel demand from consumers will drop significantly. However, the model uses the data from base scenario (no disruption) for simulation.
Chapter 6: Conclusion

6.1 Summary

Coastal communities in BC are dependent on a multi-modal transportation network to support their basic needs, such as transportation of critical supplies. The network involves both land and marine transportation modes, various stakeholders and facilities. A broad range of potential disruptions, including natural disasters and human-induced events, are threatening the regional fuel distribution system. The remote and semi-remote communities, which are at the end of the supply chain, will experience shortages of critical supplies if the regular transportation service is disrupted beyond the level that can be met using the local inventory.

Among all the critical supplies, fuel is of special importance. First, it is hard to acquire once the supply is disrupted. In addition, it is required by the general consumers and the emergency responses vehicles and facilities. Fuel is the basis of many critical services. Police vehicles, fire trucks, and ambulances are all dependent on fuel. Critical infrastructures, such as hospitals, use diesel generators to maintain operation when the electricity network is down. In this vein, fuel availability plays a major role in the community resilience to an emergency. Recognizing the importance of fuel, we believe that there is a critical need to understand fuel resilience and plan for potential fuel disruptions from the demand-side perspectives.

Previous occurrences of fuel shortages in Canada and around the world can be explored to learn how these are triggered by a myriad of disruptions, and how the fuel shortages cause problems in emergency management and disaster relieves. In the case of fuel shortage, consumer hoarding has frequently been observed. It put unnecessary pressure on the supply chain and the emergency responses. Moreover, hoarding is considered not only a resources management problem but also a
public relations problem. However, the theories and hypothesis in economics and sociology have not formed into a complete explanation. Further research is needed to understand the mechanism and impact of hoarding in different contexts.

In this thesis, a hybrid model for simulating the community fuel supply, demand and inventory is presented. The development of the model is preceded by a detailed study of consumer behaviors and community fuel inventory strategies. We first establish a hypothesized hoarding mechanism based on the literature review. The mechanism incorporates theories from standard and behavioral economics, and sociology. By defining different types and states of the consumer, the diffusion of information among the population, the value system, and the purchase behavior, we simulate how the hoarding originates and how it is amplified. Following the identification of the hoarding mechanism, we create an Agent-based consumer community resembling the consumers in Powell River. The Agent-based approach is considered suitable for modeling complex system where the individual characteristics matter. It effectively reflects the variability of parameters and features of the different individual. In this model, each consumer interacts with each other by observing the other’s behaviors, and make a decision based the gathered information and his/her current states. We believe this approach represents the actual situation to some extents and accounts for the consumer decision-making process. The model, which is developed on the AnyLogic® platform, can also be extended to include additional rules and parameters.

The virtual community we created in the model is then tested to understand the impacts of hoarding. The simulation results show that in the hoarding context, the sale of fuel surges significantly. The level of hoarding exceeds the service capacity of the gas stations and leads to long queues. Although Powell River has no historical records of fuel hoarding, the community is not immune
to it. If no interference is implemented, the hoarding will last long, which results in local fuel shortage and chaos. We then apply three response strategies to evaluate the effectiveness of them. Among the strategies being applied, purchase ceiling and limited gas station operation hours can significantly conserve the local fuel inventory by reducing either the average refuel amount per capita or the total number of consumers served. The other strategy, purchase floor, demonstrates relatively less influence on restraining hoarding. The strategies can also be combined into a new portfolio. For example, combining the two efficient strategies, the purchase ceiling and the limited operating hours, is also effective in control hoarding. This model explores the mechanism, features, and solutions of hoarding and provides fundamental information for a further study looking into the community-level fuel resilience.

Based on the bottom-up model described above, we then develop an aggregate System Dynamics model to simulate the dynamics of community fuel inventory. We use stock and flow to represent the fuel inventory, supply, and demand. The System Dynamics modeling is an approach to understand the dynamic behaviors of the complex system in recognition of the system structures. It emphasizes a continuous view, focusing not on discrete decision or event but on the structures and design underlying the decisions. We learned about the information related to the fuel delivery of Powell River community by interviewing the key stakeholders. However, in the model, we propose using the inventory target mechanism to explain the events instead of simulating the every discrete fuel delivery.

We further abstract four disruption scenarios from the real world and test the adequacy of local fuel inventory and evaluate the fuel resilience of the community. The four scenarios are developed depending on whether the supply chain or the demand side (community) is disrupted. The detailed
description of the four scenarios is provided. The simulation results indicate the importance of adopting hoarding-response strategies in an emergency. Although the community intends to build resilience by keeping additional fuel inventory, the existing inventory will be depleted soon if hoarding occurs. By implementing the strategies, the possibility of fuel shortage decreases largely in the Supply disruption and the Global disruption scenarios.

The emergency condition will become worse if the fuel tanks are damaged in the disruption. The tank failure not only results in fuel loss but also threatens the safety of the surrounding environment. Another option we propose is to lower the current inventory target. The previous study shows that there is a correlation between the tank fill level and its damage state in an earthquake. Lower the tank fill level may contribute to lower the probability of fuel loss. A lower inventory target, together with hoarding-response strategies, can also raise the community survival rate. Its performance in the Global disruption scenario is much better than the performance of the higher inventory target as it reduces the probability of fuel loss. However, considering the fact that the Global disruption is a small probability event, we cannot conclude that the low inventory target strategy has an overwhelming superiority than the high inventory target.

The simulation model presented in this thesis is ideal to study the community fuel resilience to potential disruptions. It is noteworthy that the model is highly abstracted from the reality. As a result of lacking empirical data and record, many assumptions are made to develop the model. The numbers in the simulation results may not exactly represent the actual situation. However, the trends and the relative differences in the results may still provide insights on this topic. By adding more objects and rules, the model can be expanded to explore other relative ideas.
6.2 Policy Implications

The findings from this research are most applicable to the fuel management in remote and semi-remote coastal communities similar to those found in BC. These communities, unlike the transportation center and the population hub, are at the very end of the fuel supply chain. The relative isolation motivates them to improve the resilience to potential disruptions. However, other community can also benefit from the insights due to the similarities in critical resource management and emergency response. Public sectors that are responsible for emergency management, such as Emergency Management Committee, and key stakeholders in fuel distribution networks, such as gas station managers, can review the findings that are relative to their process. The key policy implications derived from this research are summarized below.

Detailed pre-planning

The modeling results from this study indicate the critical need for a detailed pre-planning for potential fuel disruptions. The pre-planning should include a thorough assessment of community fuel supply, inventory, and demand. It is necessary to identify the available fuel resources, develop knowledge, including sources, conveyances, facilities, personnel, and demand, of fuel. The assessment should be made on different types of disruptions and the impacts of these disruptions. This assessment can provide essential information that can be used to evaluate and redesign the current community fuel system. For example, Powell River has been keeping a considerable amount of fuel inventory, aiming at enhancing the community resilience to disruptions. However, how much fuel is needed to survive from different types of disruptions? Will the transportation and storage of fuel be affected by the disruption? What are the costs of fuel storage? Answering
these questions can help us evaluate the cost-effectiveness of keeping additional fuel in different disruption scenarios.

The pre-planning also plays a major role in ensuring the availability and feasibility of response actions and policies. The planning should take both short- and long-term risks into account and consider the possible occasions when the actions and policies are implemented. Based on the findings in this study, we propose two policies, hoarding responses and fuel prioritization. The findings from this research demonstrate that the hoarding-response strategies can make great contribution in conserving fuel inventory. Considerations should be given to form an action plan to cope with hoarding. We also propose drafting a fuel prioritization plan that gives critical service providers priority in fuel access. As mentioned before, fuel is a critical resource in emergency management and disaster relief. Ensuring that the critical service have access to fuel in advance can enhance the community resilience.

Stakeholder engagement

The community responding to disruptions need to engage key stakeholder from both public and private sectors. For example, the implementation of the two policies that we suggest above directly involves local private distributors and public service sectors. It requires not only good planning but also cooperation between public and private stakeholders. Also, the private sectors may hold resources, such as vehicles and generators, which can be useful in emergency responses. Coordination is needed to make sure the private would share the assets in an emergency.

The general public is also an important stakeholder. While they are at the end of the fuel supply chain, their influences on fuel sales can make a great difference in the emergency. Clear
communication and information sharing with the public may help stop the spread of stimulus and motivate the public to behave rationally in the emergency.

6.3 Limitations and Future Research

One of the major limitations relates to the hoarding mechanism that controls consumer behavior during an emergency. The mechanism is developed based on a comprehensive literature review of hoarding theories and cases. The existing literature covers a myriad of the commodity being hoarded in various contexts and locations. The transferability of the mechanism, when applied to fuel hoarding in the study area, remains unclear. Conducting detailed consumer behavioral analysis that considers different cases in different environments may help address the problem.

In the modeling of hoarding, some detailed consumer characteristics are not included. Specifically, the refueling behaviors of consumers are not investigated in detail. The refueling behaviors are related to factors including the consumer’s activity plans, the location of the gas station, and vehicle type. The consumer’s propensity to hoard is related to age, education level, and even gender. Also, the model does not give enough consideration on the correlations between the parameters that are included in the current model. A better understanding of the consumer characteristics can contribute to better simulation of their behaviors in different contexts. In the modeling of community fuel dynamics, we propose four disruption scenarios and make assumptions on the impacts of the disruption scenarios, on fuel supply, demand, and inventory. The descriptions of the scenarios are highly abstract and are not representative of the real condition.

The other major limitation is data accessibility. The study brings up a new approach to quantitatively simulate the consumer hoarding and the community-level fuel supply. As there are few prior studies for reference, our access to resources and information are limited. The lack of
data results in relying on assumptions and expert judgments during the modeling process. It also leads to lack of validation and calibration of the models.

Several future research directions arise from the results of this thesis. First, the model can be further tested in different contexts to evaluate its applicability and accuracy. The current model is developed to fit the condition of the Powell River, which is a relatively simple case because it acquires fuel from the single source and has a less complex transportation network. The model needs to be modified to be applied to other communities. It may also be interesting to introduce economic factors, such as fuel price, inventory cost, and transportation cost, to the current model. The model can provide a more comprehensive evaluation of the current fuel system and structures if more factors are involved.

Further research is needed to enhance and validate the hoarding mechanism, including interaction rules among the population, the decision-making process, and the consumer characteristics. Develop a better understanding of the motivation, decision-making factors, and principles, and the formation of group behavior would improve the accuracy of simulating consumer behaviors significantly. The adoption of other parameters to describe the hoarding behaviors in the model may be beneficial as well. The research into this topic can contribute to identifying the features of consumers who are more likely to hoard. It may also shed new lights on how the public sectors can take precautionary measures to reduce consumer’s propensity to hoard.
References


Lin, W., Wei, K., & Jie-ying, G. (2011). Research on emergency information management based on the social network analysis. *Information Systems for Crisis Response and Management*


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