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OPTIMIZING LAST MILE DELIVERY OF DISASTER RELIEF SUPPLIES FOR OAHU, HAWAII

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THESIS

OPTIMIZING LAST MILE DELIVERY OF DISASTER RELIEF SUPPLIES FOR OAHU, HAWAII

by

Jacob Wigal

March 2023

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The state of Hawaii and island of Oahu are vulnerable to supply chain disruptions, such that any major disaster will require emergency food distribution to local populations. However, organizations across federal, state, and local government have proposed different distribution concepts that rely on different points of distribution (PODs), where no concept on their own may be sufficient to feed Oahu communities. In this work, we develop a data set and series of models to test these concepts for populations on Windward Oahu. We develop two models that select optimal POD locations for either a pickup concept, where populations drive to receive food, or a delivery concept, where food is brought to communities. We further study hybrid concepts that prefer either pickup or delivery. Our results show that ideal plans for Windward Oahu will prefer delivery PODs and utilize 17 hybrid PODs that serve both pickup and delivery purposes. Moreover, we identify four POD locations that would be used no matter which distribution concept is implemented. We recommend developing a hybrid distribution concept centered on delivery that can be tested and implemented at these four locations.

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OPTIMIZING LAST MILE DELIVERY OF DISASTER RELIEF SUPPLIES FOR OAHU, HAWAII

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ABSTRACT

The state of Hawaii and island of Oahu are vulnerable to supply chain disruptions, such that any major disaster will require emergency food distribution to local populations. However, organizations across federal, state, and local government have proposed different distribution concepts that rely on different points of distribution (PODs), where no concept on their own may be sufficient to feed Oahu communities. In this work, we develop a data set and series of models to test these concepts for populations on Windward Oahu. We develop two models that select optimal POD locations for either a pickup concept, where populations drive to receive food, or a delivery concept, where food is brought to communities. We further study hybrid concepts that prefer either pickup or delivery. Our results show that ideal plans for Windward Oahu will prefer delivery PODs and utilize 17 hybrid PODs that serve both pickup and delivery purposes. Moreover, we identify four POD locations that would be used no matter which distribution concept is implemented. We recommend developing a hybrid distribution concept centered on delivery that can be tested and implemented at these four locations.

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List of Acronyms and Abbreviations

API	Application Programming Interface
BPR	Bureau of Public Roads
C-PODs	Community Points of Distribution
CCH-DEM	City and County of Honolulu Department of Emergency Management
CVRP	Capacitated Vehicle Routing Problem
DLA	Defense Logistics Agency
DMP	Distribution Management Plan
DOD	Department of Defense
FEMA	Federal Emergency Management Agency
HFA	Hawaii Foodservice Alliance
HIEMA	Hawaii Emergency Management Agency
MCBH	Marine Corps Base Hawaii
MPH	Miles Per Hour
NOAA	National Oceanic and Atmospheric Administration
POD	Point of Distribution
Pre-POD	Pre-covery Point of Distribution
VPH	Vehicles Per Hour
VRP	Vehicle Routing Problem

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Executive Summary

Hawaii imports 90% of its food supply, leaving the island chain vulnerable to supply chain disruptions, particularly in the event of hazards such as flooding, hurricanes, and tsunamis. Oahu's Port of Honolulu is the main destination for all Hawaiian imports, and any disruption could have devastating impacts on the island's permanent residents, service-members, and tourists. In addition there are limited local food production and storage facilities available on Oahu, making it critical that emergency distribution plans be in place to support the local population should disaster strike.

However, there is uncertainty regarding the best method for handling emergency distribution. Several organizations across the federal government, state, and the island of Oahu, including the Federal Emergency Management Agency (FEMA), Hawaii Emergency Management Agency (HIEMA), the City and County of Honolulu Department of Emergency Management (CCH-DEM), and Marine Corps Base Hawaii (MCBH), are creating emergency food distribution plans for the island of Oahu. Each organization has a unique approach to emergency distribution in addition to varied assets at their disposal. These concepts include the "Pre-covery" (which aligns with plans for HIEMA, CCH-DEM, and MCBH), where supplies are prestaged in containers in various locations, the "Points of Distribution (POD)" concept (which aligns with plans for FEMA and HIEMA), where people receive supplies through drive-through stations, and the "Delivery" concept (which aligns with plans for CCH-DEM), which utilizes trusted stakeholders to deliver supplies to food-insecure communities.

This work develops a data set and series of models to test each distribution concept for Windward Oahu. Our goal is to understand the best method of distribution for a Windward communities and how many staff will be required. We introduce two optimization models that support different emergency feeding concepts: a "Pickup-Only model" and a "Delivery-Only model." The Pickup-Only model identifies the optimal POD locations where households with vehicles can collect food by minimizing round trip travel times for all drivers. The Delivery-Only model determines optimal vehicle routing for delivery trucks to bring food to households without vehicles. Two hybrid models are also developed to optimize the joint operation of the pickup and delivery concepts. These models are two-stage

solutions where one optimal plan is developed (for either pickup or delivery), constraints based on this result are set on the other model, and then solved. Hence, our hybrid distribution models are “Pickup-Delivery” where we preference drivers picking up food from PODs and “Delivery-Pickup” where we preference truck driver routes.

We evaluate all four models based on five criteria: the number and type of PODs used, dropped demand (number of people unable to receive food), staffing needs, delivery truck requirements, and excess meals (uneaten food at the end of the day). We find the Pickup-Only model distributes the most meals with the fewest staff, but had high dropped demand because it cannot serve households without vehicles. The Delivery-Only model required the least staff, but had the most dropped demand and excess meals. The Pickup-Delivery model was less effective than the non-integrated solutions, requiring more staff and resulting in more excess meals. The Delivery-Pickup model was the most effective solution, having no dropped demand, requiring the least staff, and managing excess food supply well.

Overall, we recommend using a “Delivery-Pickup” concept that prioritizes PODs for vulnerable populations and runs them in a hybrid manner where drivers can also arrive to pick up food. Hence, we recommend stakeholders develop a new POD concept where locations that can operate in a hybrid capacity for both pickup and delivery. We identify 10 locations that are likely to be used as PODs irrespective of pickup or delivery needs, and four locations that are ideal for all potential plans. These four locations — Kahaluu Regional Park, Foodland Kaneohe #8, Keolu Elementary School, and Kelaheo Neighborhood Park are ideal locations to test POD concepts and implement hybrid operations. Moreover, these PODs are near MCBH, such that military-civilian coordination can help ensure effective hybrid operations and staffing for these locations.

Acknowledgments

I express my gratitude to the exceptional individuals at the emergency management office of Marine Corps Base Hawaii, Hawaii Emergency Management Agency, Federal Emergency Management Agency, the City and County of Honolulu Department of Emergency Management, Hawaii Foodservice Alliance, and the Pacific Disaster Center for generously sharing their time, data, and expertise. Without their contribution, this research would not have been possible. I want to give a special thanks to my thesis advisor, Dr. Daniel Eisenberg, and my second reader, Dr. David L. Alderson, for their invaluable guidance and support throughout the entire process. Lastly, I am thankful to my parents, Sharon and Tim Wigal, for their unwavering encouragement.

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CHAPTER 1:
Introduction

The state of Hawaii is thousands of miles away from the mainland United States and its allies. Due to its remote position in the Pacific, the island chain imports most of its goods, including 90% of its food supply (State of Hawaii 2012). This dependency leaves Hawaii vulnerable to supply chain disruption, which can be particularly devastating in the event of hazards such as flooding, hurricanes, and tsunamis. The most critical point of failure for Hawaii's supply chain is located on Oahu, where the Port of Honolulu is the main destination for all Hawaiian imports. Any disruption to normal operation at the port could have devastating impacts to Hawaii's permanent residents, service-members, and tourists alike. The majority of each of these groups reside on Oahu, making this issue especially important for the island.

1.1 Supply Distribution in Hawaii

Figure 1.1 depicts normal supply chain distribution operations in Hawaii. Hawaii imports the overwhelming majority of its food supply, which arrives via container ship to the Port of Honolulu on Oahu. Goods are staged at the harbor before being distributed to Oahu and the other Hawaiian islands. Oahu has extremely limited food storage capacity, most of which is at the port itself. Consequently, most goods are moved directly from the port on container trucks to their final destinations for just-in-time delivery. The second busiest port in Hawaii is less than 15 miles from the Port of Honolulu at Barbers Point. Together, these two harbors accounted for nearly 75% of all cargo volume in Hawaii in 2021 (State of Hawaii 2021).

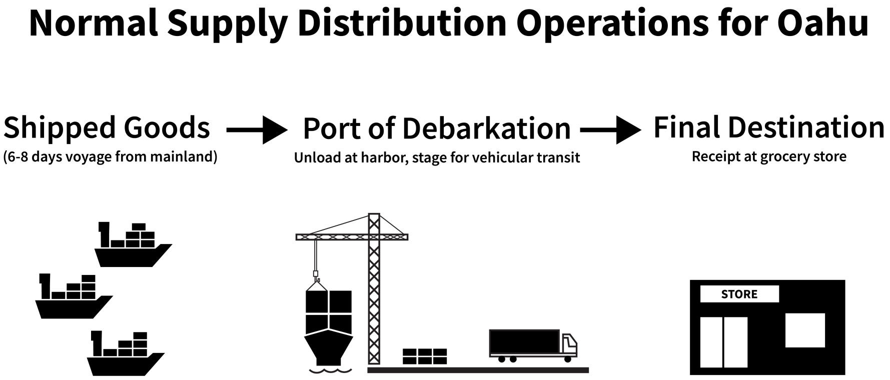


Figure 1.1. Normal Supply Distribution Operations. Once supplies arrive at the Port of Honolulu, Hawaii uses a ship-to-store distribution method due to limited storage facilities on the islands.

1.1.1 Considerations for Emergency Distribution

Hawaii's dependence on imports, lack of food storage facilities, and its centralized harbor system makes it critical that plans be in place to support the local population in the event of a disruption to the Port of Honolulu. Hawaii Emergency Management Agency (HIEMA) is currently drafting a plan for how each island can respond in the event of a Port of Honolulu closure. There is uncertainty regarding the requirements and performance of supply distribution during a future emergency. Figure 1.2 shows several key factors that impact emergency distribution operations. The effectiveness of a concept depends on the type of emergency, the features of the distribution system, and the characteristics of the population affected.

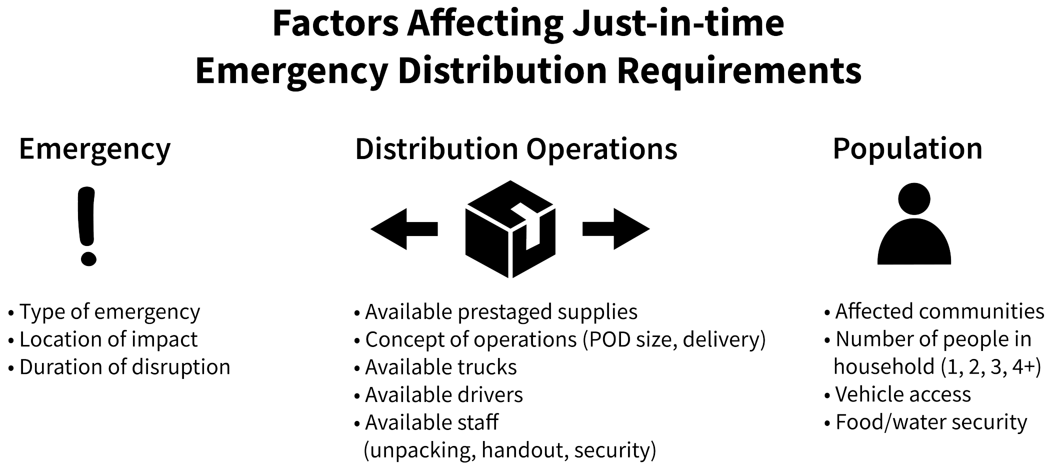


Figure 1.2. Figure examining relevant factors to consider in configuration of distribution operations. (Note: POD: Point of Distribution.)

It is necessary to understand the types of disasters that may occur in Hawaii, the feasibility of a given concept of distribution operations, and the characteristics of the population, to evaluate any emergency distribution concept.

1.2 Disasters and Supply Chains in Hawaii

The Hawaiian islands face threats to their supply chains from manmade and natural disasters. The limited availability of local food production and food storage facilities mean the consequences of a port disruption are high—in the event of a prolonged closure at the Port of Honolulu, Hawaii's supply chain will likely be empty of food within one week (Fernandes 2019). It takes six to eight days for food to reach Hawaii from the mainland by sea (City and County of Honolulu 2020), and there is concern that there will be a gap of at least three days to recover supply chain infrastructure during which no supplies may reach the islands at all (Hawaii Emergency Management Agency 2022) (see de la Cruz 2011, for an analysis of the vulnerability and recoverability of the Port of Honolulu).

Due to Oahu's position as an isolated island with a large population reliant on imported goods, supply for many goods on the island is inelastic. Supply chain disruptions affecting only a limited number of people can be extremely challenging to address. Recent and historical events that challenged supply chains in Hawaii include the Red Hill water crisis, Hurricanes Iniki and Douglas, and multiple pacific tsunamis.

1.2.1 Red Hill Water Crisis

The 2021 Red Hill water contamination crisis serves as a recent example of a significant supply chain disruption on Oahu. Fuel from the Red Hill Underground Fuel Storage Facility leaked into a freshwater aquifer that provides the water supply for residents of Joint Base Pearl Harbor-Hickam (Environmental Protection Agency 2022). Many residents subsequently noticed the tap water in their homes smelled like fuel and contained an oily sheen in appearance and experienced unusual medical ailments. The Navy estimated 8,000 families located on or nearby the base were directly affected by the leak (Lau 2022), though there were fears the contamination would spread. Tap water was shut off to these affected families to mitigate additional impacts and emergency water distribution was necessary to supply impacted communities.

Response to this crisis was extremely challenging despite its direct impacts being limited to a mostly non-civilian population on a military installation. Water production from other sources on Oahu could not shore up the shortfall in water supply. The Defense Logistics Agency (DLA), which manages the distribution of food and water for military personnel, was forced to import large quantities of bottled water from the mainland. Speaking to the fragility of Oahu's supply chain in the face of this crisis, the Commander of Defense Logistics Agency Troop Support Indo-Pacific, Erik Decker stated "we broke that supply chain with 8,000 families" (Decker 2022).

The Red Hill response relied mostly on distributing bottled water to recipients in their personal vehicles in a drive-through fashion at points of distribution, with some direct delivery to homes. Delivering bottled water to these points of distribution was constrained by the limited availability of truck drivers.

As many as 4,000 families were evacuated from their homes to nearby hotels where they could gain access to clean water, in some cases remaining there for over 3 months (Lau 2022). This may not have been possible if not for the unusually low hotel occupancy rates following the onset of the COVID-19 pandemic. The Honolulu water supply also dropped substantially as a result of the Red Hill crisis, prompting officials to encourage the public to reduce its water consumption.

1.2.2 Hurricanes

No hurricane has ever made landfall on Oahu in recorded history. The most powerful hurricane to strike Hawaii in recorded history was Hurricane Iniki in 1992. It made landfall in Kauai as a Category-4 storm, killing 7 people and damaging over 15,000 homes (Knodell 2020).

Hurricane Douglas was a Category-1 hurricane that charted a path close to Oahu and Kauai in July 2020. Despite its proximity, the hurricane resulted in minimal damage and no reported fatalities or injuries. The most significant consequences were felt in the form of infrastructure damage, where widespread flooding and debris led to closures of sections of Kamehameha Highway and several thousand people experienced power outages due to fallen trees striking power lines (Weather Channel, The 2023). The Port of Honolulu was closed for the day of the storm's approach on Sunday, July 26, but resumed operations the next day (Dicus 2020).

Future storms could pose a greater threat than those Oahu has encountered. A storm of greater severity or duration over Oahu may result in a prolonged closure of the Port of Honolulu. Many communities may also become isolated as major roads may be flooded and impassable. Given the risk of this disruption, Oahu households are currently advised by the local government to keep two-weeks supply of food and water for an emergency.

1.2.3 Tsunamis

The most extreme tsunami in both Hawaii and Oahu history occurred in 1946 following an earthquake measuring 8.6 moment magnitude near the Aleutian Islands (National Oceanic and Atmospheric Administration 2022). The tsunami was unusually powerful for an earthquake of this magnitude, causing hundreds of deaths and injuries across Hawaii, extensive flooding, and massive destruction to buildings. This historic event serves as the definitive worst-case inundation scenario for Oahu. Emergency management agencies on Oahu use this scenario for planning and commonly refer to it as the "Great Aleutian Tsunami."

A tsunami of this magnitude today would necessitate the evacuation of major portions of the island, including most communities on the windward side. This includes key military installations such as Marine Corps Base Hawaii (MCBH), which is located at Kaneohe Bay. Ports, harbors, and Oahu's main airport, Daniel K. Inouye International Airport, are also especially vulnerable to the tsunami hazard given their location on the coast and likely to experience extended downtime after a tsunami (Hawaii Emergency Management Agency 2018).

The most recent tsunami to impact Hawaii occurred in 2011 after a 9.1 magnitude earthquake occurred off the northeastern coast of Japan (National Oceanic and Atmospheric Administration 2023). This tsunami left cargo containers floating in flood waters and caused obstruction and damage to the Port of Honolulu.

1.3 Emergency Supply Distribution Concepts

The State of Hawaii has a Distribution Management Plan (DMP) that outlines what distribution should look like for any emergency or disaster. This plan, as depicted in Figure 1.3 involves coordination among multiple government agencies at different levels of jurisdiction, adding complexity beyond normal operations.

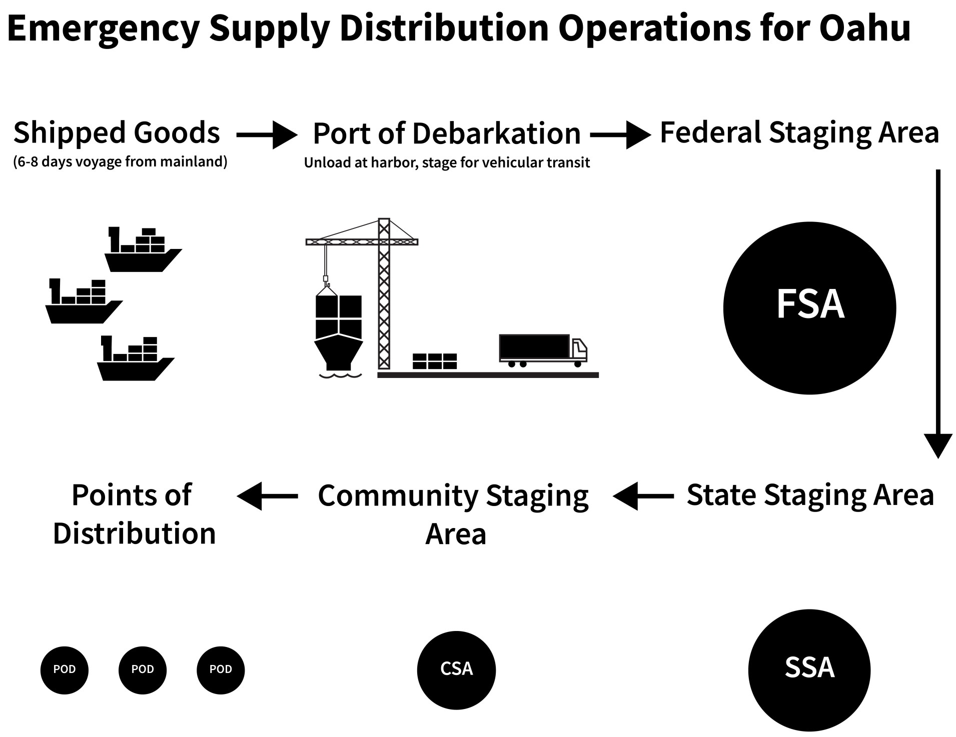


Figure 1.3. Emergency Supply Distribution Operations for Oahu. Emergency distribution adds additional staging areas and coordination between federal and local governments that complicate community access to food. Adapted from Hawaii Emergency Management Agency (2022).

Emergency supplies are acquired first by the federal government, then passed on to the state government, then to the county before they are finally received by local communities at Points of Distribution (PODs).

Organizations across the federal government, state, and the island of Oahu are each developing plans for emergency supply distribution. These include the Federal Emergency Management Agency (FEMA), HIEMA, City and County of Honolulu Department of Emergency Management (CCH-DEM), and MCBH. Each of these organizations has unique concepts of emergency supply distribution in addition to varied assets at their disposal, including:

1. **“Pre-covery” concept:** prestaging of supplies in shipping containers called Pre-

covery Points of Distribution (Pre-PODs) in distributed locations to be used when needed. This concept aligns with emergency distribution plans for HIEMA, CCH-DEM, and MCBH.

2. **“PODs” concept:** sending people to PODs to receive supplies brought in after a disaster. Supplies are distributed to vehicles similar to a drive-through. This concept aligns with emergency distribution plans for FEMA, HIEMA, and MCBH.
3. **“Delivery” concept:** using trusted stakeholders such as foodbanks to store and deliver supplies in a targeted approach to food-insecure communities. This concept aligns with emergency distribution plans for CCH-DEM.

We consider additional details for each concept.

1.3.1 Pre-covery Concept

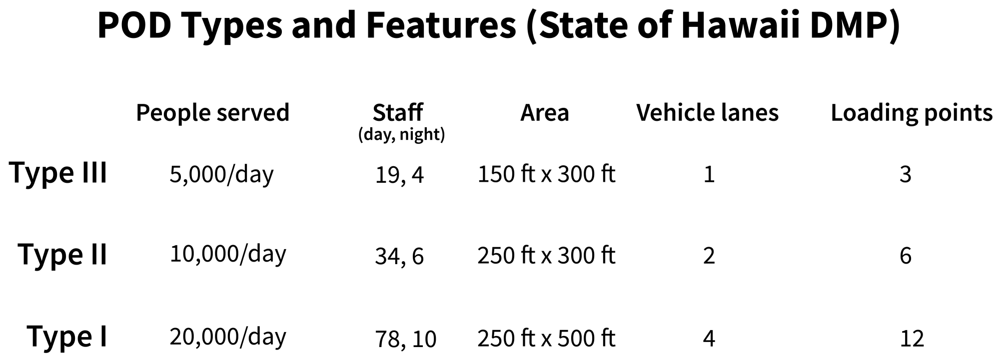
A Pre-POD is a prestaged supply of 135,000 meals stored in a storage container within the community it will serve. It is conceptualized by CCH-DEM as a “closed distribution”, meaning its supplies are to be distributed only to the most food insecure instead of the general public. Collaboration with community organizations (e.g., food banks, other non-governmental organizations) can help identify need in the community and effectively prioritize distribution. Distribution from the Pre-POD may occur both before and after a hazard event. The most food insecure of the population are unlikely to save stockpiles of any supplies distributed pre-event, and will need further supplies post-event. Staff (e.g., volunteers, truck drivers) and equipment (e.g., trucks, pallet jacks) are required to operate the Pre-POD for both pre-event and just-in-time distribution.

Location of Pre-covery PODs

The first Pre-POD was placed in the Waianae community on Oahu in January, 2022. This project was led and funded by Chad Buck, a private citizen and the CEO of Hawaii Foodservice Alliance (HFA). The location of the Pre-POD was chosen with collaboration from the CCH-DEM and is maintained by community stakeholders. CCH-DEM has plans to place a limited number of new Pre-PODs around Oahu over the next few years, prioritizing the most isolated and food insecure communities first.

1.3.2 POD Concept

PODs (sometimes referred to as community PODs or Community Points of Distribution (C-PODs) by HIEMA), are temporary facilities in centralized locations where the public must travel to obtain life-sustaining supplies following an emergency. PODs distribute two meals and one gallon of water per person each day (Hawaii Emergency Management Agency 2022). There are three types of PODs standard to FEMA emergency relief operations, from Type III (smallest) to Type I (largest), see Figure 1.4.



POD Types and Features (State of Hawaii DMP)

	People served	Staff (day, night)	Area	Vehicle lanes	Loading points
Type III	5,000/day	19, 4	150 ft x 300 ft	1	3
Type II	10,000/day	34, 6	250 ft x 300 ft	2	6
Type I	20,000/day	78, 10	250 ft x 500 ft	4	12

Figure 1.4. Standard FEMA POD types and features as defined in the State of Hawaii DMP (Hawaii Emergency Management Agency 2022).

Location of PODs

PODs are ideally positioned in centralized locations with easy ingress and egress for container trucks delivering supplies and passenger vehicles receiving supplies. Locations must also include appropriate laydown area for containers. Existing gathering places and food distribution sites such as stadiums, schools, places of worship, and grocery stores are among the locations that have been considered for the location of future PODs. No official locations have been designated for PODs on Oahu. Husemann (2022) identified preliminary locations for PODs on Windward Oahu.

1.3.3 Delivery Concept

Both the Pre-covery and PODs concepts require people to visit centralized locations to receive supplies, however some people may lack access to a vehicle or be otherwise unable to leave home during an emergency. Delivery of life-sustaining supplies may be the best distribution concept for this subset of the population. This delivery could come from a smaller box truck loaded at an existing POD or Pre-POD.

1.3.4 Comparing Concepts

Each of these concepts differ in costs and has relative advantages that must be considered in determining their usefulness for any particular emergency scenario. The "POD" and "Delivery" concepts of operations are post-storm distributions meant to distribute supplies just-in-time to meet the immediate needs of recipients. Therefore any delay to running either of these concepts (e.g., obstructed roads, lack of equipment or personnel to run operations) results in unmet needs that must be fulfilled by prestaged supplies. For the "Pre-covery" concept, it might be unreasonable to expect that all necessary supplies may be prestaged for a potential future hazard of unknown severity and duration.

Together, in a hybrid approach, these three emergency supply distribution concepts can be more than the sum of their parts. On the other hand, if we combine these methods and do it poorly it could be very ineffective: food can sit and go to waste, or people may receive an enormous amount of food when they don't need it. We want to determine what factors may make deployment of these concepts successful, while also getting a sense of the requirements necessary to deploy a specific concept in an area.

1.4 Characteristics of the Oahu Population

Understanding the unique characteristics of Oahu's local population is essential to determining how best to serve that population during a future emergency. The key factors summarized in Figure 1.2 include population size and demographics, including the number of people per household, vehicle access, and food and water security. Oahu has 1,016,508 permanent residents (Census Bureau 2020). The number of people on island is much larger however, as close to 500,000 tourists visit Oahu during any given month (Hawaii Tourism Authority 2022). Among Oahu's permanent residents are a large population of U.S. military service members, Department of Defense (DOD) civilians, and veterans, which combine to make up over 17% of Oahu's population (United States Department of Defense 2020).

In any disaster, food and water will be prioritized for the people most affected. During the Red Hill crisis, distribution was only necessary for select communities, but these communities required immediate and continuous support while others required no support at all (Santucci 2022). Identifying which communities are most vulnerable during a supply chain disruption is critical for planning efforts.

For emergency supply distribution, it is important to understand demand at the household level. The number of households, the number of people living in a household, and the vehicle access of that household are important factors in determining the requirements of any distribution concept. For example, smaller household sizes may mean more traffic congestion in the PODs concept, and more stops for a truck in the delivery concept. Also, lack of vehicle access among a community may be a great indicator that a community is not suited to the PODs concept.

The American Community Survey (2021b) reports that 9.4% of households in Oahu lack a personal vehicle, with that figure reaching as high as 30% in the Waianae community in northwest Oahu and 60% in some urban Honolulu communities. In an emergency scenario, households without vehicles would not be able to be served by the PODs concept without coordinating with others to carpool or pick up their food and water for them.

This type of coordination would be atypical for many households. Oahu residents are regularly surveyed by the U.S. Census Bureau on their means of transportation to work. For households without access to a vehicle, very few carpool regularly, while the majority rely on public transit.

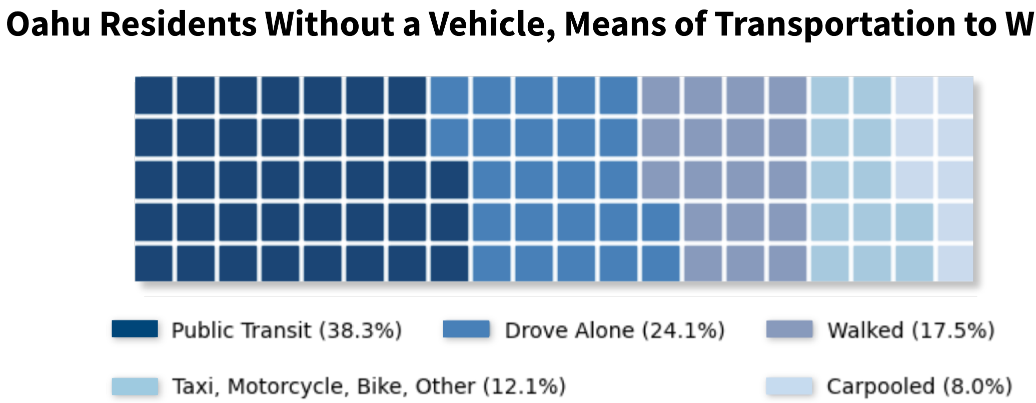


Figure 1.5. Means of transportation to work for Oahu residents with no vehicle (American Community Survey 2021a). Respondents who indicated they work from home were excluded. The large number of respondents that indicated they drove alone may have access to a work vehicle but do not personally own one.

Public transit is not compatible with the design of the PODs concept, which is intended for loading supplies onto passenger vehicles. Alternative distribution concepts such as delivery are necessary to meet the demands of households without access to vehicles.

Another important consideration for determining demand for a household is food security or preparedness. Some households may have stores of food and water that last the duration of an emergency, while others may need support the day of an emergency.

1.5 Thesis Objective

This thesis focuses on developing a model to assess the feasibility and implementation of a hybrid deployment of emergency supply distribution concepts for Oahu. Little has been done to assess how distribution concepts may perform in natural disaster scenarios, or how they may be used in a complementary fashion. It is possible that one concept may have less favorable impacts to traffic, food security, and fuel security than another (Husemann 2022). The required number of staff and assets required to implement any of these concepts is also not considered in past studies. For example, even if an analysis indicated it is optimal for residents to have a point of distribution at a specified location via the PODs concept, the CCH-DEM may be unable to staff this location, so it will serve no benefit to the local community. Towards this end, our explicit goals are:

1. Develop a model that can compare distribution concepts and determine their optimal combination for a hybrid approach.
2. Analyze the staffing requirements for hybrid distribution.
3. Provide actionable recommendations for emergency distribution that are feasible given roadway and staffing limitations.

Together, this thesis provides greater understanding of the requirements, relative advantages, and optimal integration of distribution concepts and will support more effective emergency response in future disasters.

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CHAPTER 2:
Literature Review

We review literature on emergency supply distribution operations to develop a model for last-mile distribution of emergency food in Hawaii. We build on these studies to develop an optimization model that guides hybrid distribution concepts for Oahu.

2.1 Humanitarian Relief Problems

Humanitarian relief distribution problems are a special class of supply chain management problem focused on determining where to send relief to best serve impacted communities. The three most common types of models that serve this purpose are: Location, Allocation, and Location-Allocation (Sabbaghtorkan et al. 2020).

- **Location** problems involve finding the best locations to stage operations for a given region.
- **Allocation** problems involve finding the necessary supplies and staff to deploy to meet demand at already known locations.
- **Location-Allocation** problems examine both the optimal locations for operations and the supplies and staff to meet demand at each location.

2.1.1 Location Problems

As documented by Hazewinkel (2002), one of the earliest and most influential examples of a location problem was popularized by Alfred Weber in the beginning of the 20th century. Weber's problem involved finding a point such that the sum of per-unit costs to n destination points is minimized. An early application of this problem was to find the best location to site a single warehouse such that the travel costs for customers of the warehouse would be minimized. This historical problem relates to emergency supply distribution by determining a location that is best to store food prior to delivery. This problem can also be applied with a maximization objective. For example, one could apply Weber's problem to find the location that maximizes distance from residential neighborhoods to construct an unsightly waste management facility. No matter the application, Zanjirani Farahani and Hekmatfar (2020) outline four things all location problems share:

1. some number of demand points;
2. new facilities to be located among the demand points;
3. a function for calculating the cost to traverse from demand points to the new facilities (in terms of time, monetary expense; physical distance, etc.); and,
4. a bounded, feasible solution space (e.g., the island of Oahu).

2.1.2 Allocation Problems

Allocation problems, also called resource allocation problems, involve finding the optimal assignment of a fixed amount of resources to demand points such that the cost of their assignment is minimized (Katoh et al. 2013). Applications of this problem are diverse, including a business's assignment of marketing budget to a set of advertising campaigns, a cloud computing hub's assignment of servers to customers, and an emergency management agency's assignment of supplies to a POD.

In one of the first examples of an allocation problem in the literature, Koopman (1953) examined the optimum distribution of effort in completing a search task. They sought to assign a limited budget between two tasks in search of an object with a random unknown position. This simplified approach highlights the main features of allocation problems:

1. some number of elements requiring allocation (e.g., tasks, demand points);
2. some amount of resources available to assign to those elements;
3. a function for calculating the cost of allocating resources to those elements (in terms of time, monetary expense, etc.); and,
4. a bounded, feasible solution space often defined by a time horizon (e.g., one week of operations for an emergency management agency).

2.1.3 Location-Allocation Problems

Location-allocation problems, as defined by Sabbaghtorkan et al. (2020), look for both the best location of facilities and the inventory levels assigned to those facilities. This relates to emergency distribution via the simultaneous determination of POD locations and their supply quantities for distribution. Importantly, these problems allow consideration for the relationship between facility location and inventory levels. Some facilities may require differing assets and inventory for their operation based on their location (e.g., different food quantities). Additionally, the assets and inventory necessary for facilities may be critical in determining how many new facilities can be opened. All location-allocation problems share the following features:

1. some number of demand points;
2. new facilities to be located among the demand points;
3. some amount of resources available to assign to those facilities;
4. a function for calculating distance from demand points to the new facilities (in terms of time, monetary expense, physical distance, etc.);
5. a function for calculating the cost of allocating resources to those demand points (in terms of time, monetary expense, etc.); and
6. a bounded, feasible solution space.

2.2 Special Considerations for Emergency Distribution

Planning for emergency distribution can be challenging, as it involves considering a range of factors that may be difficult to predict. The explicit formulation of these problems depends on various factors including the emergency being responded to, the capability of the responding entity to enact a certain kind of distribution operations, and the characteristics and needs of the population being served.

2.2.1 Emergency Characteristics

Emergencies are often solely described in terms of their severity. For example, many people remember that Hurricane Katrina was a Category-5 storm, but few recall the time it took for Katrina to strengthen from a Category-3 to a Category-5 hurricane (under 12 hours) (Knabb et al. 2005). However, details such as the speed of onset for a disaster can have a critical impact on emergency response coordination. Generally, disaster speed can be organized into two categories: slow onset disasters (that form over long periods and are driven by unsustainable practices) and rapid disasters

Slow and Rapid Onset Emergencies

A slow-onset emergency is defined by the United Nations Office for the Coordination of Humanitarian Affairs as “one that does not emerge from a single, distinct event but one that emerges gradually over time” (Office for the Coordination of Humanitarian Affairs 2011). Examples of a slow-onset emergency include pandemics, famines, and climate change. A key feature of slow-onset emergencies is that, theoretically, they allow ample time for coordination and prepositioning of supplies.

A rapid-onset emergency is immediate in its damage and disruption, and those affected by it require immediate response. Examples of a rapid-onset emergency include hurricanes, tsunamis, and earthquakes.

It is important to note these terms are relative, and event-specific. A weakening Category-1 hurricane with a charted course towards an expecting coastal city will allow more time for coordination than a massive 9.0 earthquake in the Midwestern United States.

The differing characteristics for both types of emergencies often inform the effectiveness for any concept of response. During the COVID-19 pandemic, many people on Oahu who had lost their primary incomes were provided with groceries by food bank popup distribution sites staffed by volunteers from the community and supplied by community donations.

This distribution concept would be entirely unfeasible during a rapid-onset emergency which may leave a community so disrupted that gathering volunteers or food donations is not possible, as community members are preoccupied with tending to their own needs.

2.2.2 Distribution Models and Concepts

There are multiple distribution models and concepts that are considered in the literature for emergency response. Some key ways these concepts differ include:

- the area of focus in the supply chain (middle mile or last mile);
- the modes of transportation used (vehicular, pedestrian);
- the locations of distribution (commercial area, food bank location, mobile pop-up, home delivery);
- consideration of required assets and inventory by location (staff, equipment, supplies);

and

- consideration of prestaging or just-in-time response.

POD-specific and related humanitarian models and case-studies

Rawls and Turnquist (2010) model a location-allocation problem while also including uncertainty about demand, survival of prestaged supplies and the condition of the transportation network following a rapid-onset emergency, namely a hurricane in the Southeastern United States. Their model does not consider the last-mile supply chain and instead focuses on the transportation of prestaged supplies from warehouses to PODs.

An et al. (2015) present a model for determining emergency facility locations that integrates facility disruption risks and the subsequent reassignment of demand, traffic congestion, and in-facility queuing delay. The model incorporates travel time for victims, service quality within the facility, and the reliability of the facility itself.

Dalal and Üster (2018) create a model to determine the location of shelters and the assignments of evacuees to shelters and from shelter to PODs. They generate random storm scenarios (hurricanes) and created fractional strength number to multiply by population to estimate demand.

Bakker et al. (2022) model a location problem choosing post-disaster facility locations for Berlin, Germany in response to a potential slow-onset emergency. They consider three concepts to be used in a hybrid fashion: PODs at public schools, “mobile PODs” or PODs opened in a temporary fashion such as a tent in a parking lot, and delivery of supplies to offsite locations such as parks or homes.

Hawaii-specific case studies

Husemann (2022) presents a model to identify POD locations for the windward side of Oahu inspired by previous studies on the US Virgin Islands. This study supports the POD concept outlined in the HIEMA DMP. This model has important limitations to note: the model does not consider whether a POD is in an inundation zone, and there are no costs to opening a POD. It is unrealistic that the City and County of Honolulu would plan on operating a POD in an area that is expected to be flooded in a disaster scenario, and that they would operate a POD irrespective of whether they have the resources available to do so. If these issues are addressed, this model can be used as a foundational piece for future work.

Shen and Kim (2020) examine the vulnerabilities of the Oahu transportation system to tidal flooding. They use data from the National Oceanic and Atmospheric Administration (NOAA) to create tidal flooding maps that show the risk of flooding on roads and critical infrastructure at four different levels of probability.

2.2.3 Population Characteristics

Natural disasters can have devastating impacts on communities, causing loss of life and damage to the infrastructure and economic systems on which communities rely. A crucial factor that influences the severity of disruption caused by a disaster is the vulnerability of a population.

Here we define *vulnerability* as the susceptibility of a community to the adverse effects of a natural disaster. It is determined by a combination of factors, including the physical, social, economic, and environmental characteristics of the community. For example, a community located in a flood-prone area with inadequate infrastructure and limited access to emergency services would be considered more vulnerable than a community with robust infrastructure and emergency response capabilities.

The most effective concepts of emergency food distribution can vary significantly depending on the characteristics of the population being served. Bakker et al. (2022) focuses on the city of Berlin which is a densely populated urban area in a high income country. The demographics of this area ultimately affect the distribution concepts considered by the model and their evaluated performance. In an urban environment, there are likely to be established networks for distributing food, such as grocery stores, restaurants, and other commercial establishments. These sites are convenient places for food distribution to occur during an emergency as they already feature the proper laydown areas, experienced personnel, and equipment for receiving and distributing large amounts of life sustaining supplies. Urban residents may have a variety of methods for reaching distribution locations such as personal vehicles, transit, or walking and biking. This same disaster in a rural area where the distribution infrastructure may be less developed would likely require the use of alternative distribution concepts such as delivery of supplies. In a low-income area where people are likely to be food insecure, the need for immediate distribution highlights the importance of prestaged supplies that can be drawn upon immediately once disaster strikes.

2.3 Our Contribution

Having reviewed the types of models commonly used in the literature and their applicability to different emergencies and populations, we now turn to the development of a model for evaluating emergency distribution in the event of a disaster on Oahu. Building upon the work of Husemann (2022), we adopt a congestion model based on the same territorial road network and destination-origin pairings. However, we aim to enhance this model by including the impact of inundation, staffing requirements, and delivery to vulnerable populations in our evaluation of a hybrid approach to distribution on Oahu.

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CHAPTER 3:
Model Formulation

The present study aims to investigate the response to a rapid-onset crisis on the island of Oahu. This emergency presents the following characteristics:

1. There is widespread and immediate demand for public assistance.
2. While there may be some pre-positioned facilities and supplies, they are insufficient to meet the demand. Responding agencies will therefore need to utilize additional public facilities, such as parking lots, schools, and churches, for the distribution of emergency supplies.
3. Most households will not evacuate and will primarily seek assistance by traveling out from their homes, provided they have access to a vehicle and the roads are not impassable.
4. Households without access to a vehicle or passable roads will require an alternative method of distribution such as delivery.

An emergency of these characteristics also presents several unknowns for responding agencies:

- What is the best method of distribution for a given community?
- Where should distribution occur?
- How many staff will be required?

To gain a deeper understanding of the logistics of emergency response to rapid-onset crises on Oahu, we focus on the windward region of the island and develop a model for post-disaster delivery of food. This chapter details the data collection, processing, and formulation used to build our model.

We develop a series of models that support different emergency feeding concepts. Part of our work builds off of previous efforts by Husemann, including data sets and a model for selecting POD locations for Windward Oahu. Where the model and data used in our study are the same, we refer the reader to Husemann (2022) for further detail. Where our approach differs, we provide a more in-depth explanation.

3.1 Data Collection and Pre-processing

We complete data collection and processing steps for several key data sets to assess POD and food distribution operations during a disaster event.

3.1.1 Points of Distribution

Key data for PODs include where they can be set up and the staffing and equipment requirements to run distribution operations.

Locations

The POD locations considered by this study include the 87 locations identified by Husemann (2022). These locations are comprised of grocery stores, schools, and state and federal land that have sufficient size and parking lots to support a POD. Each POD location is annotated with the size of the POD it can sustain (e.g., a Type I POD requires larger area and more egress points than a Type II POD. We verified the POD type for each location via onsite inspection.

Operations

The staffing requirements for a POD varies depending on the physical arrangement of equipment and organizations running the location. For instance, during the COVID-19 pandemic, HFA operated a food distribution event for nearly 16,000 people, which required 526 staff to operate (Buck 2022). This number is higher than the Hawaii Emergency Management Agency (2022) requirements which estimate that a Type I POD serving 20,000 people will require 88 staff to operate. In this study, we use the staffing requirements from HIEMA for POD operations which align with FEMA estimates for past POD operations (Table 3.1).

Upon reviewing the estimates provided by Hawaii Emergency Management Agency, we found that the number of meals available at each POD is twice the figure used by Husemann. For example, because PODs distribute *two meals per person* each day, the total number of available meals at a Type III POD is 10,000 and not 5,000.

Table 3.1. Staff Requirements for POD Operations

POD Type	Staff Required	People Served	Meals
Type I	88	20,000	40,000
Type II	40	10,000	20,000
Type III	23	5,000	10,000

Staff Requirements for POD Operations. These figures are based on HIEMA estimates provided by FEMA (Hawaii Emergency Management Agency 2022).

In addition to staffing requirements, the number of available truck drivers is important to consider in developing a model for emergency distribution. The Bureau of Labor Statistics (2021) estimates there are 2,420 truck drivers in Urban Honolulu.

3.1.2 Population

In Husemann (2022), populations on Oahu were represented by aggregated census blocks called "population nodes" which were geospatial points that represented several nearby houses connected by the local road network. Such population nodes were assigned a number of people calculated from the population of the nearby area. The number of people for each population node was used to derive feeding requirements.

This thesis enhances population nodes by adding a new attribute for each node: vehicle access. Whereas the past data assumed all households had access to a vehicle, we estimate the number of individuals at each population node without access to a vehicle, who will not be able to drive to a POD.

The data on vehicle access was obtained from the American Community Survey (2021b). It includes information on the number of vehicles per household in each census tract. This data provides the number of individuals with access to a vehicle for each tract by household type. Specifically, there are four household types considered: 1-person, 2-person, 3-person, and 4+. For the purposes of this work, households with 4 or more members are grouped into a single category and assumed to have 6 members each.

We relate each census tract to its corresponding population node and multiply the number of people per node by the percent without vehicles. First, we convert household type into people. For example, if there are 100, 3-person households in a tract that reported vehicle access, then 300 people would be assumed to have access to a vehicle. We then estimate the total percent of people in each census tract that do not have access to a vehicle. We multiply this number by each population node within each census tract to estimate people with and without access to a vehicle. This gives us an estimate of the total number of households that can drive to pick up food (has vehicle) and require delivery (no vehicle). Figure 3.1 shows the number of people at each population node without access to a vehicle.

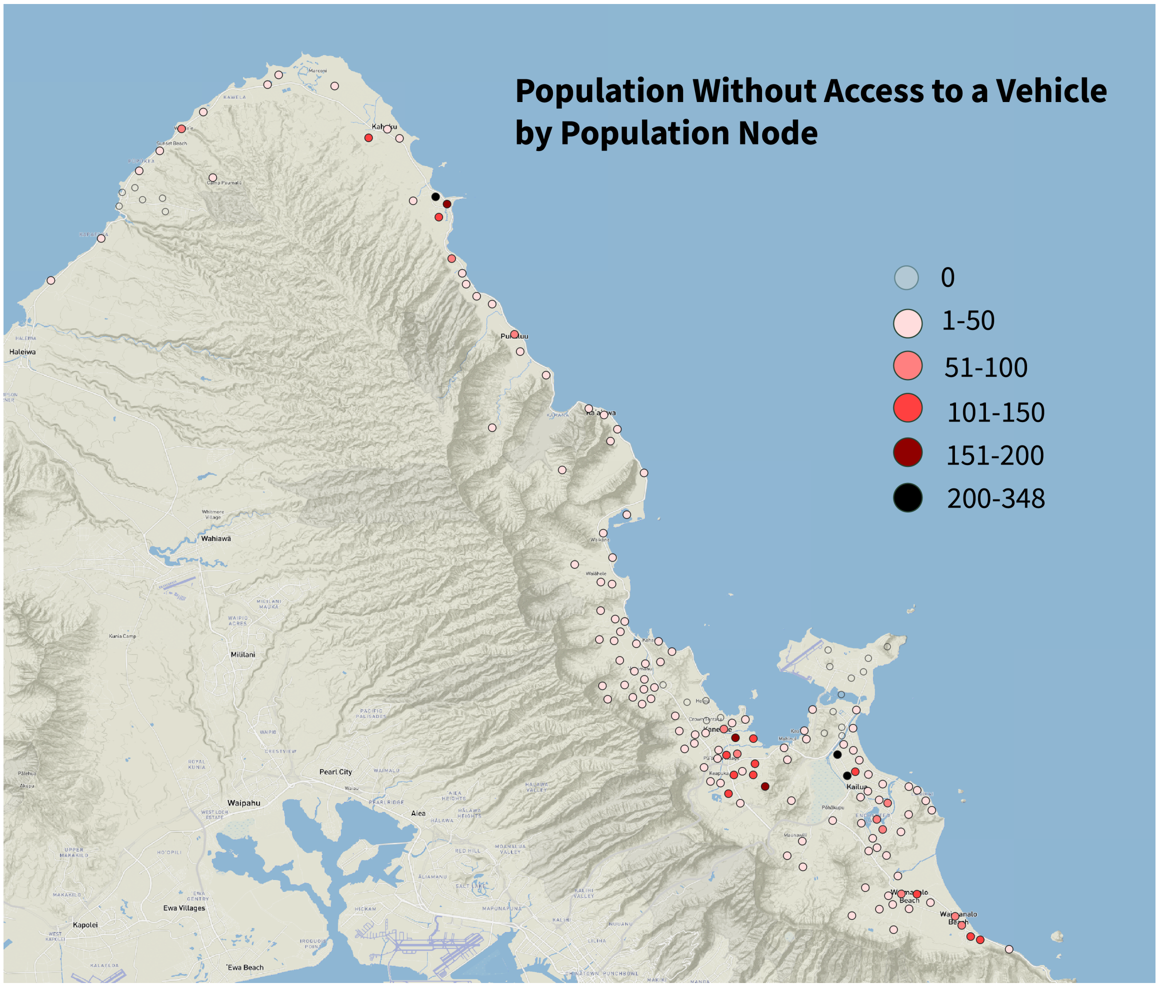

Figure 3.1. Population Without Access to a Vehicle by Population Node. Values range from 0 to 348 people.

Laie to the north and Kailua to the south have the highest concentration of individuals without vehicle access. Although most population nodes have a limited number of people (less than 50) who do not have access to a vehicle, their dispersed distribution throughout Windward Oahu poses a challenge for effective delivery.

3.1.3 Roads

The road network used in this study is adapted from Husemann (2022). This simplified representation of the Windward Oahu road network was created using data provided by the State of Hawaii Department of Transportation. Only roads that can accommodate at least 5,000 daily vehicles were included, and the road geometries were simplified to remove unnecessary modeling complexity. Moreover, errors in previous data were fixed, including connectivity among some key roads that may lead to improved traffic routing and congestion.

3.1.4 Inundation zones

We consider the impacts of disaster on POD location decisions. Specifically, we choose POD locations that are less likely to be impacted by disaster for long-term planning. For this work, we consider coastal flooding caused by sea level rise and tsunami as a key disaster. Tsunami evacuation zones for Oahu were provided by HIEMA. These evacuation zones contain the areas most vulnerable to wave surges and flooding in the event of a tsunami. This data can further inform candidate POD locations, as placing PODs in flooded areas should be avoided. There are 12 locations included in Husemann (2022) that are located in tsunami evacuation zones, depicted in Figure 3.2. For our analysis, we eliminate these 12 locations when choosing PODs.

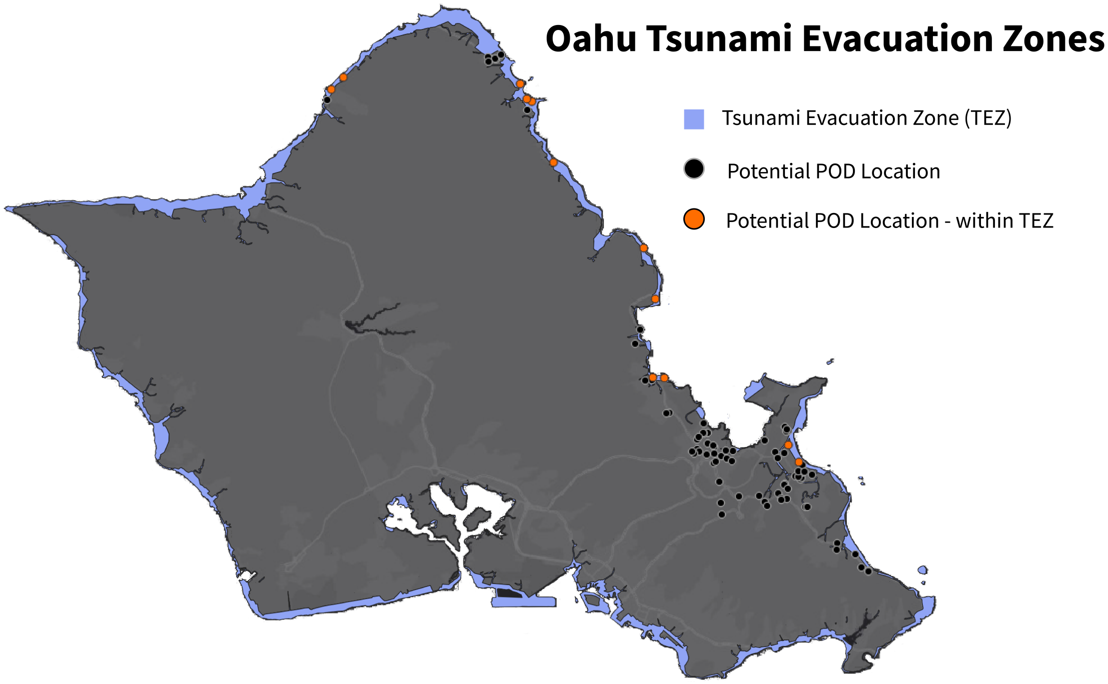

Figure 3.2. Oahu Tsunami Evacuation Zones. 12 potential POD locations originally identified by Husemann (2022) were within tsunami evacuation zones.

3.2 Windward Oahu Network

The data processing steps described above produce a network for Windward Oahu that is the foundation for our analysis of post-disaster emergency delivery of food. The model network contains 160 population nodes and 75 potential POD locations (after removing those situated in tsunami evacuation zones). The resulting network is depicted in Figure 3.3.

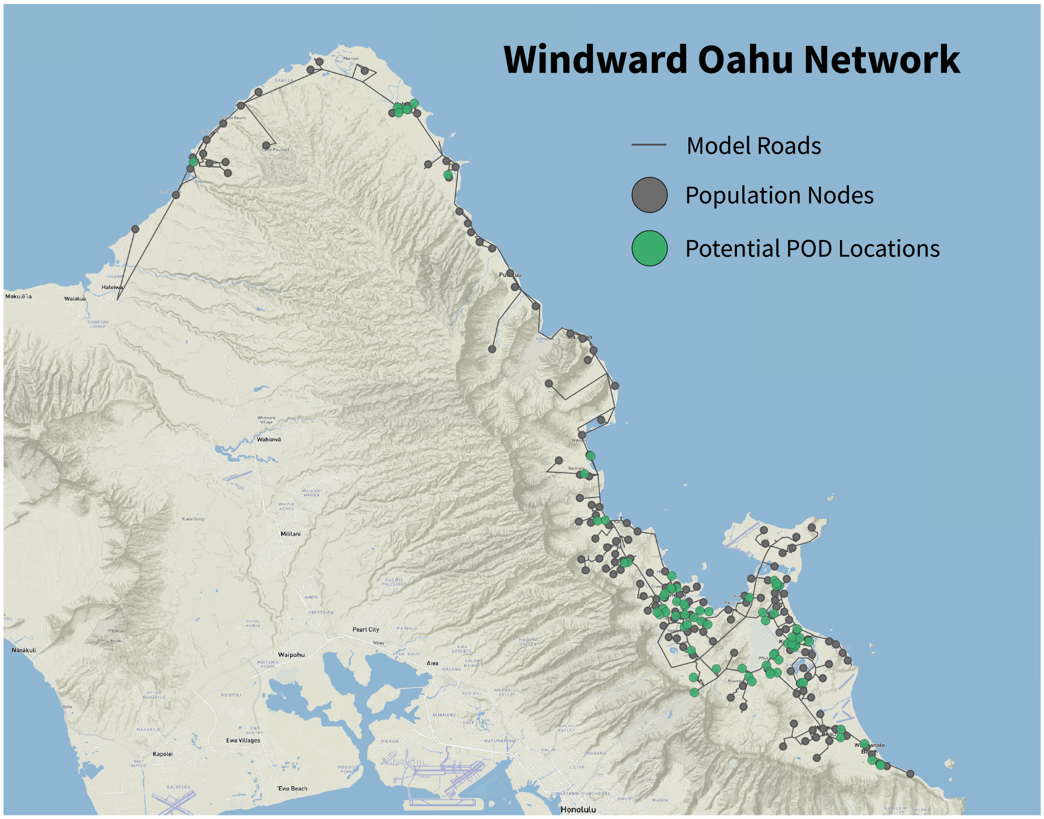

Figure 3.3. Windward Oahu Network.

The network spans from Kawailoa Beach in the North to Waimanalo Beach in the South. Potential POD locations and population nodes are primarily concentrated in the South and scarce in the North where there is lower population density, limited development, and a higher risk of flooding. The road network is more limited in the North, where Kamehameha Highway is the only road that connects the North and South. This network of roads, population nodes, and potential POD locations serves as the basis for two models:

1. **Food pickup model:** A congestion-based model to minimize round trip travel times for households with vehicles.
2. **Food delivery model:** A vehicle routing model to minimize round trip travel times for delivery trucks to deliver meals to households without vehicles.

We develop a Pickup-Only model and Delivery-Only model for Windward Oahu. For the Pickup-Only model, we can use our network directly as input data. However, for the

Delivery-Only model, we use a simplified version of the network that reduces paths between locations to be travel time estimates rather than considering the full roadway connectivity. We describe how our network model is used and any network reduction techniques employed below in the model descriptions.

3.3 Food Pickup Model

We employ the minimum-cost, multi-commodity network flow problem from Husemann (2022) to determine POD locations for communities with vehicles. This model is implemented in Python (Python Software Foundation 2001) using the open source package Pyomo (Hart et al. 2011). The original model solves a location-allocation problem that selects which PODs to open that minimizes the round trip travel time from population nodes to PODs based on non-linear traffic congestion. We refer to this model as the "Pickup-Only model" because it only considers households with vehicles and its solution is determined by minimizing the travel time for households to pick up food from a FEMA POD.

3.3.1 Model Formulation

The model formulation from Husemann (2022) is presented here in its entirety as a basis for our analysis.

Indices and Sets

$i \in N$	nodes (alias j, s, t)
$(i, j) \in A \subseteq N \times N$	arcs
$(s, t) \in D \subseteq N \times N$	set of all origin and destination pairs
$r \in R$	sections for piece-wise linear approximation ($\bar{r}$ = total number of sections)
$Out_i \subset A$	set of all outbound arcs from node i
$In_i \subset A$	set of all inbound arcs to node i
$(i, t) \in Feeders \subseteq A$	feeder arcs from POD i to sink node t

Data [units]

b_{st}	supply rate at node s destined for node t ($b_{st} < 0$ represents demand) [Vehicles Per Hour (VPH)]

u_{ij}	nominal capacity of arc (i, j) [VPH]
s_{ij}	unrestricted speed of arc (i, j) [Miles Per Hour (MPH)]
d_{ij}	length of arc (i, j) [miles]
$avail_{ij}$	1 if arc (i, j) is available for use, 0 otherwise
q	maximum intended travel window for all origin-destination round trips [hours]
POD_Type_t	largest POD type possible at destination i

Calculated Data [units]

λ_{ij}	interval width on arc (i, j) for calculating piece wise linear congestion $\lambda_{ij} = 2u_{ij}/\bar{r}$
h_{ijr}	total travel time for all vehicles traversing segment r on arc (i, j) $h_{ijr} = (r\lambda_{ij})\left(\frac{d_{ij}}{s_{ij}}\right)\left(1 + 0.15\left(\frac{r\lambda_{ij}}{u_{ij}}\right)^4\right)$
$slope_{ijr}$	slope of segment r for arc (i, j) $slope_{ijr} = \frac{h_{ijr} - h_{ijr-1}}{\lambda_{ij}}$
$intercept_{ijr}$	y intercept of line section r for arc (i, j) $intercept_{ijr} = -slope_{ijr}(r\lambda_{ij}) + h_{ijr-1}$

$maxPODFlow_{ij}$	maximum number of vehicles served by a POD of a given type
$minPODFlow_{ij}$	minimum number of vehicles served by a POD of a given type
MPD	number of meals required per person per day
$Household$	number of people per household
$MaxPODs$	maximum number of PODs on Oahu. = 120.

Decision Variables [units]

Y_{stij}	flow rate of supply originating at node s destined for node t transiting arc (i, j) [VPH]
Y_{ij}	total flow rate transiting arc (i, j) [VPH]
Z_{ij}	travel time on arc (i, j) [vehicle hours]
$Dropped_{st}$	dropped quantity of supply originating at node s destined for node t [vehicles]
$Excess_{st}$	excess quantity of demand originating at node s destined for

	node t [vehicles]
POD_{ij}	binary variable = 1 if POD chosen for flow on a $feeder$ arc [0,1]

Formulation

$$\min_{Y,Z,Dropped,Excess} \quad \sum_{(i,j)\in A} Z_{ij} + \sum_{(s,t)\in D, s\neq t} \frac{q}{2} \cdot Dropped_{st} \tag{3.1}$$

$$\text{s.t.} \quad \sum_{(i,j)\in Out_i} Y_{stij} - \sum_{(j,i)\in In_i} Y_{stji} + Dropped_{st} = b_{st} \qquad \forall i \in N, (s,t) \in D, i = s \tag{3.2}$$

$$\sum_{(i,j)\in Out_i} Y_{stij} - \sum_{(j,i)\in In_i} Y_{stji} - Excess_{st} = -b_{st} \qquad \forall i \in N, (s,t) \in D, i = t \tag{3.3}$$

$$\sum_{(i,j)\in Out_i} Y_{stij} - \sum_{(j,i)\in In_i} Y_{stji} = 0 \qquad \forall i \in N, (s,t) \in D, i \neq s, i \neq t \tag{3.4}$$

$$Y_{stij} \le b_{st} \qquad \forall (s,t) \in D, (i,j) \in A \tag{3.5}$$

$$Y_{ij} = \sum_{s,t\in D} Y_{stij} \qquad \forall (i,j) \in A \tag{3.6}$$

$$Y_{ij} \le 2u_{ij} avail_{ij} \qquad \forall (i,j) \in A \tag{3.7}$$

$$Z_{ij} \ge intercept_{ijr} + slope_{ijr} \cdot Y_{ij} \qquad \forall (i,j) \in A, \forall r \in R \tag{3.8}$$

$$Excess_{st} = Excess_{ts} \qquad \forall (s,t) \in D \tag{3.9}$$

$$Dropped_{st} = Dropped_{ts} \qquad \forall (s,t) \in D \tag{3.10}$$

$$Y_{stij}, Y_{ij}, Z_{ij}, Dropped_{st}, Excess_{st} \ge 0 \qquad \forall (i,j) \in A, (s,t) \in D \tag{3.11}$$

$$\sum_{(i,j)} POD_{ij} \le MaxPODs \qquad \forall (i,j) \in Feeders \tag{3.12}$$

$$\sum_{(i,j)} MaxPODFlow_{ij} \le POD_{ij} \frac{POD\_Type_i}{MPD * Household} \qquad \forall i,j \in Feeders \tag{3.13}$$

$$\sum_{(i,j)} MinPODFlow_{ij} POD_{ij} \ge \frac{POD\_Type_i}{MPD * Household} * MinCap \forall i,j \in Feeders \tag{3.14}$$

Discussion

We now provide a condensed description of the model's key features. For a comprehensive understanding of the model formulation and constraints, we refer the reader to Husemann (2022, pages 30-34).

The objective function 3.1 minimizes the cumulative travel time rate of vehicles from a population center s to a POD t while applying a penalty cost for any dropped demand. Constraints 3.8 set a lower bound for the travel time rate over each road segment by using the Bureau of Public Roads (BPR) function, a standard function for roadway traffic congestion (Good 2019). The BPR function sets a road's total travel time close to its travel rate when the number of vehicles on the road is below its design capacity. As the number of vehicles increases beyond the design capacity, the BPR function uses a quadratic polynomial to increase the travel time. Any vehicles that cannot complete round trips to collect food within a POD's open hours ($q = 12$ hours) are considered dropped demand.

The model includes a set of virtual arcs, called *Feeders*, which connect all PODs to a virtual node that serves as a sink for all vehicle flows. These arcs are passable only if a POD is open . The minimum and maximum flow to a POD is determined based on the POD type, as set by Constraints 3.13 and 3.14.

Solving the Pickup-Only model from Husemann (2022) as-is with the new data and network described above is likely to produce new results, including a new set of PODs to open and different total travel time for each population node. However, we also modify the model to support our analysis centered on minimizing total staff requirements. We modify the model in the following ways:

1. We add a parameter for staffing requirements, r_i for each POD i. We assume the minimum staff requirement for any POD equals that of the largest POD Type that could open at that location. For example, a POD that is rated as Type I has $r_i = 88$ even though the location could open as a smaller POD type.
2. We introduce a decision variable TS which is the total staffing requirements, or the sum of all open pods multiplied by their staffing requirements (i.e., the $POD_{ij} = 1$ if a POD at location i is open $\forall (ij) \in Feeders$). *Feeders* is the set of arcs connecting each potential POD location to a sink node for optimal routing and choice. These arcs

are only used if the corresponding POD is chosen for food pickup.

3. We add a penalty term to the objective function representing the amount of staff used across all open PODs.

3.3.2 Model Extensions

All model changes are presented below. Please refer to Husemann (2022) for additional set, parameter, decision variable, and constraint definitions as needed.

Data [units]

r_i	staff required at POD i to open [people].

Calculated Data

B	weight applied to TS in objective function. = 10.

Decision Variables [units]

TS	the total staff requirements across all PODs

Formulation

$$\min_{Y,Z,Dropped,Excess} \sum_{(i,j)\in A} Z_{ij} + \sum_{(s,t)\in D, s\neq t} \frac{q}{2} \cdot Dropped_{st} + B \cdot TS \tag{3.15}$$

$$\text{s.t.} \quad \sum_{(i,j)\in Feeders} PODs_{ij} \cdot r_i = TS \tag{3.16}$$

Discussion

The objective function Eq 3.15 now minimizes the total round trip travel time for each origin-destination pair (st) across each road network arc (ij), where Z_{ij} is the total vehicle-hours spent on each road segment in our network model (calculated from Y_{ij}, the total number of vehicles on a road segment), q is the allowed travel time window, and $Dropped_{st}$ is the number of vehicles that stay home for an origin-destination pair due to insufficient roadway capacity ($Dropped_{st} = Excess_{ts}$ for round trips). Including the term $10 \cdot TS$ in the objective, based on Eq 3.16, we now penalize choosing PODs that have high staffing requirements that do not contribute much to reducing travel time. We also penalize opening too many PODs that might lower overall travel time for the network, but require more staff. Hence, the parameter B in the objective has units of vehicle-hours per staff and is a weight representing a balance between staff requirements and difficulty for households to pick up food.

To ensure the model was solved within a reasonable amount of time, a 5% optimality gap was employed, meaning that any solutions from this model are guaranteed within 5% of the optimal solution.

3.4 Food Delivery Model

We solve a modified version of a Capacitated Vehicle Routing Problem (CVRP) to determine optimal delivery of food to households without vehicles. A CVRP is a form of Vehicle Routing Problem (VRP) (a class of travelling salesman problem), in which vehicles are routed among delivery points to minimize their total distance traveled for round trips. A CVRP is a VRP that includes capacity constraints that limit routing decisions (e.g., travel time, truck size, road congestion). The output of a CVRP is the delivery route for vehicles, travel time required to make the deliveries, and the total deliveries at each location. We use this model to determine how to optimally deliver food to population nodes that have households without vehicles. Hence, we refer to this model as our "Delivery-Only model."

3.4.1 Model Formulation

We modify the traditional CVRP as follows to represent the food delivery problem.

Indices and Sets

$i \in N$ nodes $N = N_c \cup N_p \cup N_d$ (alias j)
N_c: Population nodes
N_p: PODs

	N_d: Depot
$(i, j) \in A$	arcs $A = A_r \cup A_s$ A_r: Routes from i to j A_s: Supply arcs from i to j
$t \in T$	Trucks = $\{1, \ldots, T\}$

Parameters [units]

S_i	Supply of food for pickup at node $i \in N_p$ [meals]
D_i	Demand of food for delivery at node $i \in N_c$ [meals]
C	Capacity of a truck. Assumed 1,000 meals
$TT_{i,j}$	Travel time for route $i, j \in A$ [minutes]
UT_i	Unloading time at node $i \in N$ [minutes]
WT	Max total route time for a truck. Assumed 480 minutes (8 hours)
B	weight applied to P in objective function. = 10.

Decision Variables [units]

X_{ijt}	Amount of food carried by truck t over arc (ij) [meals]
Y_{ijt}	1 if arc (ij) is traversed by truck t; 0, otherwise
P_i	Unmet demand at population i [meals]

Objective Function

$$\min_{x,y} z = \sum_{i,j \in A} \sum_{t \in T} TT_{ij} Y_{ijt} + \sum_{i \in N_p} \sum_{j:(j,i) \in A} \sum_{t \in T} UT_i Y_{jit} + 10 \cdot \sum_{i \in N_c} P_i \tag{3.17}$$

Constraints

$$\text{s.t.} \quad S_i + \sum_{t\in T}\sum_{j:(j,i)\in A} X_{jit} \geq \sum_{t\in t}\sum_{j:(i,j)\in A} X_{ijt} \qquad \forall i \in N_p \tag{3.18}$$

$$\sum_{t\in T}\sum_{j:(j,i)\in A} X_{jit} - D_i \geq \sum_{t\in t}\sum_{j:(i,j)\in A} X_{ijt} \qquad \forall i \in N_c \tag{3.19}$$

$$X_{ijt} \leq C \cdot Y_{ijt} \qquad \forall (ij) \in A \quad \forall t \in T \tag{3.20}$$

$$\sum_{(i,j)\in A} TT_{ij} Y_{ijt} + \sum_{i\in N_c}\sum_{j:(j,i)\in A} UT_i Y_{jit} \leq WT \qquad \forall t \in T \tag{3.21}$$

$$\sum_{(i,j)\in A} Y_{ijt} \leq 1 \qquad \forall t \in T \tag{3.22}$$

$$\sum_{j:(i,j)\in A} Y_{ijt} = \sum_{j:(j,i)\in A} Y_{jit} = 1 \qquad i \in N_d \quad \forall t \in T \tag{3.23}$$

$$D_i \cdot (1 - \sum_{j:(i,j)\in A_r} Y_{ijt}) = P_i \qquad \forall i \in N_c \quad \forall t \in T \tag{3.24}$$

$$Y_{ijt}; \in \{0, 1\} \qquad X_{ijt} \geq 0 \qquad \forall (ij) \in A \quad \forall t \in T \tag{3.25}$$

$$P_i \geq 0 \qquad \forall i \in N_c \tag{3.26}$$

Discussion

The objective function 3.17 minimizes the total travel and delivery time for all trucks across all arcs in the network while minimizing unfulfilled demand at population nodes. The balance between meeting the demands of vulnerable populations and ensuring operational efficiency is set with parameter B.

Constraints 3.18 ensure trucks routed to a POD pick up the associated supply of food (500 or fewer meals). Constraints 3.19 ensure that trucks assigned to travel to a given population node deliver food that meets demands. A delivery can only be made to a population node if it satisfies that node's entire demand. Constraints 3.20 ensure that trucks can only visit nodes assigned to their route. Moreover, it ensures only a single arc is assigned to each vehicle route in the network as the maximum flow, C, is set to the capacity of a single vehicle (assumed to be 1,000 meals). Constraints 3.21 ensure that the trucks complete their routes within a time limit, W, representing drive time labor regulations. The unloading time for each delivery is represented by the parameter UT, assumed to be 1 minute for every 5 meals unloaded. Constraints 3.22 restrict the number of trucks that can visit a node to one. These constraints ensure that there are no duplicate pickups or deliveries. Constraints 3.23 specify that all trucks must begin and end their routes at the depot. Constraints 3.24 track whether delivery to a population node has occurred, and if not, applies a penalty that is equivalent to the demand at that particular node. Finally, Constraints 3.25 and 3.26 set routing decisions as binary variables and flow decisions (i.e., the quantity of food on a truck) and penalties as non-negative continuous variables.

3.4.2 Modifications from Traditional Routing Problems

We make several modifications to the traditional CVRP to determine appropriate delivery routes for Windward communities. Specifically, we aim to route a small fleet of delivery trucks that pick up and deliver food from POD locations where food is prepositioned for Windward communities. Like a traditional CVRP, all delivery routes begin from a single centralized depot. However, we have set the distance from this depot to all PODs as zero to effectively ensure that all vehicles begin their routes from a POD, capturing a scenario where drivers can start their trips close to the communities they serve. Moreover, this reflects a probable scenario where trucks and drivers on the island are restricted and may be arriving directly from another job. In addition, we have set the distance from all nodes back to the depot as zero, allowing the trucks to conclude their routes at the last delivery site. While this assumption may be reasonable in some cases, it may not be applicable in all emergency situations, where drivers may need to drive to and from a centralized depot as part of their trip time. Furthermore, we assume that all trucks are empty at the beginning of their routes and must pick up food from potential POD locations. Accordingly, round trip routing is achieved from the central depot, to at least one POD, to at least one population node in need, and then back to the central depot. A single truck may make multiple pickups and deliveries in a single, 8-hour period by visiting multiple PODs and serving many population nodes.

Finally, we also include a penalty term, P, for unmet demand in our CVRP objective to ensure all populations are covered. This forces the model to prefer longer routes as long as populations receive food. Taken together, our resulting CVRP is an NP-hard model involving integer decisions for choosing vehicle routes and balance of flows involving the pickup and delivery of food.

To simplify solution effort and time, we make several simplifications to the CVRP and network model. First, we assume that all trucks will pick up meals in increments of 500 (1/2 truckload) or less. This approach involves node splitting as described by Clarke and Wright (1964). Specifically, PODs with more than 500 meals available for pickup are split into nodes with supply of 500 or less. This means that if a vehicle is routed to a node it will either make a full pickup or delivery and ensures that each POD or population node is covered by a single vehicle. Still, due to the node splitting, multiple trucks may visit the same POD by visiting split nodes from the same location. Travel time between split nodes is assumed to be 0.

We also reduce our Windward Oahu network model to ignore roadway design and only consider travel time between locations. These simplifications lead to fewer binary decision variables and less model complexity, simplifying solution time with established heuristic algorithms.

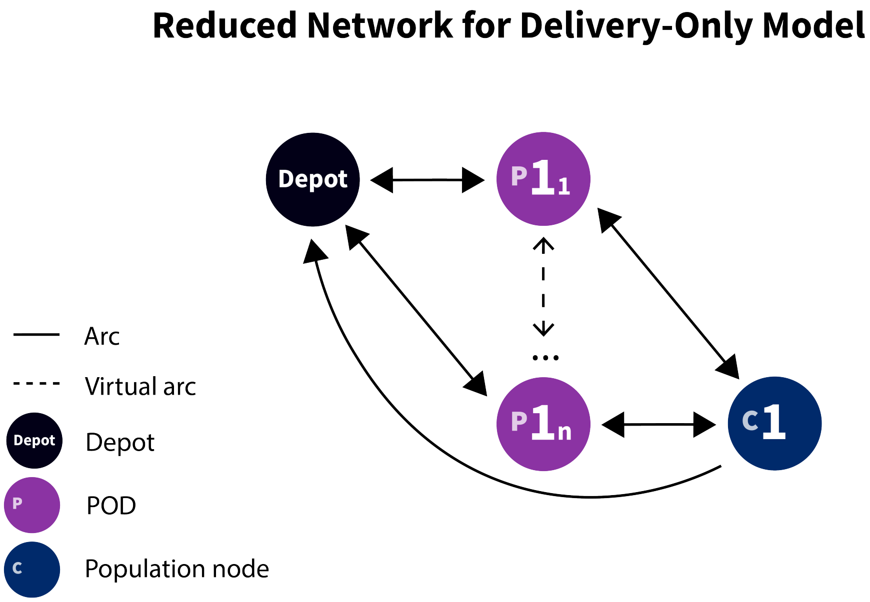
Reduced Network for Delivery-Only Model

Figure 3.4. Reduced Network for Delivery-Only model. We simplify the Windward Oahu network model for the Delivery-Only model solve. Specifically, individual roads are ignored and a single arc is given between the starting node (depot), POD nodes, and population nodes. The travel time of this arc is estimated based on shortest path through the road network given congestion. Moreover, some nodes are split to allow multiple vehicles to visit the same location and to simplify pickup and delivery decisions. For example, a POD with more meals than a given pickup quantity (500 meals) is split into multiple nodes each with 500 or less meals for pickup. Virtual arcs with 0 travel time are added between split nodes to allow a single vehicle to pick up multiple times at the same POD. Similarly, routing arcs are added between the depot and population nodes to allow vehicles to complete routes from any virtual node.

3.4.3 Implementation and Solution

We implement the Delivery-Only model using Google OR-Tools, an open source Python package for optimization (Google 2023a). Specifically, we use the Python-based Application Programming Interface (API) for Google OR-Tools to pass our model and data into a `RoutingModel` object. Because this model in Google OR-Tools is solved via a specific network algorithm, the problem instance does not strictly conform to the algebraic description in Section 3.4.1. However, for the purposes of discussion, we treat these two as equivalent.

To efficiently solve the vehicle routing problem, we take advantage of heuristic methods built-in to Google OR-Tools that are custom-designed for CVRPs. First, we employ a network algorithm to create routing options. To find the optimal solution, the model iteratively improves upon an initial feasible solution. We utilized the "savings" algorithm proposed by Clarke and Wright (1964) as our first solution strategy. The Clarke and Wright savings algorithm compares pairs of nodes to identify the potential savings in transportation costs and combines the pairs with the highest savings into a single route. This process continues until all nodes are included in the solution.

Then, the model employs a heuristic method to avoid sub-optimal solutions. We select the guided local search metaheuristic to avoid getting trapped in local optima while searching for solutions. Guided local search achieves this by adding a penalty term to the distance of each edge based on how similar the candidate solution is to previous solutions (Kilby et al. 1999). This penalty encourages diversification and enables the algorithm to explore previously unexplored regions of the solution space. This combination of techniques simplifies the model solve and ensures near-optimal solutions comparable to those produced by a conventional solver.

Additional details of the configuration used for Google OR-Tools are available in Appendix B.

3.5 Hybrid Feeding Concepts and Models

The goal of this work is to study hybrid feeding concepts that include both pickup and delivery. However, these models have separate formulations and must be solved separately. Moreover, their solutions impact one another since pickup and delivery are competing for the same resources, including:

- **POD locations:** each model wants to consider the same locations as pre-positioning for food pick or delivery. Completing both tasks at a single POD can create operational difficulties for drivers and staff.
- **Food:** each model is drawing from the same limited resource at PODs. Specifically,

meals designated for pickup by households with vehicles cannot be designated for delivery to households by trucks.

- **Roadway capacity:** as households drive to pick up food, they will create traffic that slows delivery progress. Moreover, delivery trucks on roads make many stops that can slow POD food distribution operations.
- **Staffing:** there are limited staff to operate PODs and drive vehicles. Assigning staff to support pickup and delivery pulls from the same pool of workers available for emergency response.

For these reasons, we develop hybrid solutions that combine our Pickup-Only and Delivery-Only models. Each hybrid solution uses a two-stage setup, where the first stage solves one model to optimality and then assigns restrictions on resource and routing decisions to the second model. Then, the second model is solved to optimality to find the combined capability.

3.5.1 Pickup-Delivery Strategy

In this strategy, we first solve the Pickup-Only model to determine the optimal number of PODs needed and the staffing requirement. Since the vast majority of the distribution will occur to households with vehicles, it may be beneficial to prioritize planning efforts around them. We can then use the outputs from this model as inputs for the Delivery-Only model, which will produce the total number of trucks, PODs, and staff required for the population.

Specifically, we run the Pickup-Only model given the Windward Oahu network. Then, we calculate the excess food at PODs that open for optimal pickup and reduce the total available food for the corresponding PODs in the Delivery-Only model network. Any PODs that are at full capacity are assumed unavailable for the Delivery-Only model. Moreover, we estimate the travel time between nodes in the delivery network based on congested road travel time output from the Pickup-Only model. This impacts shortest routes and potential delivery requirements within the maximum allotted drive time defined by the model. Figure 3.5 presents the complete set of inputs and outputs exchanged between the Pickup-Only and Delivery-Only models in this strategy.

3.5.2 Delivery-Pickup Strategy

In this strategy, we first solve the Delivery-Only model to determine the optimal number of trucks and PODs required, along with the staffing requirement. Since individuals without access to vehicles are likely the most vulnerable segment of the population, it may be advantageous to prioritize distribution around them initially. We can then use the outputs from this model as inputs for the Pickup-Only model, which will produce the total number of PODs and staff required for the population.

Specifically, we run the Delivery-Only model given the reduced network. We assume routing is based on free flow travel time and all PODs are available. Then, we calculate the excess food at selected PODs and reduce the total available food for the corresponding PODs in the Pickup-Only model network. Moreover, we force these PODs to be used in the Pickup-Only model by fixing associated POD decision variables, which incurs their staffing requirements. This restriction will lead to re-routing to prioritize these open PODs for pickup. Figure 3.5 presents the complete set of inputs and outputs exchanged between the Pickup-Only and Delivery-Only models in this strategy.

3.6 Evaluating Model Outputs

To assess the effectiveness of each model's results, we consider five evaluation metrics:

- **PODs:** the number and type of each POD needed for the plan.
- **Dropped demand:** the total number of meals not received by people in need in the solution.
- **Staffing requirement:** the number of staff required by the solution.
- **Delivery truck requirement:** the number of trucks required by the solution.
- **Excess meals:** the number of excess meals that is available at PODs but unused (neither picked up nor delivered).

Each metric evaluates a different aspect of the model's performance. The POD plan is a key result that informs where and how many PODs to open. Avoiding dropped demand is paramount to ensure all households have food. The availability of staff is often limited during emergencies, making it challenging to execute response plans. Therefore, minimizing staffing requirements is a crucial priority for emergency response to ensure that plans can

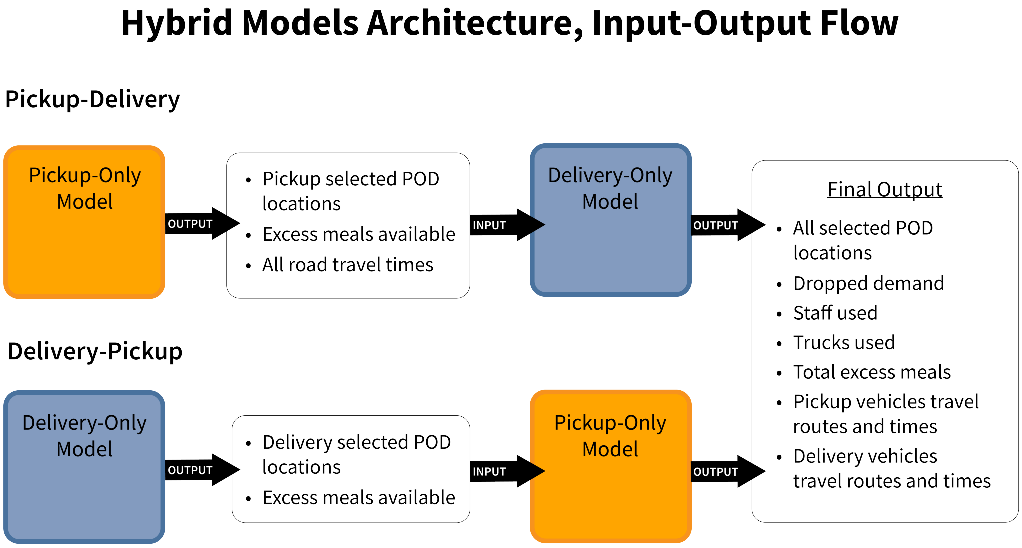

Figure 3.5. Hybrid Models Architecture, Input-Output Flow. For the Pickup-Delivery strategy, the Pickup-Only model selected POD locations, excess meals available at each POD, and the travel times from all nodes in the network to all other nodes are input into the Delivery-Only model before the outputs of each are aggregated to produce a final solution. For the Delivery-Pickup strategy, the Delivery-Only model selected POD locations and excess meals available at each POD are input into the Pickup-Only model before the outputs of each are aggregated to produce a final solution.

be carried out effectively. Likewise, delivery trucks and drivers are also scarce during emergencies, so it is important to minimize the number of required delivery trucks required. Finally, minimizing excess meals is important because excess meals may indicate the wasting of resources that could have been better utilized elsewhere, but it is considered the least critical among the five factors. In emergencies, having a surplus of food is preferable to scarcity because excess meals can still serve as backup supplies.

Through an assessment of the models' performance based on the defined metrics, we can obtain valuable insights into the food distribution strategies that prove most effective in emergency situations. Leveraging the results from the models, we can then compare different distribution concepts to determine their feasibility for Windward Oahu.

CHAPTER 4:
Analysis and Results

Using the methods presented in Chapter 3, we generate potential POD plans for emergency distribution of food on the windward side of Oahu. We consider four models:

1. **Pickup-Only** where PODs are chosen to minimize travel time for people to drive to PODs and receive food.
2. **Delivery-Only** where PODs are chosen to minimize travel and drop-off time for delivery trucks bringing food from PODs to households without vehicles.
3. **Pickup-Delivery** a two-stage solution where we select optimal pickup PODs first, then choose delivery PODs based on remaining food and locations.
4. **Delivery-Pickup** a two-stage solution where we select optimal delivery PODs first, then choose pickup PODs based on remaining food and locations.

Each model is evaluated according to the five evaluation metrics detailed in Section 3.6.

4.1 Optimal Pickup Locations

We run the Pickup-Only model to obtain an optimal solution that minimizes round trip travel time for drivers and staffing requirements for PODs. The selected PODs and resulting network congestion are displayed in Figure 4.1. Using Pyomo and the CBC solver (Forrest et al. 2022), the model contains 511,830 variables and 304,779 constraints, and it solves in approximately 31 minutes on an M1 Macbook Pro with 32 gigabytes of memory. Our baseline solution has an optimality gap of 3.8%. The solution appears in Figure 4.1.

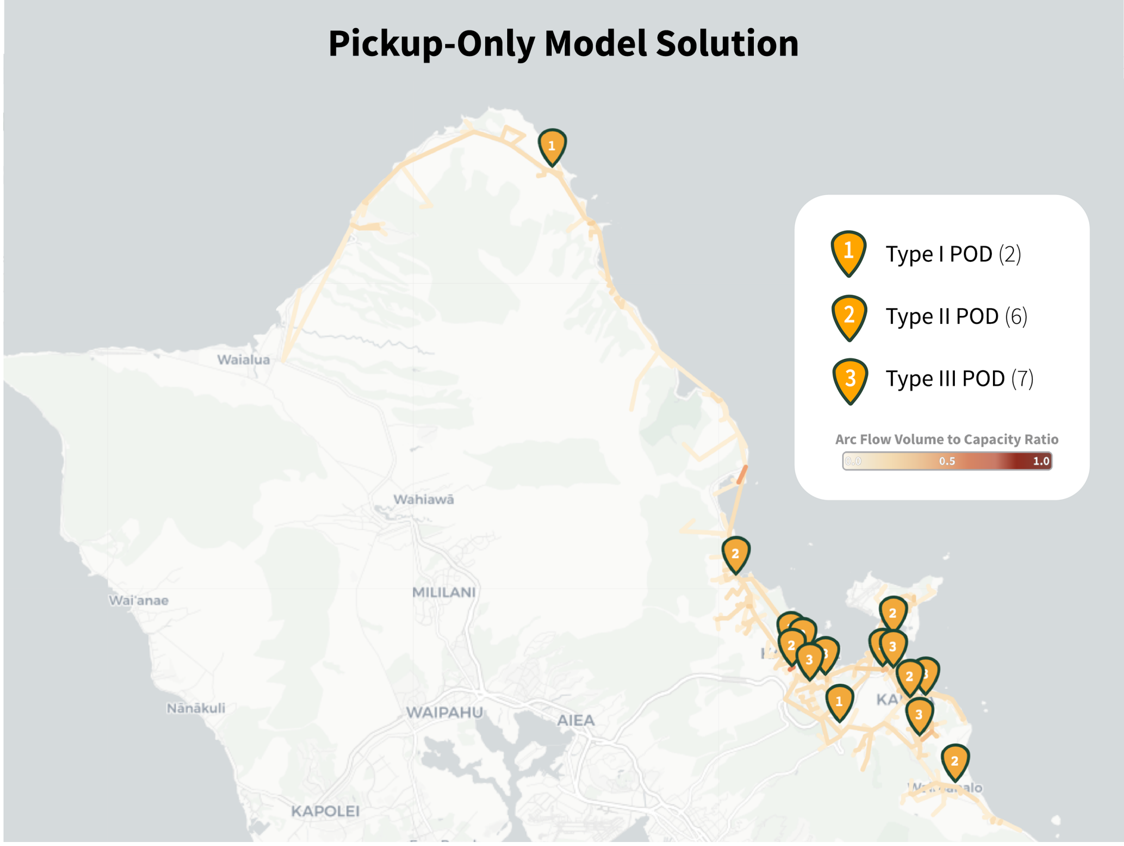

Figure 4.1. Pickup-Only Solution. 15 PODs are chosen for this distribution plan, with the majority in population centers near MCBH. A full list of the selected PODs for this solution is listed in Appendix A, Table A.2.

To satisfy the demand of the population who can drive, 15 PODs are required. The Pickup-Only model selected 2 Type I PODs, 6 Type II PODs, and 7 Type III PODs, all located within the southeastern portion of the windward side of Oahu near Marine Corps Base Hawaii and Kaneohe Bay, with the exception of one POD at Kahuku in the north.

Table 4.1 presents the performance of this plan. The staffing requirement for the 15 PODs is 577 people. No delivery vehicles were used, causing a dropped demand of 10,452 meals for people unable to drive. There were 7,580 excess meals available at the PODs that remained unconsumed.

Table 4.1. Pickup-Only model Performance.

# of PODs	Dropped Demand	Staff	Delivery Trucks	Excess Meals
15	10,452	577	0	7,580

Despite these limitations, we find our pickup POD plan more efficient and desirable than previous studies. When using similar data and inputs to the Pickup-Only model, Husemann (2022) produced a POD plan that used 63 PODs to achieve similar coverage of communities. This plan also favored Type III PODs because it only considered travel time in its objective and did not consider staffing requirements. The higher number of small PODs reduces traffic by both minimizing the number of people traveling to the same destination and the distance they must travel, but also requires a larger staff of 1,616 people. Moreover, the previous POD plan produces significant excess food of 445,770 meals that would be potentially wasted.

We also measure traffic congestion to help identify which communities will take the longest to access emergency food. The greatest congestion is observed on the roads leading to specific communities in Kaneohe and the central windward coast near Kualoa, but it was not enough to impact travel times. The average round trip travel time was 17.1 minutes with a standard deviation of 15.0 minutes. However, the longest round trip travel times are shown in Table 4.2. The longest round trip travel time is 86.5 minutes. Thus, the majority of the Windward population will be able to access food quickly (30 min or less), where a small minority will have significantly longer travel times (over 1 hour).

Table 4.2. Five Longest Round Trip Travel Times (Pickup-Only).

ID	Distance (Miles)	Travel Time (Minutes)
population134	55.8	86.5
population81	54.2	83.2
population102	40.6	63.1
population103	40.0	61.7
population134	36.9	57.6

4.2 Optimal Delivery Routing

We run the Delivery-Only model in Google OR-Tools to minimize number of trucks and dropped demand. We solve this problem on an M1 Macbook Pro with 32 gigabytes of memory using the network search algorithms described in Section 3.4.3. There are 137 population nodes, 1 depot, 75 POD locations which are split into 1,440 nodes, and a distance matrix of size size 1,578 by 1,578. The model solves in approximately 10 minutes. The selected PODs are displayed in Figure 4.2.

The solution is comprised of 17 PODs of Type III, with no Type I or Type II PODs. Type III PODs are the most appropriate as the demand is small (10,452 meals) and spread across a wide area (see Figure 3.1). There are no PODs selected in the central portion of the windward coast between Waiahole and Laie because all available locations are within inundation zones (see Figure 3.2).

The performance of this model is presented in Table 4.3. To fulfill the demand for food delivery, the model requires 7 trucks and 17 PODs. The staffing requirement for the PODs is 391 people. The Delivery-Only model prioritizes selecting PODs near the delivery locations to reduce travel times, leading to many PODs with very few meals picked up at each. As a result, 159,548 meals remained unconsumed either still at a POD or in the back of a truck. However, during a longer duration emergency, the surplus meals could become advantageous by enabling the delivery concept to operate for an extended period without requiring additional resupply. Note: this solution is novel and there are no previous studies to compare such results. To the best of the author's knowledge, this is the only delivery-based emergency food distribution plan designed for Windward Oahu. Importantly, households with vehicles were not covered by this solution, leading to a dropped demand of 262,102 meals.

Table 4.3. Delivery-Only model Performance.

# of PODs	Dropped Demand	Staff	Delivery Trucks	Excess Meals
17	262,102	391	7	159,548

Table 4.4 provides additional details regarding the routes covered by the trucks. Five of

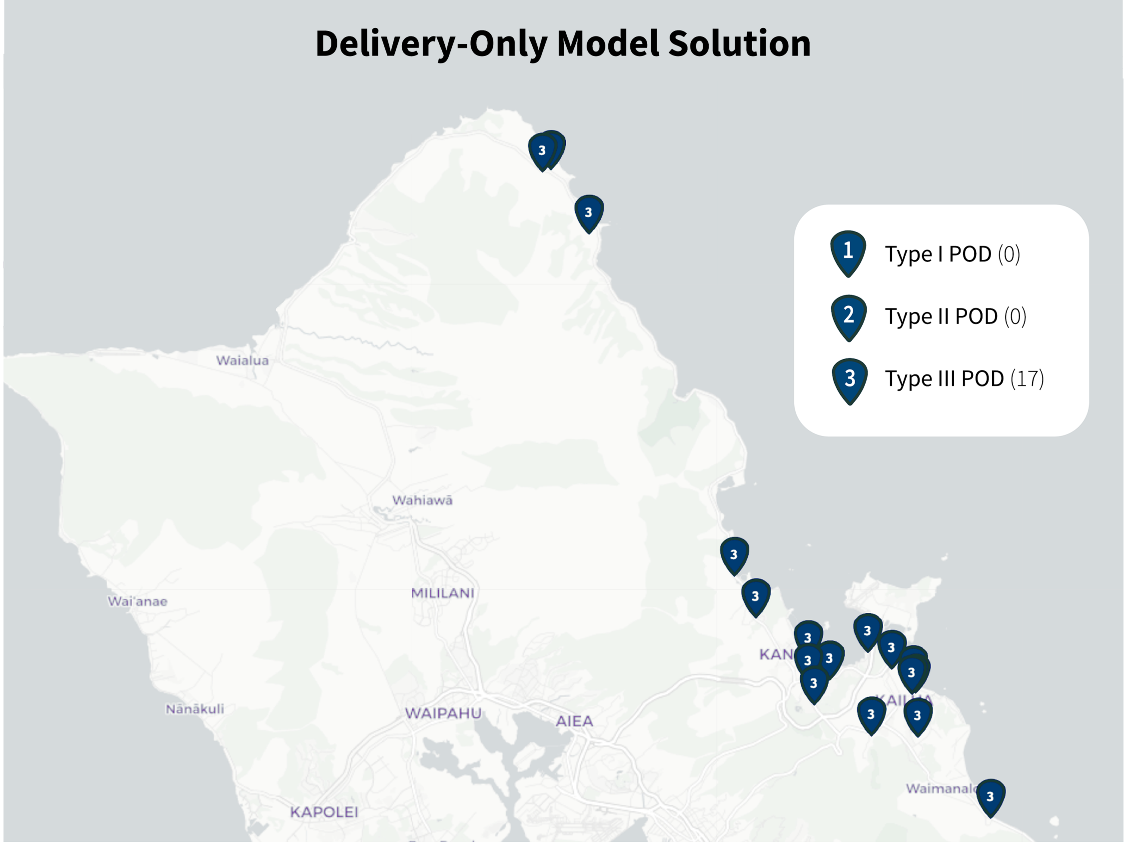

Figure 4.2. Delivery-Only Solution. 17 PODs are chosen for this distribution plan. All PODs are small and are more distributed outside population centers. A full list of the selected PODs for this solution is listed in Table A.3.

the 7 trucks required over 6 hours to complete their routes, with the longest route taking 7 hours and 37 minutes (Truck 4). Trucks 1, 3, 4, 5, and 6 visited PODs in the Kaneohe and Waimanalo communities while making deliveries nearby, indicating significant demand for deliveries in those areas. We find delivery trucks will visit anywhere between 1 to 4 different PODs. Additionally, some trucks delivered less than 1,000 meals and complete their travel in less than 4 hours. This finding suggests that it may be possible to constrain delivery vehicles to visiting fewer PODs while still completing their routes within the 8-hour time limit. However, it is important to note that the Delivery-Only model assumes no road congestion. In the event of flooding or other similar incidents leading to road closures, the delivery routes may take longer than anticipated.

Table 4.4. Delivery Truck Route Statistics (Delivery-Only).

ID	PODs Visited	Time (Minutes)	Meals Delivered
Truck 1	pod27	206	984
Truck 2	pod40, pod51, pod76	451	1,978
Truck 3	pod8, pod11	203	918
Truck 4	pod10, pod64,	311	1,218
Truck 5	pod35, pod50, pod69, pod76	457	1,914
Truck 6	pod12, pod76, pod80, pod83	423	1,588
Truck 7	pod1, pod34, pod46	423	1,852

Note: max delivery and travel time for a truck is 480 minutes (8 hours).

4.3 Hybrid Solutions

In previous sections, we explore results from two separate models for emergency food distribution: the Pickup-Only model and the Delivery-Only model. Both models have unique strengths and limitations. While the Pickup-Only model is effective for distributing food, it requires affected individuals to have access to vehicles, which may pose a difficulty for certain vulnerable populations. In contrast, the Delivery-Only model eliminates the need for transportation, but it demands more resources since it requires delivery to widely dispersed locations.

To address these challenges, we now consider the performance of two hybrid models that combine the strengths of the Pickup-Only and Delivery-Only models.

4.3.1 Pickup-Delivery Model

The Pickup-Delivery model involves solving the Pickup-Only model, then using the selected PODs and excess meals to determine the available supply at each POD for the Delivery-Only model. The congestion throughout the Pickup-Only model network is used to calculate the distance between nodes for the Delivery-Only model. The solve times for each of the two models is comparable to when they are run in isolation, running in a combined approximate 42 minutes. Figure 4.3 displays a map of the selected PODs using this strategy.

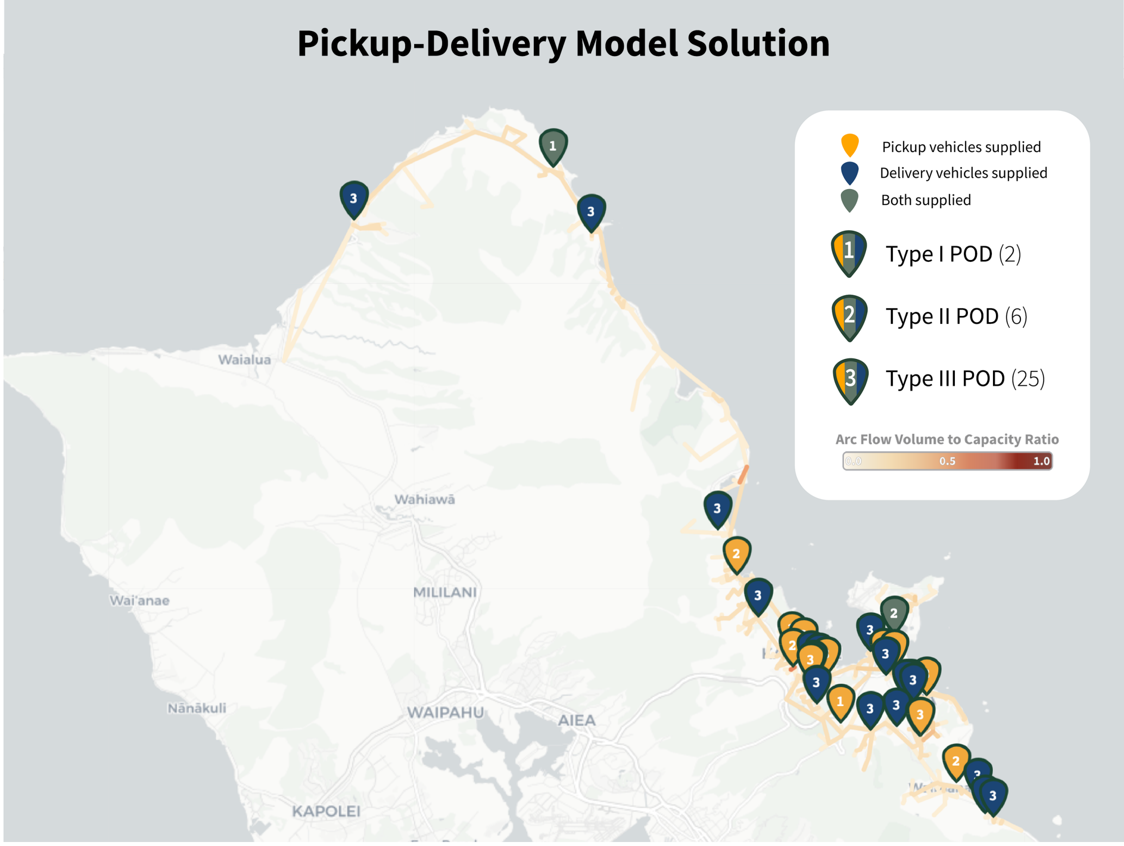

Figure 4.3. Pickup-Delivery Model Solution. 33 PODs are chosen for this distribution plan, with only 2 operating as both pickup and delivery. This is the only plan that would locate PODs near Waialua on the North Shore. A full list of the selected PODs for this solution is listed in Table A.4.

The solution is comprised of 2 Type I PODs, 6 Type II PODs, and 25 Type III PODs. Only two PODs are used for both pickup and delivery. This is likely due to limited excess meals available in the Pickup-Only model solution, which leads the Delivery-Only model to select 18 additional Type III PODs. This inefficiency is a result of the Delivery-Only model's preference to open PODs near population nodes with a large number of households without vehicles, rather than minimizing the number of PODs chosen.

Table 4.5 provides additional details regarding the routes covered by the trucks. Unlike other solutions, optimal routing requires every delivery truck to visit multiple PODs. Specifically, each truck will visit 2-4 PODs with a minimum drive time of 212 minutes (3 hours and

32 minutes) and a maximum drive time of 464 minutes (7 hours and 44 minutes). In this solution, we also find more trucks delivering over 1,000 meals, and fewer trucks near their full capacity. This suggests a more evenly distributed plan, such that if any one truck does not succeed at meeting its delivery schedule, fewer households without vehicles should be impacted in the worst-case.

Table 4.5. Delivery Truck Route Statistics (Pickup-Delivery).

ID	PODs Visited	Time (Minutes)	Meals Delivered
Truck 1	pod44, pod47, pod48	312	1,498
Truck 2	pod14, pod18, pod22, pod26	339	1,580
Truck 3	pod1, pod4, pod36	345	1,414
Truck 4	pod3, pod9	212	916
Truck 5	pod76, pod81, pod87	338	1,356
Truck 6	pod32, pod35, pod47	428	1,936
Truck 7	pod46, pod64, pod73	464	1,752

The performance of this model is presented in Table 4.6. In order to meet the demands of all population nodes, we need 7 trucks and 33 PODs. The staffing requirement for the PODs is 991 people. However, the results indicate a surplus of 174,500 meals that were not consumed, either still at a POD or in the back of a truck. This large excess is due to the opening of a large number of Type III PODs. There are limited excess meals available in the Pickup-Only model solution, which leads the Delivery-Only model to select additional PODs not included in that first solution. While this is not an ideal outcome, our integrated solution outperforms the Pickup-Only and Delivery-Only solutions by avoiding dropped demand.

Table 4.6. Pickup-Delivery Model Performance.

# of PODs	Dropped Demand	Staff	Delivery Trucks	Excess Meals
33	0	991	7	176,128

4.3.2 Delivery-Pickup Model

The Delivery-Pickup model involves solving the Delivery-Only model, then using the selected PODs and excess meals to determine the available supply at each POD for the Pickup-Only model. The solve time for the delivery model is equivalent to running in isolation (approximately 10 minutes), but its solution fixes several PODs as open, which simplifies the pickup model. The subsequent pickup model has 511,813 variables and 304,779 constraints, and a solve time of 13 minutes. So the combined solve time is shorter at approximately 23 minutes. Figure 4.4 displays a map of the selected PODs.

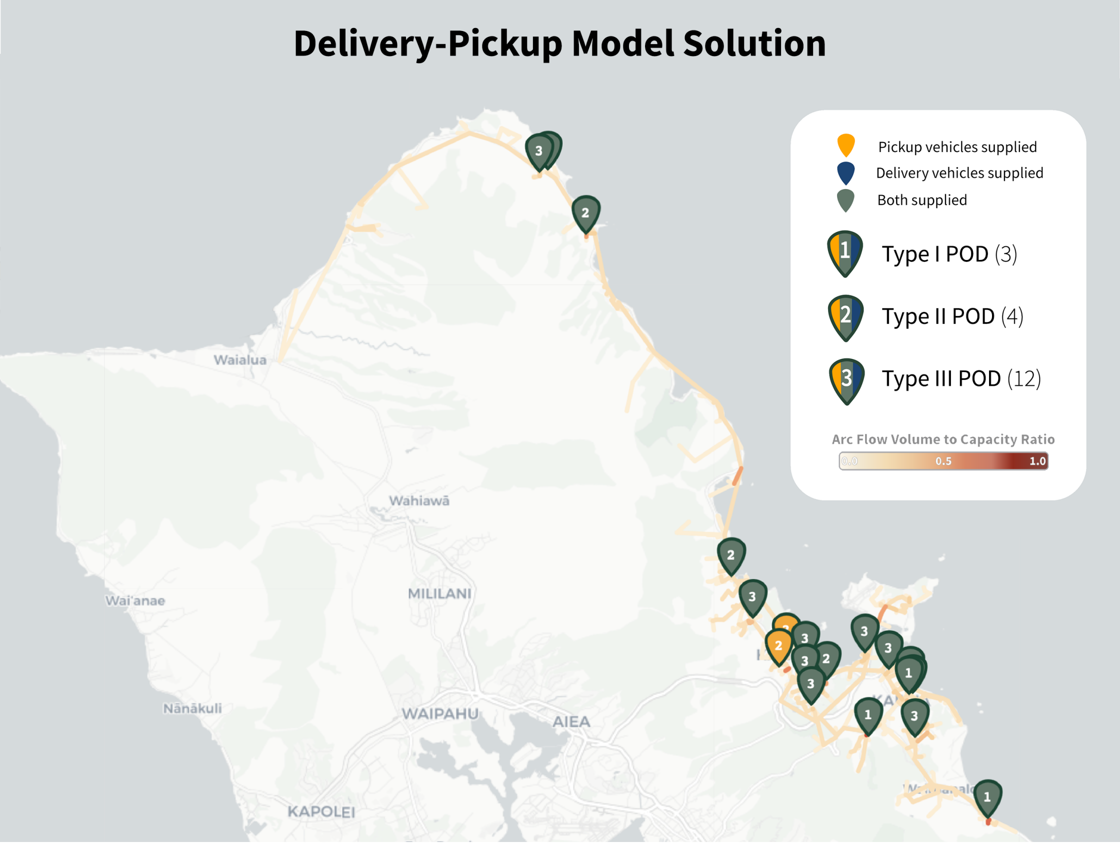

Figure 4.4. Delivery-Pickup Model Solution. 19 PODs are chosen for this distribution plan, with 17 operating as both pickup and delivery. A full list of the selected PODs for this solution is listed in Table A.5.

The solution is comprised of 3 Type I PODs, 4 Type II PODs, and 12 Type III PODs. Only two additional PODs were required by the Pickup-Only model solution that were not already in the Delivery-Only model solution, and 17 PODs are used for both pickup and delivery. The fact that both models mostly choose Type III PODs implies that satisfying the demand of Windward Oahu could be possible with fewer PODs, provided that some Type III PODs are replaced with Type I or Type II PODs.

The traffic over this network is worse than Pickup-Delivery solution. This is likely because two of the most congested roads were leading up to Type I PODs (pod1 and pod34). This may highlight a challenge for emergency response. The congestion results from this model are optimal, meaning individuals were directed through the network in a coordinated manner to minimize congestion. However, in an actual emergency situation, it is highly unlikely that congestion can be avoided completely. Placing Type I PODs near low-capacity roads should be avoided.

The average round trip travel time for all pickup trips was 20.2 minutes with a standard deviation of 21.2 minutes. The longest round trip travel times are shown in Table 4.7. The longest trip was by a community in the North Shore (population158) which traveled 134.0 minutes (2 hours and 14 minutes) round trip. Notably, all five of the longest travel times were for communities on the North Shore, underscoring the significance of prepositioned supplies for these remote communities.

Table 4.7. Five Longest Round Trip Pickup Travel Times.

ID	Distance (Miles)	Travel Time (Minutes)
population158	87.8	134.0
population142	73.4	113.8
population152	66.4	103.2
population154	66.8	102.8
population152	48.5	76.6

The performance of this model is presented below in Table 4.8. In order to meet the demands of all population nodes, 7 trucks and 19 PODs were required. A total of 720 personnel were needed to staff the PODs, and there was an excess of 47,580 meals that were left unconsumed, either at a POD or in the back of a truck. Overall, this solution uses the fewest PODs to cover the entire population, the fewest staff, and has fewer excess meals than the other hybrid solution.

Table 4.8. Delivery-Pickup Model Performance.

# of PODs	Dropped Demand	Staff	Delivery Trucks	Excess Meals
19	0	720	7	47,580

4.4 Comparison of Results

We compare each result based on our performance metrics as well as differences in round trip travel times for drivers picking up food and routes for delivery trucks.

4.4.1 Comparison of Performance Metrics

The performance of all model solutions is presented in Table 4.9.

Table 4.9. Comparison of Performance of All Model Solutions.

Model	# of PODs	Dropped Demand	Staff	Delivery Trucks	Excess Meals
Pickup-Only	15	10,452	577	0	7,580
Delivery-Only	17	262,102	391	7	159,548
Pickup + Delivery Sum	32	0	968	7	167,128
Pickup-Delivery	33	0	991	7	176,128
Delivery-Pickup	19	0	720	7	47,580

Note: "Pickup + Delivery Sum" adds the results from the Pickup-Only and Delivery-Only models together except for dropped demand.

The Pickup-Only model is an effective solution for emergency food distribution, except for the most vulnerable populations. It utilizes larger centralized PODs to satisfy demand, which minimizes the need for staff. This model distributes 262,102 meals with only 577 staff. However, dropped demand is still a significant issue with the pickup as the plan assumes individuals have the ability to drive to pick up food themselves. This poses a difficulty for those who lack vehicles or are physically unable to leave their homes. Despite the incomplete coverage this model provides, the Pickup-Only model offers the most efficient utilization of staff among the four solutions analyzed in this study (on a meal-to-staff basis), which could be highly beneficial in situations where staffing is limited.

The Delivery-Only model requires the least staff but also serves the fewest number of people, and as a result has very high dropped demand. The geographically dispersed demands in the Delivery-Only model require smaller, spread out PODs to ensure that all individuals have access to food. However, utilizing these PODs solely as loading points for delivery trucks results in a large number of excess meals. Nonetheless, the Delivery-Only model provides valuable information on locations that could be critical for distributing food to vulnerable populations. The results of delivery models can also inform decisions about prepositioning supplies, as seen in the "Pre-covery" concept. A POD location that is suitable for loading a truck for deliveries is likely to be a good place to preposition supplies for emergency situations because these locations are in central areas that are easily accessible to those in need.

A simple approach to a hybrid distribution plan would be to simply combine the Pickup-Only and Delivery-Only plans together. This plan requires 32 PODs, 968 staff, and has 167,128 excess meals and does not drop food demand. While the simple combination of pickup and delivery plans may appear more desirable than the Pickup-Delivery solution on some metrics, it is also more vulnerable to disruptions. The lack of coordination between the pickup and delivery operations can result in uneven distribution of excess meals between PODs. For instance, the PODs that are optimal for delivery may no longer be suitable when pickup is occurring, leading to a mismatch between the two operations. Suppose a delivery truck visits a POD to reload and finds that all the meals have been picked up households with vehicles, causing a shortfall for the delivery truck. In that case, it may not be clear which other POD could supply the truck to make up for the shortfall, leading to disruptions in the delivery operations.

In contrast, the Pickup-Delivery model performs less effectively than the combined Pickup + Delivery Sum plan, but it is less vulnerable to disruption due to its coordination of pickup and delivery. The Pickup-Delivery plan requires additional staff and a greater number of excess meals than Pickup & Delivery. This less effective performance suggests that utilizing the excess meals from PODs to serve the most vulnerable population may not be a viable option. One possible method to enhance viability of the Pickup-Delivery model could involve allotting extra supply exclusively for delivery vehicles at each POD that has been already selected by the Pickup-Only model. This approach would enable delivery vehicles to load up at existing PODs without increasing staffing requirements or generating additional excess meals that may result from creating new PODs.

The Delivery-Pickup model stands out as the most effective solution for complete coverage of Windward Oahu. Among the models with no dropped demand, the Delivery-Pickup model requires the least number of staff members to operate. Additionally, this model is particularly successful in managing excess food supply, second only to the Pickup-Only model solution. The Delivery-Pickup model chose only four more PODs than the Pickup-Only model, and only two more PODs than the Delivery-Only model. Had the Delivery-Only model been limited to establishing fewer but larger PODs, it is plausible that the overall population could be served with fewer PODs and staff than currently recommended by the Delivery-Pickup model.

4.4.2 Additional Considerations

Besides our performance metrics, we also compare results based on the travel time experienced by drivers to pick up food and the delivery truck routes used to bring food to communities. These comparisons only apply for models with unique solutions.

Driver Round Trip Travel Time

Prioritizing pickup over delivery in POD location selections as is done in the Pickup-Delivery model results in shorter round trip travel times for communities driving to pick up food from PODs, presented in Table 4.10. The average trip was 3.1 minutes shorter when pickup was prioritized, and the longest trip was shorter by 47.5 minutes. The PODs in the Pickup-Delivery solution are situated in more convenient locations for those who are driving to them.

Table 4.10. Round Trip Travel Time Statistics for Hybrid Models.

Model	Average	Standard Deviation	Longest Trip
Pickup-Delivery	17.1	15.0	86.5
Delivery-Pickup	20.2	21.2	134.0

Round Trip Travel Time Statistics for Hybrid Models [minutes]. Note: travel times for the Pickup-Only model are the same as Pickup-Delivery.

Delivery Truck Routes

The Pickup-Delivery and the Delivery-Pickup models produce very similar routing plans. The total time spent by vehicles on the road in the Pickup-Delivery model is 2,464 minutes, while it is 2,474 minutes in the delivery-first model. However, in the Pickup-Delivery solution, delivery vehicles visited two more PODs than in the Delivery-Pickup solution. One possible explanation for this difference is related to the *a priori* modeling decisions. In the Delivery-Only model, vehicles cannot deliver to a population node unless they have enough load to satisfy the entire demand of that node. As a result, the model tends to prioritize routing to PODs with small demands (i.e., whenever a truck needs to top off its load). In the Pickup-Delivery solution, there are two PODs with excess demand. After splitting these PODs into increments of 500 or less, two of the resulting split nodes had abnormally small supplies, with supplies of 10 and 70, respectively. As a result, the delivery vehicles may have visited these small nodes instead of a node with a larger supply.

4.4.3 Overall Recommendation

Our recommendation is to implement a Delivery-Pickup strategy that prioritizes PODs for hybrid operations. This requires PODs to be used for both pickup and delivery, as emergencies can be unpredictable in terms of the affected population. For example, during an emergency, PODs can initially serve the most vulnerable populations exclusively through delivery services before being opened to the general public for pickup. The Delivery-Pickup plan provides the most efficient and viable solution to make this happen.

Moreover, we identify POD locations that are ideal candidates to act as test locations to practice and implement plans. Specifically, we identify PODs that are common among multiple model solutions, such that any POD plan will likely require them to operate for pickup or delivery. Table 4.11 lists all PODs that are selected by more than one model, along with the corresponding vehicle types each POD supplied. Ten PODs were selected by more than one model: pod1, pod8, pod27, pod35, pod46, pod50, pod60, pod64, pod69, and pod76.

Four PODs (pod8, pod27, pod50, and pod69) were identified as optimal for all models, which implies that they are well-suited for serving both pickup and delivery. These PODs are shown in Figure 4.5. The four PODs are situated in Kaneohe and Kailua, namely: Kahaluu Regional Park, Foodland Kaneohe #8, Kalaheo Neighborhood Park, and Keolu Elementary School. Given their suitability for serving as distribution points for both pickup vehicles and delivery vehicles, these locations may be prioritized over other potential locations for emergency food distribution.

Table 4.11. PODs Selected by Multiple Models.

ID	Pickup	Delivery	Pickup-Delivery	Delivery-Pickup
pod1		D	D	PD
pod8	P	D	PD	PD
pod27	P	D	P	PD
pod35		D	D	PD
pod46		D	D	PD
pod50	P	D	P	PD
pod60	P		P	P
pod64		D	D	PD
pod69	P	D	P	PD
pod76		D	D	PD

Note: an empty cell signifies that a POD was not chosen by a particular model.

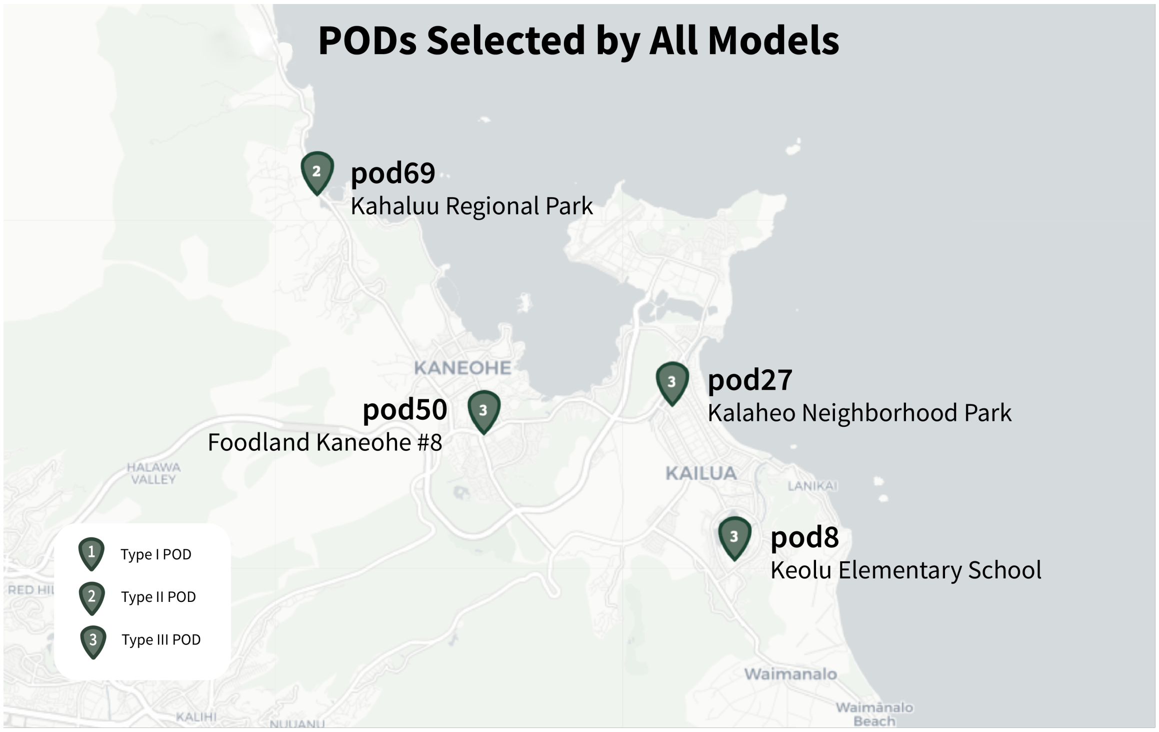

Figure 4.5. PODs Selected by All Models.

CHAPTER 5:
Conclusion

This work addresses a gap in the planning of emergency supply distribution concepts in natural disaster scenarios. Specifically, we develop a data set and series of models to assess the feasibility and implementation of hybrid distribution concepts for Windward Oahu. By comparing pickup and delivery concepts and determining their optimal combination for a hybrid operations plan, we provide actionable recommendations for emergency distribution that are feasible given roadway and staffing limitations. Additionally, we analyze the staffing requirements for hybrid distribution, which will help decision makers plan and allocate resources more effectively. Ultimately, the insights from this work will help to improve emergency supply distribution planning, which can potentially save lives and mitigate other negative impacts of natural disasters on communities.

5.1 Results Summary

We provide four distinct perspectives on how decision makers can prioritize emergency food distribution to communities in Windward Oahu. After considering their priorities, decision makers can utilize these perspectives to create optimal plans. For example, if CCH-DEM or HIEMA prioritizes prepositioning or delivering food only to the most vulnerable population in a targeted manner, they may prefer using the Delivery-Only model and plan to open POD locations specified in Table A.3. Alternatively, if the agencies aim to identify the best POD locations for reaching all individuals during an emergency situation, they should prefer the delivery first model and consult Table A.5. Lastly, for decision makers who are concerned about limited staff, the Pickup-Only model is efficient, and Table A.2 can offer guidance on which PODs and staff allocation is required.

We also identify four PODs that are important candidates for either pickup, delivery, or hybrid concepts. These PODs are: Kahaluu Regional Park (pod69), Foodland Kaneohe #8 (pod50), Kalaheo Neighborhood Park (pod27), and Keolu Elementary School (pod8). All four PODs are situated in Kaneohe and Kailua near MCBH. Thus, there is a strong opportunity for the military installation to coordinate with local authorities to preposition and staff these locations. Moreover, we recommend these locations be used as test-beds for practicing and implementing a food distribution plan (pickup, delivery, or hybrid). This will prepare local communities for future disasters and help coordinate among military and civilian agencies that both benefit from emergency feeding for Windward Oahu.

5.2 Analysis Limitations and Assumptions

While our results offer significant insights into the feasibility and implementation of a hybrid deployment of emergency supply distribution concepts for Oahu, the present study has limitations.

One limitation is that we only apply a penalty in the Pickup-Only model for staff and not excess food. As a result, our model may suggest opening several large PODs that minimize travel time but incur significant waste. To address this limitation, one would need to add a penalty for excess food as well. This could help balance the need for staff alongside the goal to only bring food into communities that will be picked up or delivered.

A limitation specific to our Pickup-Delivery model is that we do not prioritize delivery vehicles to use excess meals from PODs already selected to be open. This could also be dealt with through prioritizing existing food sources or penalizing additional staff in the Delivery-Only model. Incorporating new constraints to ensure delivery vehicles pick up from existing PODs may reduce excess meals and required staff without increasing the number of delivery vehicles required or their time spent driving. Thus, future work should explore alternative prioritization strategies for delivery vehicles.

Our Delivery-Only model relies on several assumptions that need further analysis. It assumes that the truck capacity is 1,000 meals, and unloading 5 meals takes 1 minute. The accuracy of the results can be enhanced by incorporating more authoritative data on delivery truck operations, including fleet capacity for different vehicles and ranges of times for loading/unloading. The Delivery-Only model also assumes drivers are able to begin their routes from a POD and do not have to travel back to any centralized depot. However, fleet vehicles are generally stored at a hub location owned by the contracted distributor. Most of these distributors are located near the Port of Honolulu, which is far from Windward Oahu and MCBH. Future work should explore how incorporating a true start and end point for delivery vehicles with variable distance from pickup/drop-off locations.

Finally, it is important to consider the robustness of any emergency food distribution plan, as unforeseen events and disruptions can occur during emergency response. The current solutions assume that every POD, road, delivery, will operate as planned. However, it is possible that these plans may encounter unforeseen circumstances that could impact their effectiveness. Future research should explore whether any of the proposed plans offer greater flexibility and adaptability in the face of unexpected events.

5.3 Summary and Future Work

Overall, the limitations and assumptions in our models provide opportunities for future work to refine and improve our approach to emergency supply distribution planning. By addressing these limitations and assumptions, we can develop more robust models that provide decision makers with more accurate and actionable recommendations.

While this analysis was primarily developed with Oahu in mind, this study's findings and conclusions could provide a useful framework for emergency response planning for other locations. By implementing hybrid distribution strategies that reduce dropped demand, minimize staffing and equipment requirements, and prevent food waste, emergency response planners in different regions can efficiently serve diverse segments of the population.

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APPENDIX A:
Points of Distribution (PODs)

Table A.1. Full List of PODs

ID	Name	Type	Longitude	Latitude
pod1	Head Start Pope	1	-157.694	21.328
pod2	Pope Elem School	1	-157.694	21.328
pod3	Kamehameha Schools - Waimanalo	3	-157.698	21.331
pod4	Malama Honua - PCS	3	-157.702	21.339
pod5	Waimanalo Elem & Inter School	2	-157.715	21.347
pod6	Waimanalo District Park	1	-157.715	21.343
pod7	Kaelepulu Mini Park	3	-157.732	21.394
pod8	Keolu Elem School	3	-157.735	21.372
pod9	Keolu Hills Neighborhood Park	3	-157.736	21.372
pod10	Kailua Inter School	3	-157.737	21.396
pod11	St. Anthony School - Kailua	3	-157.738	21.4
pod12	Kailua District Park	1	-157.739	21.395
pod13	Target Kailua #2697	1	-157.739	21.392
pod14	SW Kailua Oahu 1087	2	-157.74	21.391
pod15*	Little Learners Preschool	3	-157.741	21.402
pod16	Kailua Elem School	3	-157.741	21.396
pod17	Huakailani School	2	-157.741	21.392
pod18	Foodland Kailua #37 - Oahu	3	-157.743	21.393
pod19*	Kainalu Elem School	3	-157.748	21.414
pod20	SW Aikahi Oahu 2208	2	-157.748	21.423
pod21	Kailua High School	2	-157.748	21.384
pod22	Olomana School	3	-157.749	21.377
pod23	Aikahi Elem School	3	-157.749	21.424

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Table A.1. Full List of PODs

ID	Name	Type	Longitude	Latitude
pod24	Kama' Aina Kids- Aikahi	3	-157.75	21.423
pod25	Kailua Baptist Christian Preschool	3	-157.75	21.387
pod26	Aikahi Community Park	2	-157.751	21.426
pod27	Kalaheo Neighborhood Park	3	-157.751	21.408
pod28	Kailua Methodist Preschool	3	-157.751	21.387
pod29	Maunawili Neighborhood Park	2	-157.753	21.376
pod30	Head Start Maunawili	3	-157.753	21.377
pod31	Pohakupu Mini Park	3	-157.755	21.381
pod32	Kawai Nui Neighborhood Park	1	-157.755	21.405
pod33	Windward School for Adults	3	-157.757	21.409
pod34	Maunawili Valley Neighborhood Park	1	-157.763	21.372
pod35	Keaalau Neighborhood Park	2	-157.764	21.417
pod36	Trinity Christian School	3	-157.764	21.375
pod37	Le Jardin Academy	1	-157.768	21.379
pod38	Hawaii Pacific University	1	-157.782	21.379
pod39	Kaneohe Bayview Neighborhood Park	1	-157.786	21.41
pod40	Kaluapuhi Neighborhood Park	2	-157.786	21.403
pod41	Windward Nazarene Academy Preschool	3	-157.79	21.404
pod42	Head Start Puohala Elementary	2	-157.79	21.41
pod43	Nuuanu Pali State Wayside	3	-157.793	21.367
pod44	Kaneohe Community and Senior Center	3	-157.794	21.406
pod45	Golf Academy of America	1	-157.794	21.375
pod46	Pali View Baptist Preschool	3	-157.795	21.389
pod47	Calvary Episcopal Preschool	3	-157.797	21.403
pod48	St. Mark Lutheran School	3	-157.799	21.408
pod49	Kaneohe Civic Center Neigh. Park	2	-157.799	21.413
pod50	Foodland Kaneohe #8 - Oahu	3	-157.799	21.401
pod51	Parker Elem School	3	-157.799	21.414

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Table A.1. Full List of PODs

ID	Name	Type	Longitude	Latitude
pod52	SW Kaneohe Oahu 0207	1	-157.803	21.422
pod53	Kaneohe Community Park	2	-157.803	21.415
pod54	Kapunahala Neighborhood Park	2	-157.803	21.407
pod55	St. Ann’s Early Learning Center	3	-157.805	21.422
pod56	King Inter School	3	-157.806	21.428
pod57	St. Ann’s Model School	3	-157.806	21.422
pod58	Kaneohe District Park 2	2	-157.809	21.409
pod59	Heeia Elem School	3	-157.809	21.419
pod60	Heeia Neighborhood Park	3	-157.81	21.418
pod61	Kaneohe District Park 1	2	-157.81	21.411
pod62	Windward Community College	1	-157.812	21.408
pod63	Hakipuu Learning Center - PCS	2	-157.813	21.409
pod64	Ahuimanu Community Park	3	-157.829	21.436
pod65	Ahuimanu Elem School	1	-157.831	21.435
pod66*	Laenani Neighborhood Park	3	-157.832	21.459
pod67*	Kualoa Regional Park	2	-157.838	21.513
pod68*	Kahaluu Regional Park 1	3	-157.84	21.46
pod69	Kahaluu Regional Park 2	2	-157.841	21.458
pod70	Kahaluu Elem School	3	-157.845	21.458
pod71*	Kaaawa Elem School	2	-157.847	21.548
pod72	Waiahole/Waikane Nature Preserve	3	-157.849	21.492
pod73	Waiahole Elem School	3	-157.852	21.483
pod74*	Hauula Elem School	2	-157.908	21.606
pod75*	Foodland Laie #32 - Oahu	3	-157.923	21.647
pod76	Brigham Young University - Hawaii	2	-157.925	21.642
pod77*	Laie Elem School	2	-157.926	21.649
pod78*	Malaekahana State Recreation Area	3	-157.93	21.659
pod79	Kahuku Golf Course	1	-157.943	21.679

Continued on next page

Table A.1. Full List of PODs

ID	Name	Type	Longitude	Latitude
pod80	Punana Leo O' Ko'Olauloa	3	-157.947	21.676
pod81	Kahuku High & Inter School	1	-157.947	21.676
pod82	Kahuku District Park	1	-157.95	21.676
pod83	Kahuku Elem School	3	-157.952	21.675
pod84	Kamehameha Schools - Kahuku	3	-157.952	21.677
pod85*	Sunset Beach Neighborhood Park	2	-158.051	21.664
pod86*	Sunset Beach Christian School	3	-158.059	21.656
pod87	Foodland Pupukea #27 - Oahu	3	-158.061	21.648

Note: PODs listed with an "*" were within inundation zones and excluded from models.

Table A.2. Pickup-Only Model Selected PODs

ID	Name	Type	Longitude	Latitude
pod38	Hawaii Pacific University	1	-157.782	21.379
pod81	Kahuku High & Inter School	1	-157.947	21.676
pod5	Waimanalo Elem & Inter School	2	-157.715	21.347
pod17	Huakailani School	2	-157.741	21.392
pod26	Aikahi Community Park	2	-157.751	21.426
pod53	Kaneohe Community Park	2	-157.803	21.415
pod58	Kaneohe District Park 2	2	-157.809	21.409
pod69	Kahaluu Regional Park 2	2	-157.841	21.458
pod7	Kaelepulu Mini Park	3	-157.732	21.394
pod8	Keolu Elem School	3	-157.735	21.372
pod27	Kalaheo Neighborhood Park	3	-157.751	21.408
pod33	Windward School for Adults	3	-157.757	21.409
pod41	Windward Nazarene Academy Preschool	3	-157.79	21.404

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Table A.2. Pickup-Only Model Selected PODs

ID	Name	Type	Longitude	Latitude
pod50	Foodland Kaneohe #8 - Oahu	3	-157.799	21.401
pod60	Heeia Neighborhood Park	3	-157.81	21.418

Table A.3. Delivery-Only Model Selected PODs

ID	Name	Type	Longitude	Latitude
pod1	Head Start Pope	3	-157.694	21.328
pod8	Keolu Elem School	3	-157.735	21.372
pod10	Kailua Inter School	3	-157.737	21.396
pod11	St. Anthony School - Kailua	3	-157.738	21.4
pod12	Kailua District Park	3	-157.739	21.395
pod27	Kalaheo Neighborhood Park	3	-157.751	21.408
pod34	Maunawili Valley Neighborhood Park	3	-157.763	21.372
pod35	Keaalau Neighborhood Park	3	-157.764	21.417
pod40	Kaluapuhi Neighborhood Park	3	-157.786	21.403
pod46	Pali View Baptist Preschool	3	-157.795	21.389
pod50	Foodland Kaneohe #8 - Oahu	3	-157.799	21.401
pod51	Parker Elem School	3	-157.799	21.414
pod64	Ahuimanu Community Park	3	-157.829	21.436
pod69	Kahaluu Regional Park 2	3	-157.841	21.458
pod76	Brigham Young University - Hawaii	3	-157.925	21.642
pod80	Punana Leo O' Ko'Olauloa	3	-157.947	21.676
pod83	Kahuku Elem School	3	-157.952	21.675

Table A.4. Pickup-Delivery Model Selected PODs

ID	Name	Type	Supplied	Longitude	Latitude
pod38	Hawaii Pacific University	1	P	-157.782	21.379
pod81	Kahuku High & Inter School	1	PD	-157.947	21.676
pod5	Waimanalo Elem & Inter School	2	P	-157.715	21.347
pod17	Huakailani School	2	P	-157.741	21.392
pod26	Aikahi Community Park	2	PD	-157.751	21.426
pod53	Kaneohe Community Park	2	P	-157.803	21.415
pod58	Kaneohe District Park 2	2	P	-157.809	21.409
pod69	Kahaluu Regional Park 2	2	P	-157.841	21.458
pod1	Head Start Pope	3	D	-157.694	21.328
pod3	Kamehameha Schools - Waimanalo	3	D	-157.698	21.331
pod4	Malama Honua - PCS	3	D	-157.702	21.339
pod7	Kaelepulu Mini Park	3	P	-157.732	21.394
pod8	Keolu Elem School	3	P	-157.735	21.372
pod9	Keolu Hills Neighborhood Park	3	D	-157.736	21.372
pod14	SW Kailua Oahu 1087	3	D	-157.74	21.391
pod18	Foodland Kailua #37 - Oahu	3	D	-157.743	21.393
pod22	Olomana School	3	D	-157.749	21.377
pod27	Kalaheo Neighborhood Park	3	P	-157.751	21.408
pod32	Kawai Nui Neighborhood Park	3	D	-157.755	21.405
pod33	Windward School for Adults	3	P	-157.757	21.409
pod35	Keaalau Neighborhood Park	3	D	-157.764	21.417
pod36	Trinity Christian School	3	D	-157.764	21.375
pod41	Windward Nazarene Academy Preschool	3	P	-157.79	21.404

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Table A.4. Pickup-Delivery Model Selected PODs

ID	Name	Type	Supplied	Longitude	Latitude
pod44	Kaneohe Community and Senior Center	3	D	-157.794	21.406
pod46	Pali View Baptist Preschool	3	D	-157.795	21.389
pod47	Calvary Episcopal Preschool	3	D	-157.797	21.403
pod48	St. Mark Lutheran School	3	D	-157.799	21.408
pod50	Foodland Kaneohe #8 - Oahu	3	P	-157.799	21.401
pod60	Heeia Neighborhood Park	3	P	-157.81	21.418
pod64	Ahuimanu Community Park	3	D	-157.829	21.436
pod73	Waiahole Elem School	3	D	-157.852	21.483
pod76	Brigham Young University - Hawaii	3	D	-157.925	21.642
pod87	Foodland Pupukea #27 - Oahu	3	D	-158.061	21.648

Note: "P" indicates a POD was visited by a pickup vehicle, "D" indicates a POD was visited by a delivery vehicle, and "PD" indicates a POD was visited by both.

Table A.5. Delivery-Pickup Model Selected PODs

ID	Name	Type	Supplied	Longitude	Latitude
pod1	Head Start Pope	1	PD	-157.694	21.328
pod12	Kailua District Park	1	PD	-157.739	21.395
pod34	Maunawili Valley Neighborhood Park	1	PD	-157.763	21.372
pod35	Keaalau Neighborhood Park	2	PD	-157.764	21.417
pod40	Kaluapuhi Neighborhood Park	2	PD	-157.786	21.403

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Table A.5. Delivery-Pickup Model Selected PODs

ID	Name	Type	Supplied	Longitude	Latitude
pod63	Hakipuu Learning Center - PCS	2	P	-157.813	21.409
pod69	Kahaluu Regional Park 2	2	PD	-157.841	21.458
pod76	Brigham Young University - Hawaii	2	PD	-157.925	21.642
pod10	Kailua Inter School	3	PD	-157.737	21.396
pod11	St. Anthony School - Kailua	3	PD	-157.738	21.4
pod27	Kalaheo Neighborhood Park	3	PD	-157.751	21.408
pod46	Pali View Baptist Preschool	3	PD	-157.795	21.389
pod50	Foodland Kaneohe #8 - Oahu	3	PD	-157.799	21.401
pod51	Parker Elem School	3	PD	-157.799	21.414
pod60	Heeia Neighborhood Park	3	P	-157.81	21.418
pod64	Ahuimanu Community Park	3	PD	-157.829	21.436
pod8	Keolu Elem School	3	PD	-157.735	21.372
pod80	Punana Leo O' Ko'Olauloa	3	PD	-157.947	21.676
pod83	Kahuku Elem School	3	PD	-157.952	21.675

Note: "P" indicates a POD was visited by a pickup vehicle, "D" indicates a POD was visited by a delivery vehicle, and "PD" indicates a POD was visited by both.

APPENDIX B:
Google OR-Tools Configuration

Google OR-Tools is an open source programming package for optimization used in this thesis. the API for Google OR-Tools is available in Python, Java, C++, and C#. Google OR-Tools is similar to other optimization packages such as Pyomo (Hart et al. 2011). The general description of Google OR-Tools is as follows, “OR-Tools is an open source software suite for optimization, tuned for tackling the world’s toughest problems in vehicle routing, flows, integer and linear programming, and constraint programming” (Google 2023a).

Like other optimization packages, Google OR-Tools installs and runs locally on a computer. Google OR-Tools enables the creation of a model object that comprises all elements of an optimization model, including indices, sets, decision variables, parameters, objectives, and constraints. After creating a model, one can use either use built-in solver routines or send the problem to a commercial solver such as Gurobi or CPLEX.

The primary reason we use Google OR-Tools in this work over other similar optimization packages is its built-in algorithms for solving VRPs. As all VRPs are NP-hard, they require additional algorithms to identify candidate routing solutions and to avoid returning locally optimal, yet dominated solutions. As described in Ch. 3, Section 3.4.3, we use the “savings” algorithm by Clarke and Wright (1964) and the guided local search metaheuristic for testing local optima. Both of these techniques are built-in to Google OR-Tools and do not require additional implementation. We use the following inputs to implement both algorithms in Google OR-Tools.

These parameters are passed to the Google OR-Tools Routing Model class. More detail on the model class is provided by Google OR-Tools (Google 2023b). This class embeds built-in routing algorithms and can call an integer or mixed-integer programming solver.

Table B.1. Parameters Used in Google OR-Tools Solution

```
search_parameters = pywrapcp.DefaultRoutingSearchParameters()
search_parameters.first_solution_strategy =
    (routing_enums_pb2.FirstSolutionStrategy.SAVINGS)
search_parameters.local_search_metaheuristic =
    (routing_enums_pb2.LocalSearchMetaheuristic.GUIDED_LOCAL_SEARCH)
search_parameters.time_limit.FromSeconds(600)
```

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