NPS-LM-21-012

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An Analysis of Vertical Lift Platforms in Support of Humanitarian Assistance and Disaster Relief Operations

December 2020

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Prepared for the Naval Postgraduate School, Monterey, CA 93943.

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Defense Management at the Naval Postgraduate School.

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ABSTRACT

The purpose of this research was to examine how the capabilities of the various vertical lift platforms, coupled with their unit cost, can be modeled and optimized to inform future decisions when tasking theater assets to assist in humanitarian assistance and disaster relief (HA/DR) operations. A multi-criteria analysis was used to compare alternatives across key performance measures, such as search and rescue (SAR) capability, load capacity, range determination, and crew performance limitations. Additionally, we gave operational commanders a realistic assessment of daily capacity and cost, as well as the limitations thereof, through Monte Carlo risk simulation. Results from our models provided both an optimal vertical lift aircraft mix and scalable results in terms of daily pounds of goods delivered.

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ABOUT THE AUTHORS

CDR Scott Chirgwin graduated from Oregon State University on a Naval ROTC scholarship. He reported to flight school in June of 2005 and received his wings of gold in 2007. He has served in four helicopter squadrons including HS4, HSC85, HS11, and HSC14 and deployed six times on three different aircraft carriers. He has had the unique experience to participate in two separate HADR missions in the Philippines and Japan. His notable qualifications and awards include Seahawk Weapons and Tactics Instructor (SWTI), CVW SOF Strike Lead and Air Medal for his work during Operation Tomodachi. He is earning his MBA in acquisitions and contract management at NPS and his follow-on orders are to HSC22 in Norfolk VA as the Commanding Officer.

ENS Davis Katakura is a Student Naval Aviator. He commissioned from the US Naval Academy with the class of 2019 where he received a Bachelor of Science in Mathematics with Economics. After attending the Naval Postgraduate School, he will be attending Naval flight training in Pensacola, FL.

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ACKNOWLEDGMENTS

CDR Chirgwin—I would like to thank my wife, Denise Chirgwin, who has been so inspirational and supportive to me throughout this process. She is always willing to put her obligations aside to help me when I get stressed and to offer comfort and sound advice. She is my rock! To my boys, Lincoln and George, thank you for your humor and resilience! I would also like to thank my thesis partner, Davis Katakura, who is truly intelligent and wise beyond his years, though he will never say it. He will be a fantastic naval officer and indispensable wardroom member. Lastly, to my thesis advisors, Professor Aruna Apte and Professor Ken Doerr: they were never too busy to listen when we had questions, teach us when we were confused, or hold us accountable when we got fatigued. We truly owe them a tremendous credit.

ENS Katakura—I would like to thank my thesis partner, Scott Chirgwin, for his diligence, support, and contributions to our research. He will make an outstanding commanding officer, and I am beyond fortunate for his mentorship and wisdom as I begin my career with the Navy. I would like to thank the Acquisition Research Program for their support and sponsorship of our research. Their help in our research process has been instrumental to the presentation of our results. Lastly, I would like to thank our tremendous advisors, Professor Aruna Apte and Professor Ken Doerr. Their enthusiastic and constant support are what made our research possible. From their instruction to advisor roles, both professors are indispensable to the mission of the Defense Management School and the Naval Postgraduate School.

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LIST OF ACRONYMS AND ABBREVIATIONS

ATMSR	Aviation Type/Model/Series Report
CNAF	Commander, Naval Air Forces
CVIC	Carrier Intelligence Center
CVN	Aircraft Carrier
HA/DR	Humanitarian Assistance and Disaster Relief
LHA	Landing Helicopter Assault
LHD	Landing Helicopter Dock
LOS	Line of Sight
LPD	Landing Platform/Dock
LZ	Landing Zone
MASHPAT	Marine Assault Support Helicopter Planning Assistance Tool
NATEC	Naval Air Technical Data and Engineering Services Command
NATOPS	Naval Air Training and Operating Procedures Standardization
NM	Nautical Mile
O&M	Operations and Maintenance
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OHDACA	Overseas Humanitarian Disaster and Civic Aid
SAR	Search and Rescue
VAMOSC	Visibility and Management of Operating and Support Costs
VTOL	Vertical Takeoff and Landing

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I. INTRODUCTION

In early 2011, I (Commander Chirgwin, a lieutenant at the time) was enjoying liberty in Hong Kong while on my third deployment aboard the aircraft carrier USS *Ronald Reagan* (CVN-76). All the local news outlets were reporting an earthquake off the coast of Japan and the resultant tsunami that followed. The tidal surge from the wave was being shown as well. The phone rang in my hotel room; it was my department head. We briefly discussed the reports of devastation in Japan, and our conversation concluded with a mandatory recall to the ship for immediate underway.

> In the early afternoon on March 11, 2011, a magnitude 9.0 earthquake occurred 130 kilometers off the shore of Sendai, on the eastern coast of Honshu Island, Japan. Within less than an hour, tsunami waves measuring up to 40 meters high crashed almost six miles inland, inundating 561 square kilometers. With a population of 14.8 million people, the prefectures along the northeastern coast were the worst affected, with 129,500 houses destroyed and 265,324 severely damaged by the earthquake, tsunami, or ensuing fires. (Moroney et al., 2013, p. 85)

The first few days of relief support were chaotic. The CVN had transited the Pacific with such speed that we left most of the carrier strike group behind. In addition, it would be a few days before the C-2 Greyhound carrier onboard delivery aircraft could acquire relief goods. The consumable supplies that were initially delivered to the disaster-stricken populace were from the reserve stores held on our ship. Warm clothing and blankets were needed as well, due to the cold temperatures that time of year. Many sailors donated personal items such as clothing and blankets to the relief effort. Damage to the infrastructure caused by the tidal surge was so extensive that all roads and lines of communication were completely wiped out, which, though a problem for ground transportation vehicles, was a scenario that helicopters are uniquely designed to overcome. This is due in large part to a helicopter's ability to take off and land vertically in small and, in some cases, unprepared areas such as grass fields. Additionally, there were no organic operational airfields in our assigned relief area, so the CVN acted as the logistics hub for supply distribution. The first days of flights were as much about finding the pockets of isolated dispersed people as they were about re-supply. Once we identified a group of people, we would land the aircraft in a parking lot or nearby field and unload everything we had. We used the unloading time to communicate via geographic maps and "pointy talkies" (cards depicting food, water, shelter, etc.) to identify the location of any other stranded civilians At the end of the day, we turned in the information on that day's relief effort to the intelligence personnel within the carrier intelligence center (CVIC). CVIC in turn started to build a database, annotating location and quantity supply drops, in addition to systematically labeling the landing zones (LZs).

The meltdown of the Fukushima nuclear plant presented another complication because it required a standoff for the CVN due to concerns about radiological exposure. The helicopter radios operate through line of sight (LOS), and because of this standoff, the curvature of the earth and altitude at which helicopters operated made communications challenging. The airwing responded by launching fixed wing aircraft, which was beneficial for two reasons. The fixed wing aircraft were able to identify additional isolated communities and function as a communication relay between helicopters and the ship. The E-2C Hawkeye was critical in providing coordination and communication between all air and surface assets. Once airborne, we would contact the E-2C and receive our relief tasking and LZ assignment. After 10 days of relief work, the CVN was directed back to original deployment tasking, but the relief effort in Japan continued well beyond that.

II. LITERATURE REVIEW

Humanitarian assistance and disaster relief (HA/DR) literature emphasizes the core challenge of disaster uncertainty with regards to planning, costs, and operations. These challenges present the Navy's vertical lift asset as a uniquely capable, but also expensive, tool in HA/DR. Historically, HA/DR has used linear programs to analyze asset mixes and logistics solutions for relief operations. We use linear programming in particular to address a gap in the literature, specifically in determining the optimal use of vertical lift assets and in conducting a capacity (total pounds of supplies) risk assessment. This capacity risk assessment will afford the decision-maker access to delivery performance metrics given a selected mix of vertical lift assets and disaster parameters. A real-time, input-reliant, and user-friendly mathematical model will allow HA/DR decision-makers the ability to utilize vertical lift assets cost-efficiently and effectively.

A. CHALLENGES

HA/DR solutions must first consider its formidable challenge clearly outlined in the literature, namely the unpredictability of a disaster's origin and magnitude and the subsequent difficulties with coordinating a response. The speed and magnitude of each disaster requires different operational responses, as shown in Figure 1. Prepositioning of disaster relief resources is highly beneficial for slow-onset disasters, but significantly less useful or feasible for disasters of a sudden nature. Sudden-onset disasters pose an additional challenge for budgeting, as designated relief funding for the Navy's HA/DR operations lags the relief efforts and instead bleeds into the Navy's Operations and Maintenance (O&M) budget. With disaster relief's unique challenges of preparation, demand, and costs, existing HA/DR literature identifies vertical lift capabilities as particularly useful assets.

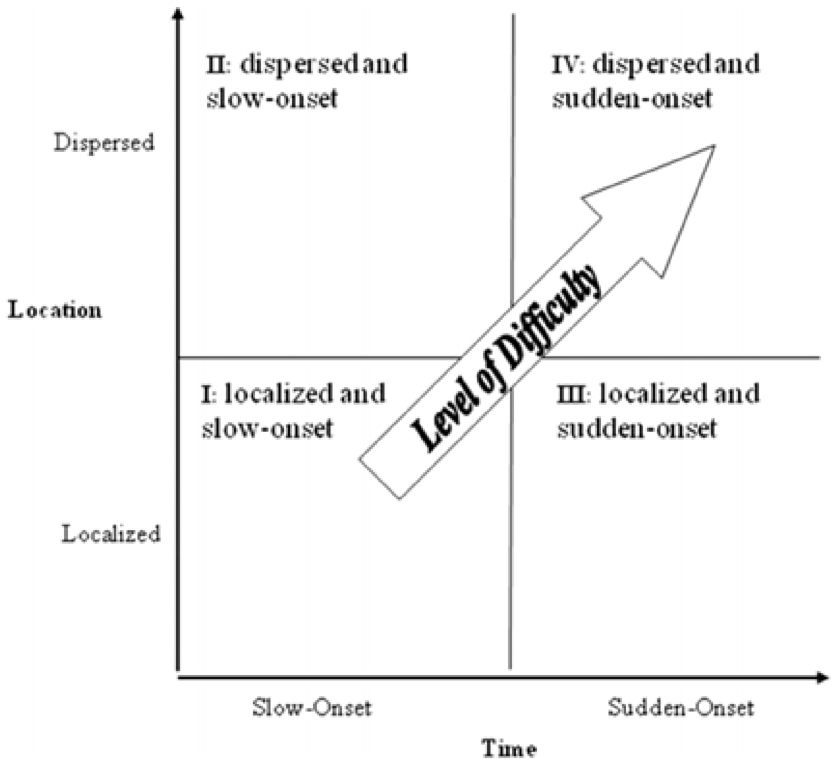


Figure 1. Classification of Disasters. Source: Apte (2009).

Humanitarian operations in response to disasters are extremely dynamic and complex systems. The complexity of natural disasters is due to their inherent unpredictability, short response timeline, and unpredictable demand signal. The United Nations Office for the Coordination of Humanitarian Affairs (OCHA) has implied, though not formally stated, that the first 72 hours of a disaster are the most critical when it comes to saving lives by employing relief efforts. Many state and federal relief organizations agree and tailor disaster preparedness kits to a 72-hour timeline. Immediate response is needed in order to save human lives and reduce suffering. Elleman (2007) illustrated the desperation of victims of the 2004 Indonesian tsunami, stating that by the 5th and 6th days, victims would rush airborne helicopters to receive supplies.

Apte and Yoho (2018) determined that in addition to decision-makers inability to predict demand for future disasters, post-hoc analysis of past disasters is often inadequate. Further compounding the issues of demand is the surge capacity (supplies and services) associated with disasters. Apte (2009) categorized disasters in a framework that compares location against time (see Figure 1).

Building upon this framework, Ures (2011) concluded that all disasters will experience a sharp demand increase or "capacity spike," but the speed of onset sets these disasters apart. Disasters that display a slow onset, such as a tropical storm that develops into a hurricane, can be mitigated and prepared for through asset prepositioning or proactive deployment (Yoho & Apte, 2014). Sudden onset disasters such as the Haitian earthquake in 2010, however, will demonstrate an inability for decision-makers to properly prepare, thus requiring surge capacity external to the disaster. The primary means of transportation to satisfy capacity in a sudden-onset disaster will be via vertical lift (Moffat, 2014; Ures, 2011).

Total HA/DR costs can be problematic to decision-makers as we look to the future and are at odds with the desired 72-hour response timeline. Herbert et al. (2012) detailed some of the regulatory bureaucracy associated with HA/DR support. Their research indicates that the Navy will systematically preposition resources prior to the official orders from the secretary of defense (SECDEF) to expedite response time. Prepositioning, while operationally and logistically sound, tends to mask some expenses because the Overseas Humanitarian Disaster and Civic Aid (OHDACA) grant of funds lags the execution of this process. As a result, misalignment costs are absorbed into the Navy's Operations and Maintenance (O&M) budget. In evaluating historical disasters, Navy and Marine vertical lift aviation platforms are the most essential asset to HA/DR operations.

B. SOLUTION: VERTICAL LIFT

Vertical lift platforms such as helicopters are uniquely tailored for the HA/DR contingencies and well suited for the resultant environment. Helicopters offer the ability to render services and supplies to isolated personnel and provide search and rescue (SAR) to disaster-stricken populations. Consequently, vessels that carry vertical lift assets are the best suited ships for HA/DR operations. Flight operations, however, constitute a sizeable portion of relief costs, so it is important to use them efficiently.

Greenfield and Ingram (2011) and Moffat (2014) identified HA/DR as a growing mission within the Department of Defense and an evolving core competency in the Navy. The authors determined which ships in the Navy provide the most capability to HA/DR and, perhaps equally as important, which ships do not. In both research papers, the authors concluded that ships that possess vertical lift assets such as helicopters are overwhelmingly more suited to conduct HA/DR missions. Moffat (2014) utilized a capability scoring system to rank ship types in terms of overall capability to support HA/DR. He concluded that the landing helicopter assault (LHA), landing helicopter dock (LHD), and aircraft carrier (CVN) provided the most capability, mostly due to organic helicopter assets. Moffat also concluded that the LHD, landing platform/dock (LPD), and LHA were the most cost-effective platforms for HA/DR. Apte and Yoho (2018) validated these findings, highlighting that ships with the capabilities to embark helicopters are far more effective in the execution of HA/DR missions. Their research further concluded that in the past, the Navy has deployed ships such as minesweepers and vessels lacking vertical lift capabilities. In one such instance, the USS *Hopper* (DDG 70) deployed to Bangladesh in response to Cyclone Sidr but lacked both a helicopter detachment to provide vertical lift support and a shallow enough draft to employ small boat teams. The USS *Hopper,* although deployed with good intentions, was completely ineffective at providing relief support.

Ures (2011) evaluated three separate disasters: the 2004 Indian Ocean tsunami, the 2010 Haiti earthquake, and the 2010 Pakistani floods. The researcher identified individual cost drivers within these specific disasters and the associated sources of cost to inform budgetary decisions about future disasters. Ures concluded that the capabilities provided by vertical lift aircraft are both expensive and the most demanded. The author recommended that ship selection should be tailored toward vessels with large flight decks because they can better support helicopter flight operations. Herbert et al. (2012) seemed to confirm the same overall cost profile in their evaluation of the tsunami in Japan. Their research confirmed that flight operations are the primary costs drivers in HA/DR, attributing to 68% of the total reimbursable costs to those operations. It is important to note that although both Ures and Herbert et al.identified flight operations as the costliest capability, they disagreed on type of aircraft (fixed vs. rotary). We attribute these differing conclusions to the variability inherent to disasters and in U.S. response.

C. MODELING

Given the wide range of naval vessels available for HA/DR support, logistical planners must maximize the capabilities offered across platforms. Linear programming models are a common tool utilized within the literature to optimize HA/DR operational performance. Although linear programs have been used for determining optimal ship vessel compositions and logistics planning, our research uses linear programs to find the ideal mix of vertical lift assets. This vertical asset mix solution is not only useful itself to HA/DR planners but is also useful within our research to conduct a risk analysis of relief performance.

A portion of the HA/DR literature is devoted to discovering the optimal assets, planning, and schedules to respond to future disasters. Apte and Yoho (2017a, 2017b, 2018) classified the capabilities offered by naval surface vessels and employed a linear programming model to determine the optimal asset mix for HA/DR missions. Budget cuts and constrained HA/DR budgets motivated Apte and Yoho's (2017a, 2018) research, as the optimal mix accounts for a minimized budget. Clementson and Fisher (2011) compared the utilities of helicopter mixes that exist within predetermined groupings (e.g., carrier strike group, amphibious readiness group, etc.), although no attempt at modeling was completed. We, too, seek an optimal assortment of assets using modeling, but specifically for vertical lift platforms, as this is not assessed within the literature. Minimizing the costs of vertical lift operations is likewise considered through the flight costs of operations.

In addition to using mathematical modeling as a method to determine the most valuable platforms for HA/DR missions, some of the literature has focused on the delivery of assets to relief areas and the transportation of affected populations to safer areas. Apte and Salmeron (2009), Mogilevsky (2013), and Scott and Watson (2018) all utilized optimization modeling to focus their research on the vertical air lift delivery of resources to disaster-stricken areas. Their research pertains to heavy resupply of relief resources destined for distribution hubs. Our research focuses on the movement of aid from these distribution centers to the actual recipient, as vertical lift assets represent the most valuable delivery tool when transportation infrastructure is rendered unusable. Much of the logistical challenges surrounding aid delivery reside in the planning of last-mile distribution routes of helicopters. Ozdamar (2011) and Xavier et al. (2011) utilized a linear program to model the helicopter deliveries optimized for minimum transit time in a hypothetical HA/DR scenario. Ozdamar's research concluded that for simpler academic purposes, their proposed linear program offers quick solutions. However, due to computational limits, larger transportation scenarios will require a heuristic approach. Though our research focuses its use of modeling on the optimal mix of vertical lift assets, we build upon Ozdamar's approach by employing probability distributions to analyze a forecast of HA/DR delivery performance.

Given the abundant research with respect to optimization surrounding HA/DR, there lies a need for decision-makers and planners to assess the projected performance of the assets devoted to relief missions. Information regarding the efficiency and utility of platforms, though useful in pre-disaster planning, becomes less relevant as the actual assets within the disaster theater begin their disaster response. What becomes more necessary is an accurate forecasting system that equips decision-maker models with the ability to input the assets available for the relief effort and the parameters pertaining to the realized disaster environment. Wray (2009) acknowledged the complicated nature pertaining to Marine Corps helicopter scheduling and the importance of a user-friendly tool in a fast-paced, dynamic environment. Apte and Salmeron (2009) used a two-stage stochastic optimization model to guide decision-making within a budget constraint through the various stages of HA/DR response efforts. Still, an accurate forecasting method for vertical lift assets is needed. HA/DR planners need not only information on the most efficient mix of vertical lift assets, but also a forecasting tool that provides accurate performance and reliability metrics given the disaster at hand.

D. THE GAP IN THE LITERATURE

Our research aims to determine the optimal mix of vertical lift assets through a mathematical modeling capacity analysis across available HA/DR platforms. However, we must also differentiate between a theoretical mix of vertical assets and the actual assets devoted to a relief effort since we acknowledge that the optimal solution of our model will not necessarily yield a practical recommendation of assets. In order to determine the actual performance of our recommended assets, we conduct a risk analysis to address the uncertainty of HA/DR logistics. Our risk analysis consists of scenario-based simulations to determine delivery capacity performance. The results of our risk analysis afford HA/DR decision-makers delivery reliability metrics given a user-selected mix of vertical lift assets and disaster operation parameters.

The potential impracticality of an optimal solution prompts us to conduct a capacity risk assessment of supplying HA/DR demand in addition to mathematical modeling. The literature acknowledges that estimating the precise amount of demand for disaster-affected areas is indeed one of the most significant challenges to HA/DR planning (Apte, 2009). Our capacity risk analysis acknowledges that in practice, true demand of relief recipients will virtually always overshadow the amount supplied, particularly in the first 72 hours of relief missions. The important question to ask regarding vertical lift assets' contributions to HA/DR pertains to the total amount that vertical lift assets can supply within a timeframe of operations.

Since relief scenarios differ both qualitatively and quantitatively from each other, the proper use of operational parameters carries significant weight. The scenario-based approach to HA/DR missions is not uncommon in the literature. Clementson and Fisher (2011) analyzed the use of helicopters in HA/DR missions to maximize the number of sorties executed by pre-determined mixes of aircraft with the lowest costs per flight hour. Given various scenarios and pre-set flight paths for sortie loading and delivery, Clementson and Fisher were able to assess the amount of supplies that could be delivered for the duration of the HA/DR relief mission. Our research similarly estimates an assortment of aircraft's ability to accomplish the maximum number of sorties, but with the critical element of variability added to our design. Clementson and Fisher acknowledged their research purposely excluded uncertainty from their methodology. However, in our capacity risk analysis, we acknowledge uncertainty as the driving determinant of vertical lift relief performance. Within the first 72 hours of relief operations, flight routes cannot be determined with certainty, as landing zone locations are subject to environmental conditions, competition for relief resources, and communications with the area. Coordinators and pilots alike must be prepared to embark to a makeshift landing zone at little notice.

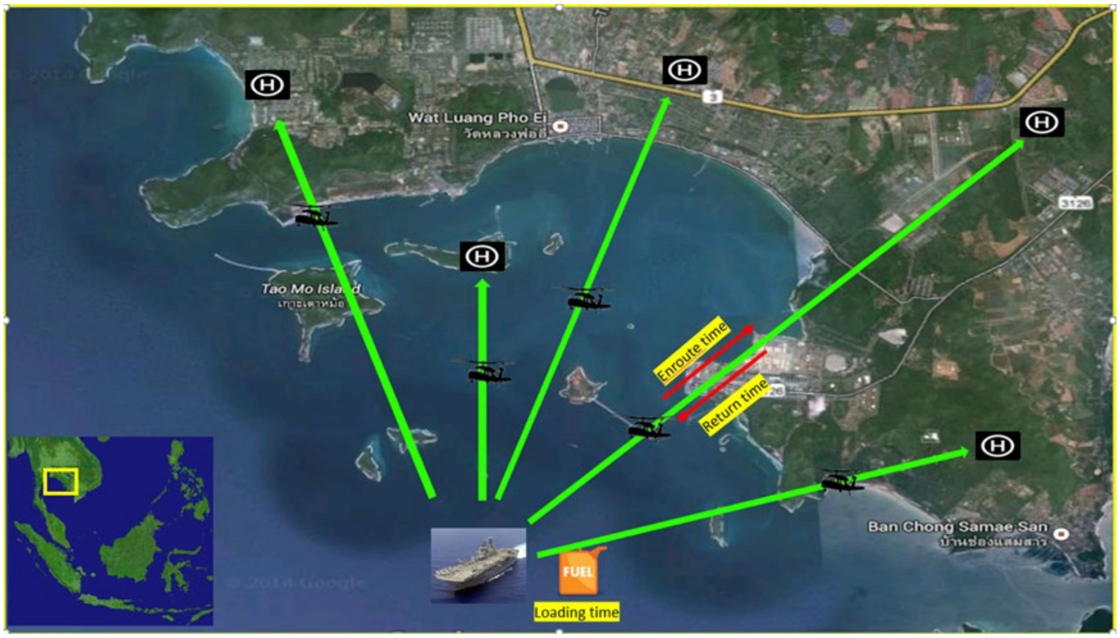
A responsive dispatching tool is important for vertical lift relief planning due to the need for expedience and the dynamic identification of landing zones. Relief must be delivered quickly once landing zones are identified, and aircraft may be redirected during HA/DR missions. The uncertainty surrounding landing zones contributes to the importance of an expedient and efficient means of dispatching vertical assets to complete sorties and calculating the projected performance of relief deliveries. Indeed, the importance of dispatching helicopter flights for varying mission types is widely recognized in the aviation community. In the realm of Marine Corps assault helicopters, Wray (2009) argued for the use of the Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT), a no-cost computer program that allows logistical planners to view projected outcomes of mission performance. MASHPAT users can streamline their scheduling work by inputting desired parameters, such as load time, and outputting a proposed flight plan.

Our risk analysis design similarly allows decision-makers to assess delivery reliability using a streamlined interface. Using our risk analysis simulation, the user can identify the delivery capacity of a selected assortment of vertical lift assets given the parameters of landing zone distance, loading, and refueling times. As more data can be gathered about the displaced population, demand requirements become clearer. Our risk analysis simulation can provide a real-time assessment of reliability and the projected performance of vertical relief efforts. Risk analysis affords decision-makers accurate projections of vertical lift asset performance in the early stages of disaster relief to better coordinate with allied relief actors. Understanding the projected performance of vertical lift assets assists in clearing logistical uncertainties and effectively aiding as many affected individuals as possible.

III. METHODOLOGY

The focus of our thesis work is to build a realistic set of models to understand the capabilities and costs associated with helicopter support during HA/DR operations. To do this, we built two different types of models, a linear programming model and a risk analysis model, utilizing Monte Carlo simulation. These models use the Microsoft Excel add-ins Solver and Crystal Ball, respectively. The linear programming model would determine the optimal number and type of aircraft to be used to either maximize capacity in terms of pounds of relief goods or to minimize cost. The risk analysis model is designed to indicate and identify the risk associated with the delivery of supplies in terms of pounds delivered. For example, a user could determine with 80% certainty the amount of capacity that could be counted on per day given a specific aircraft type and quantity. In this chapter, we discuss the data collected, the costs associated, and the modeling process.

Figure 2 illustrates graphically the real-world scenario we are modeling in our disaster response. The basic premise is that a vertical lift asset such as a helicopter would onload fuel and supplies onboard an afloat staging base such as an aircraft carrier or an amphibious assault ship such as an LHD/LHA because of their utility in HA/DR (Apte & Yoho, 2018). For the purpose of our model, these ship types act as supply points or hubs that are capable of continuous resupply. The vertical lift assets onboard would load supplies and then deliver them to their assigned landing zone. The helicopters would then return to the hub, take on more supplies and fuel, and make additional trips until pilots reach their maximum flight hour daily limit.



Original map retrieved from Google Earth, FEB 2012.

Original LHD image retrieved from Google, MAR 2020.

Figure 2. Notional HA/DR Operation

A. DATA

The data that supported our research model came in two parts for our analysis. The first part was variable cost data (fuel), which was provided by the organization Naval Visibility and Management of Operating and Support Costs (VAMOSC). The second portion of the data is Hours of flight time = (Distance to LZ [nautical mile (NM)])/(Maximum Range Airspeed (NM/hr). These technical manuals are utilized to define certain aircraft capabilities such as capacity limitations, transit airspeeds, and the reliability of SAR. Ultimately, to make similar comparisons across multiple aviation platforms, we utilized variable costs versus performance capabilities to derive an optimal solution of aircraft employment. The aircraft chosen for evaluation were vertical lift assets, which includes both helicopters and Vertical Takeoff and Landing (VTOL) aircraft such as the V-22 Osprey. We did not include helicopters suited for attack-type roles such as the AH-1 Cobra because of their limited ability to carry supplies for HA/DR. Further, we did not include aircraft that are being phased out of the Navy and Marine inventory but that have previously participated in HA/DR. These aircraft include CH-46s and certain variants of the Navy Seahawk such as the SH-60F.

B. VERTICAL LIFT COST

VAMOSC provided our research with a sortable report called the Aviation Type/Model/Series Report (ATMSR) that broke aviation costs into distinct cost elements. These elements are primarily unit-level manpower, unit operations, and maintenance. There are two additional cost categories, which are sustaining support and continuing system improvements. ATMSR also provides “count” reporting for total flight hours, barrels of fuel, and number of aircraft in the inventory. Our research utilized the unit operations cost exclusively for determining variable costs to flight operations in support of HA/DR. Utilizing database filters allowed us to filter unit operations into multiple sub-elements, eventually isolating operations element 2.1.1.1 (energy), which reports the cost of aviation propulsion fuel purchased to support flight operations of Navy and Marine aircraft (VAMOSC, 2020). While this is a simplified way to determine aviation costs, it allowed us to better compare aviation platforms from a cost/capability analysis utilizing our linear programming model.

To utilize a common metric in the linear programming model, we determined cost per flight hour for each aviation asset. This was accomplished by dividing total costs in terms of fuel used by the number of aircraft flight hours used in the reporting period. We narrowed our focus to Pacific Fleet, active duty, operational squadrons only, and cost calculations were limited to 2018 data only for recency. Figure 3 represents the derived data and is displayed in terms of cost/hour as a ratio. Analyzing the following data, we see that both the MV-22 and the CH-53 account for a greater cost per flight hour by 3.78 and 3.63 times that of the UH-1, respectively.

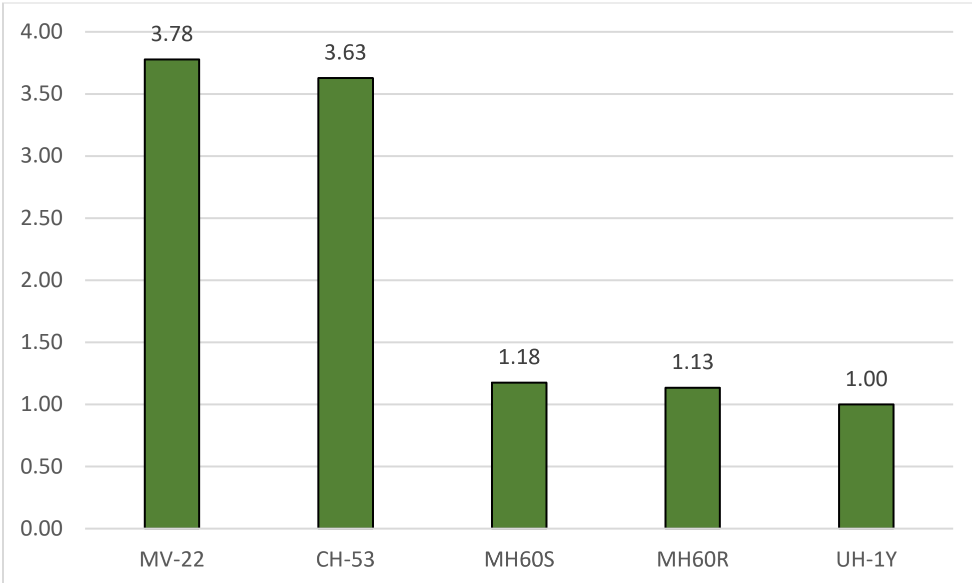


Figure 3. Ratio of Cost per Flight Hour by Aircraft Type

There are limitations to determining vertical lift costs. Herbert et al. (2012) captured HA/DR costs as well as the authorities and funding sources for HA/DR operations. Those authors further separated large cost components of HA/DR, such as flight operations, ship operations, and contracts, among others. They determined that the bulk of the costs associated with HA/DR to the DOD are aviation-related (Herbert et al., 2012). Cost determinations in their research were appropriate because they were trying to determine cost allocations to HA/DR for the purpose of reimbursement.

In the design of our model, we sought to capture aviation costs from a variable cost standpoint (fuel only). The reason for this decision was to evaluate aircraft that are already deployed and being diverted to a disaster area for relief. We considered all other associated costs to be sunk. Manpower cost elements, for example, include not only the amount paid for billeted personnel within the squadron, but also allowances for temporary active duty members, retirement, bonus/incentive pay, etc. maintenance cost includes items such as consumable parts (bolts, nuts, wires) and repairable parts (starter motors, pumps), but it also includes cost elements such as depot-level maintenance facilities. Our research did not include variable maintenance costs incurred because that data is not provided by VAMOSC. These costs would be incurred at various points throughout the year and do not represent the incremental variable costs attributable to HA/DR operations.

C. VERTICAL LIFT CAPABILITIES

We analyzed vertical lift capabilities by breaking them down into three parts: aircraft capacity, SAR capability, and relief radius. The aircraft data for these computations was provided by the Naval Air Technical Data and Engineering Services Command (NATEC) website and associated Naval Air Training and Operating Procedures Standardization (NATOPS) manuals for each airframe. When deciding which capabilities to evaluate, we looked at the most demanded capabilities (Apte & Yoho, 2018). We then compared those demands to ones that could be provided with vertical lift assets. Relief radius is discussed in more detail later, but it adds another dimension of distance or range to tether those capabilities. Figure 4 highlights the capabilities that vertical lift aircraft can achieve in response to natural disasters. The levels depicted are dimensionless in quantity and merely represent a potential demand signal for a given disaster scenario. The intent of Figure 4 is to overlap vertical capabilities with demand.

Deamnd	Level	Deamnd	Level
Aircraft support	10	Fuel	4
Landing Craft support	5	Personnel transfer	2
Search and rescue	1	Fresh water production	1
Dry goods	7	Personnel support	4
Refrigerated goods	2	Berthing capability	2
Fresh water	2	Medical support	2
Roll-On/Roll-Off	4	Salvage Ops	2

Demanded Capacity

Search & Rescue

Relief Radius

Figure 4. HA/DR Demanded Capabilities. Adapted from Apte and Yoho (2018).[1]

1. Vertical Lift Free Capacity

We define capacity as the amount of supplies the aircraft can move, in pounds. There are several limitations to this capacity number, such as maximum gross weight of

[1] This figure was adapted from the source by adding capability overlays.

the aircraft, cubic displacement of the cargo, and trade-offs with fuel and crew weights. Additionally, aircraft gross weights can vary with environmental factors; for example, altitude, temperature, and humidity can affect engine performance and thus limit maximum gross weight (Naval Air Systems Command, 2019b). To control for the variability of environmental factors, we modeled each aircraft to the same environmental conditions when considering performance factors produced by applicable NATOPS manuals. Further, to accurately represent aircraft capacity, we developed a free aircraft capacity metric, which is the difference between maximum capacity and maximum fuel, in pounds. For example, the MH-60S helicopter has a maximum internal capacity of 5,500 lb and a maximum fuel capacity of 2,400 lb, accounting for fuel in the main tanks only (Naval Air Systems Command, 2019b). It would therefore have a free capacity of 3,100 lb in this case. Finally, there is an old aviation adage that states, "The only time you have too much fuel is when you're on fire," which is why we assumed that aircraft would never leave the hub without maximum fuel. Figure 5 represents a comparison of aircraft free capacity by type.

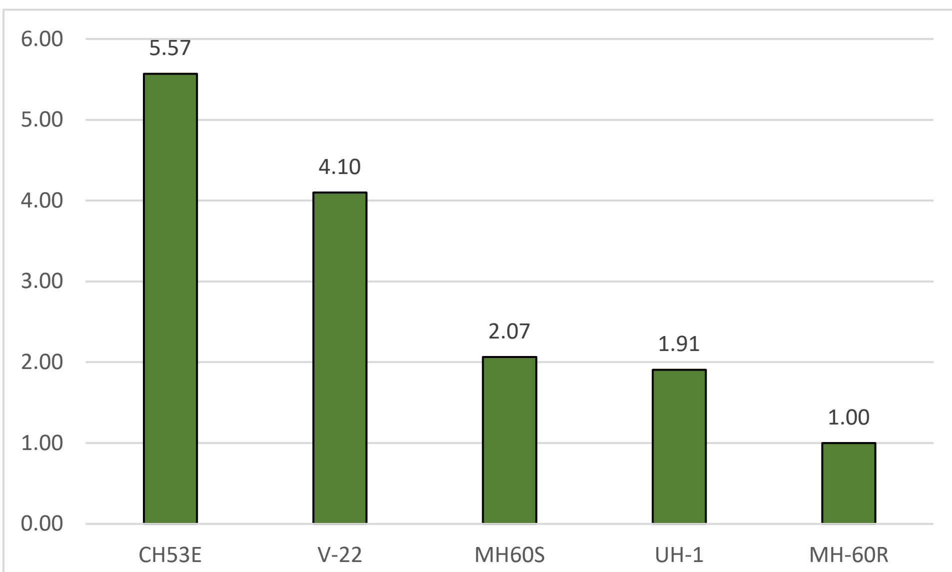


Figure 5. Ratio of Free Capacity by Aircraft Type

2. Search and Rescue

The next most-frequently demanded capability to HA/DR as it relates to helicopters is the ability for aircraft to identify and recover stranded personnel. While all vertical lift platforms are capable of SAR operations, we identified the UH-1, MH60R, and MH60S aircraft to be the most capable and preferred platforms to perform this function. The H-53, for example, is not recommended to be a primary SAR platform due to its large size, which generates significant rotor downwash that can injure personnel below (Naval Air Systems Command, 2019a). Additionally, the larger required landing zone area of the V-22 and H-53 make them less capable to effect ground recovery when significant amounts of debris are present or suitable landing zones are not available. It can be noted, however, that evacuation of large groups of personnel is better suited to the larger helicopters that are more accommodating in terms of size and seating configurations. Our research addresses the need for evacuation of people in extremis but does not include mass evacuations of people, as that would be better suited to transport aircraft.

3. Relief Radius

The range in which aircraft can travel, deliver supplies, and return to its hub is not infinite. Utilizing the performance data charts for level flight profiles available in the respective NATOPS publications, we modeled the selected performance databased on an operation from the sea, such as that launched from an amphibious-based platform, LHD, or aircraft carrier. To isolate environmental factors, the performance charts were selected to represent a common altitude and temperature. By analyzing these performance charts that indicate airspeed and fuel burn rate, our research determined what we refer to as a "relief radius," depicted in Figure 6. The relief radius represents the maximum relative ranges an aircraft can safely travel to service a landing zone with supplies and return to the hub without the aircraft being in extremis in terms of remaining fuel.

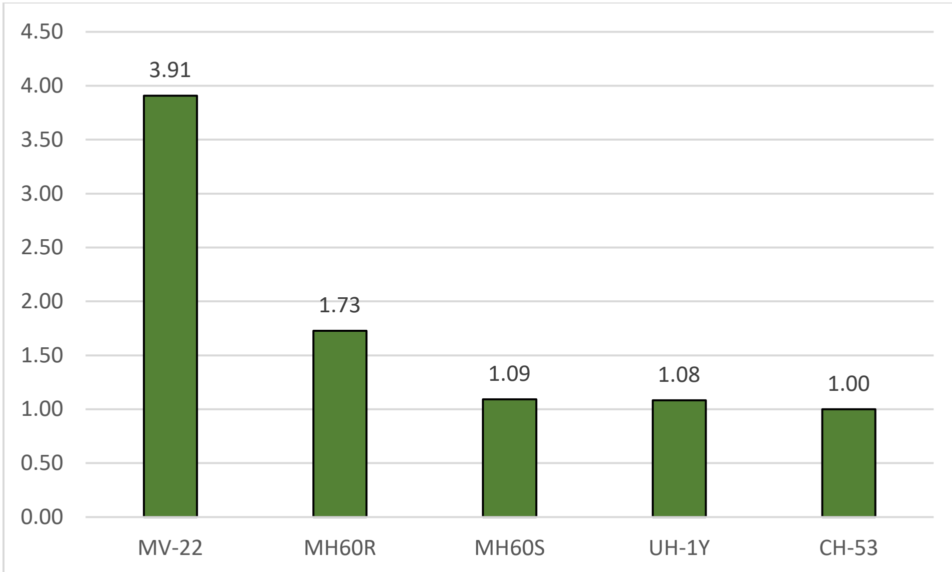


Figure 6. Ratio of Relief Radius by Aircraft Type

D. LINEAR PROGRAM MODELS

Linear programs allow the efficient identification of an optimal solution of vertical lift aircraft given a set of constraints defined by a given scenario. We chose to analyze two linear programs to compare across two sets of optimal solutions. The first linear program consists of minimizing the cost of the optimal solution, subject to a minimum lift delivery requirement. The second linear program maximizes free lift capacity while subject to a budget constraint. Both linear programs and their parameters are outlined in the following section.

Index and Set

i = Type of Aircraft [1, 2, 3, …, 6] (1: MH-60S; 2: MH-60R; 3: CH-53E; 4: UH-1; 5: MV-22 short range; 6: MV-22 long range)

Input Data

C_i = Cost of aircraft sortie ($US/sortie)

A_i = Available number of aircraft

T_i = Available number of aircraft sorties[2]

[2] Upper bound of Ti is 80% of available Pacific Fleet aircraft as mandated by SECDEF (Mattis, 2018)

S_i = Search and rescue (SAR) capability score[3]

L_i = Maximum usable free lift capacity (lbs)

M_i = Aircraft limit capacity (lbs)

J_i = Maximum aircraft fuel capacity (lbs)

F_i = Cost per flight hour ($US/flight hr)

H_i = Hours per sortie (hours/sortie)

E_i = Sorties per day (sorties/day)

R_i = Range capability score[4]

D = Total capacity demand

B = Total budget

Calculated Parameter Data

$$L_i = M_i - J_i \quad (1)$$

$$C_i = M_i - J_i \quad (2)$$

$$T_i = A_i * E_i \quad (3)$$

Decision Variables

X_i = Number of aircraft sorties

Objective Function for Minimizing Total Cost

$$Minimize \quad \sum_{i=1}^{6} C_i X_i \quad (4)$$

Constraints

$$\sum_{i=1}^{6} L_i X_i \leq D \quad (5)$$

$$\sum_{i=1}^{6} S_i X_i \leq 0 \quad (6)$$

---

3 S_i = 0.75 if the aircraft can perform SAR (MH-60S, MH-60R, UH-1). S_i = -0.25 for all other aircraft.

4 R_i = 0.9 if the aircraft has long range capabilities (i.e., > 120 nautical miles; MV-22 long range). R_i = -0.1 for all other aircraft.

$$\sum_{i=1}^{6} R_i X_i \leq 0 \tag{7}$$

$$X_i \leq T_i \qquad \forall i = 1,2,3,...,6 \tag{8}$$

$$X_i \geq 0 \textit{ and integer} \tag{9}$$

In Equation 1, the maximum usable lift capacity (L_i) is calculated as the difference between the aircraft's limit capacity (M_i) and fuel capacity (J_i). We assume that each aircraft operates with a full tank of fuel and can lift a cargo weight that equals the remaining limit capacity. Equation 2 explains the cost of an aircraft sortie (C_i) as the product of the aircraft's cost per flight hour (F_i) and hours per sortie (H_i). Since the decision variables (X_i) are measured in sorties, the unit costs must likewise be measured per sortie. F_i is calculated through VAMOSC data based on fuel consumption per aircraft. H_i is independently determined by aircraft based on our scenario simulations.

Objective Function 4 seeks to minimize the total cost of sortie operations in order to determine the optimal product mix of aircraft. This Objective Function is subject to Constraints 5−9 as a linear programming model. Constraint 5 represents the demand requirement. In other words, the optimal solution, measured in number of sorties, must deliver at least the capacity, *D*. Constraint 6 accounts for the SAR capability requirements. Our linear program requires that at least 25% of the optimal mix be able to conduct SAR missions. As outlined in the Search and Rescue section of this paper, UH-1, MH60R, and MH60S are the only platforms that can conduct SAR. Constraint 6 is therefore derived as follows:

$$\frac{X_1 + X_2 + X_4}{\sum_{i=1}^{6} X_i} \geq 0.25 \tag{10}$$

$$0.75X_1 + 0.75X_2 - 0.25X_3 + 0.75X_4 - 0.75X_5 - 0.75X_6 \geq 0. \tag{11}$$

Inequalities 10 and 11 represent Constraint 6 with each aircraft's assigned SAR capability score (S_i) based on the operational requirements for SAR-capable aircraft. Similarly, Constraint 7 requires that at least 10% of the optimal mix posess long-range capabilities. This proportional requirement is accounted for by the range capability score (R_i) for each aircraft as follows in Inequalities 12 and 13.

$$\frac{X_6}{\sum_{i=1}^{6} X_i} \geq 0.10 \tag{12}$$

$$-0.1X_1 - 0.1X_2 - 0.1X_3 - 0.1X_4 - 0.1X_5 + 0.9X_6 \geq 0 \tag{13}$$

The constraints contained in Equation 8 limit the decision variables to the total number of available aircraft sorties (T_i) derived from the total available aircraft within the Pacific Fleet (A_i) and number of sorties feasible per day (E_i). Equation 9 requires the linear program to produce a non-negative, integer solution.

Objective Function for Maximizing Lift Delivery

$$\textit{Maximize} \qquad \sum_{i=1}^{6} L_i X_i \tag{14}$$

Constraints

$$\sum_{i=1}^{6} C_i X_i \leq B \tag{15}$$

$$\sum_{i=1}^{6} S_i X_i \leq 0 \tag{16}$$

$$\sum_{i=1}^{6} R_i X_i \leq 0 \tag{17}$$

$$X_i \leq A_i \; \forall i = 1,2,3,\ldots.,6 \tag{18}$$

$$X_i \geq 0 \; \textit{and integer} \tag{19}$$

The lift capacity maximization model utilizes the budget provided by the cost minimization model to determine the maximum amount of cargo that can be lifted in HA/DR support missions. The linear program for maximizing lift capacity largely shares the same parameters and constraints as the cost minimization linear program; the differences reside in Expressions 14 and 15. Objective Function 14 seeks to maximize the total lift capacity delivered by sorties. Constraint 15 bounds the solution within a total budget (B) for sortie missions. B is directly determined from the optimal value from objective function 4. Specifically, B equals the total cost determined in cost minimization objective function plus an additional 10% budget buffer. Constraints 16−19 are the same as the cost minimization model.

E. MODELING RISK

The parameters and constraints within our linear programs rely on our defined risk scenario, modeled after Operation Tomodachi, which outlines the operations of dispatched vertical lift assets. In particular, the scenario determines sortie duration (H_i) and number of sorties per day (E_i). In turn, our linear programs provide optimal mixes of vertical lift aircraft that are inputted and analyzed in our risk simulation model. Our risk simulations allow us to analyze the lift delivery performance of vertical lift assets both individually as aircraft platforms and as a solution offered by the linear programs as previously stated in the Linear Program Models section of this paper.

1. Explanation of Risk Model and Crystal Ball

Our simulations consider vertical lift HA/DR operations as an iterative process dependent on the total flight time determined by landing zone locations. Figure 7 demonstrates the iterative flow of an aircraft dispatched for HA/DR missions. The following subsections address the decision path of a single aircraft performing sorties.

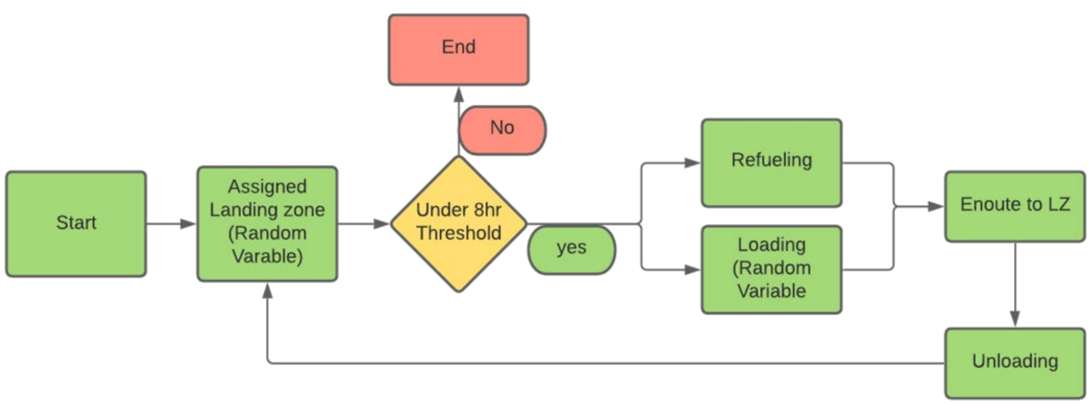


Figure 7. Iterative Decision Tree of Sortie Operations

2. Assigned Landing Zone Distance and Decision Point

The first step of a dispatched aircraft is to receive its LZ location and thus its distance to dispatched destination. Our simulation considers distance as a random variable following a uniform distribution with a minimum value of 10 NM and maximum value of 120 NM. We assume that all U.S. vessels operate 10 NM from shore and extend 120 NM inland, and that each landing zone has an equal chance of residing anywhere within that range. In terms of flight time, our model assumes that each aircraft flies at a constant, aircraft-specific speed and under the same set of conditions. Calculating the total time of flight (hrs) involves a simple conversion of distance and airspeed equaling distance to LZ (NM) divided by the maximum range airspeed (NM/hr).

Once an aircraft receives its dispatch instructions, it must assess crew limitations, as we assume that each aircraft maintains the same pilots and crew for each mission day. The number of possible sorties is limited by crew fatigue regulations. Commander, Naval Air Forces (CNAF) Instruction M-3710.7 delineates maximum allowable time for pilots and aircrew to be in performance of their flight-related duties. Crew rest restriction states that pilots should be allowed 8 hours of uninterrupted rest in every 24-hour period (CNAF, 2016). The maximum flight recommended for helicopter aircraft is 12 hours; however, at 16 hours of continuous awake time, pilot performance begins to drop, and at 18 hours, pilots begin to experience a 25% performance drop (CNAF, 2016). It should be noted that these times do not include meals, aircrew briefings, preflight, or postflight operations. For this reason, our simulation and many commanders alike limit total pilot flight time to between 8 and 8.5 hours depending on the last sortie. For example, if the last sortie can be completed before the 8.5-hour total time mark, then it will execute, and if not, the pilots will not complete the sortie.

3. Refueling, Loading, En Route, Unloading, and Return

Once an aircraft decides to embark, it undergoes the parallel tasks of refueling and loading. We assume that time to accomplish both of these tasks is a constant 30 minutes across each type of aircraft. For the loading evolution, the amount of cargo loaded onto each aircraft sortie is a random variable. Using the Pearson-Tukey formula, we can derive the inputs to the lognormal distribution of mean and standard deviation utilizing a three-point estimation of the following parameters: 95th percentile and median capacity per aircraft trip. It is important to note these parameters are approximations from subject matter experts within the aviation field because the actual data pertaining to each aircraft sortie is unknown. Table 1 represents the output data for the lognormal distribution used for determining the random variable "capacity" within our risk model.

Table 1. Lognormal Parameters by Aircraft Type

Aircraft Type	Mean (lbs)	Standard Deviation (lbs)
MH-60S	2,422.65	475.92
MH-60R	1,172.65	230.77
CH-53E	6,530.53	1,285.85
UH-1	2,235.28	440.31
MV-22	4,806.23	946.15

Cargo load is considered a random variable because load capacity is restricted by volume, rather than by weight. In other words, the density of the cargo will vary from sortie to sortie, and thus the total lift capacity delivered. Upon arrival of the cargo at the LZ, we assume a constant unloading time of 30 minutes and a return flight time equal to its en route time. The distance that the aircraft will travel to deliver supplies is modeled by a uniform distribution out to the relief radius, and airspeeds are assumed to be maximum airspeed for each aircraft at maximum gross weight as determined by the respective NATOPS manuals. The one exception to these airspeeds is the V-22, which has been restricted to a maximum of 250 NM/hr to comply with airspeed limits within controlled airspace below 10,000 feet mean sea level in accordance with general operating and flight rules (Aeronautics and Space, 2020).

F. DESCRIPTION OF RESULTS

Using the optimal solutions provided in both linear programs, we input the conglomeration of aircraft into our risk independently to conduct Monte Carlo simulations. Each Monte Carlo simulation represents a single day of HA/DR operations and the total amount of lift delivered to LZs. The accumulation of all simulated lift quantities delivered by the independent aircraft forms a distribution for further analysis. We test the simulated distribution's resemblance to the normal distribution according to the central limit theorem. In doing so, we determine whether the effect of an additional aircraft linearly increases the total free lift capacity delivered by all vertical lift aircraft. The accumulation of all lift delivery relies on two functions, each reliant on a single random variable. The first function is the total number of sorties flown by each aircraft with the input of distance assigned to

LZ dispatch as a random variable. The second is a random density function dependent on the weight of free cargo loaded onto each sortie by aircraft type. The total weight of cargo is aggregated by aircraft type and then indexed by the total number of sorties flown by each of those aircraft types. This index is repeated across Monte Carlo simulations to produce a distribution representing the estimated delivery quantity of one day of HA/DR operations.

Additionally, based on the distribution, we can determine the reliability of lift delivery. In other words, the United States would be able to provide a 95% reliability of Navy and Marine Corps vertical lift aircraft delivered to HA/DR relief efforts. By providing these metrics, the United States can more efficiently use its vertical lift assets and better coordinate internationally for humanitarian assistance missions.

IV. ANALYSIS

Our results include two main sets of metrics. First, we extract the optimal mixes from our cost minimization and capacity maximization linear programs. Second, we determine the median and 95% reliability capacities for the optimal mixes' performance of one day of HA/DR delivery. The outputs of our research, therefore, jointly provide the ideal configuration of vertical lift assets for our 2011 Japan disaster scenario and reliability quantities for what the U.S. Navy can contribute to HA/DR missions.

A. LINEAR PROGRAMMING ANALYSIS

The results for both our daily cost minimization model and daily load maximization model consist of the total number of sorties and total number of aircraft required. The cost minimization model considers the historical account of the U.S. Navy's tsunami relief for Japan to determine the total daily cargo required. Notably, the MH-60S and UH-1 aircraft are the most efficient and thus used exhaustively for the cost minimization and lift maximization models, respectively.

1. Scenario Application for Cost Minimization Model

For our cost minimization model, we determine the minimum amount of delivery for capacity demand required based on the U.S. Navy's response to the tsunami-affected area. We estimate the total capacity demand required based on the historical number of persons displaced and in need of assistance when U.S. Navy and Marine Corps vertical lift assets could reach the disaster area. As a sudden-onset disaster, Japan in 2011 required as many vertical lift assets, and thus naval vessels to carry the assets, at the disaster scene as possible. As each vessel arrived to the scene, more accurate disaster data could be collected with regard to displaced and missing persons. We assume in our models total U.S. responsibility for all displaced persons to identify the maximum scope of the Navy and Marine Corps' vertical lift support. However, we realize in a realistic scenario, the United States would cooperate with the other nations and non-governmental organizations for HA/DR.

All vertical lift–capable rotary aircraft were transported by U.S. Navy vessels to the tsunami relief region by March 19, 2011 (Aurelio et al., 2012). By this day, an estimated 255,074 displaced persons needed assistance, as illustrated in Figure 8 (United States Agency for International Development [USAID], 2011a-r). Our linear program models assume this total estimation of displaced persons for the calculation of the total cargo delivery requirement. The USAID guidebook recommends that 7.8 lb of relief materials (water, food, medical supplies) be available for each displaced person each day (USAID, 2005). The total daily cargo requirement for each day as the product of expected displaced persons and recommended daily cargo per person is 1,989,577 lb. Within our cost minimization model, we use 2 million pounds of total cargo as our constraint for total capacity demand, *D*.

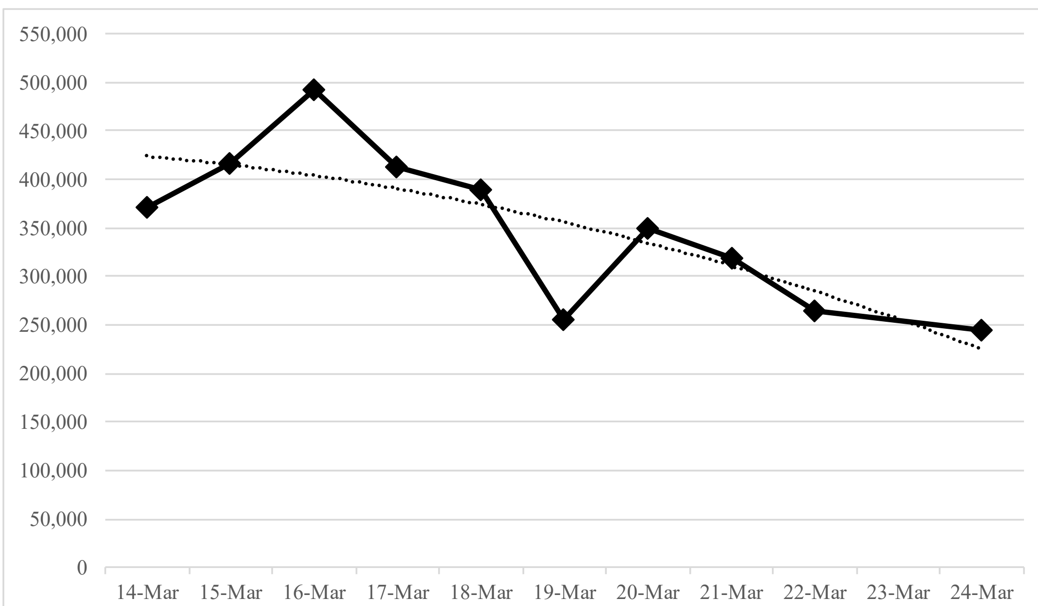


Figure 8. Total Displaced Persons by Date. Adapted from USAID (2011a–r).

2. Daily Cost Minimization Model Results

The results of our cost minimization model are outlined in Table 2. The first row denotes the total number of sorties required for one day of HA/DR support missions, fulfilling the 2 million pounds of relief cargo requirement. The second row contains the average number of sorties accomplished by each aircraft per day, based on the Monte Carlo simulations we ran. Dividing the number of sorties required by the average number of sorties per day yields in the third row the total number of aircraft required (rounded to the nearest whole number) for one mission day. This assortment of aircraft represents our optimal mix based on the cost minimization perspective. According to our model, the MH-60S provides the most cost-efficient utility, as all 75 available aircraft are exhausted. The last row of Table 2 contains the daily cost of operating each sortie by aircraft. The optimal value, or total cost of one day of HA/DR operations under the cost minimization model, is $490,439.17.

Table 2. Daily Cost Minimization Model Results

	MH60S	CH53E	UH-1	MV-22 Short	MH-60R	MV-22 Long	**Total**
Number of Sorties	237	1	182	66	0	54	**540**
Number of Sorties/Day	3.16	2.9	3.2	4.94	3.01	2.06	-
Number of Aircraft	**75**	**0**	**57**	**13**	**0**	**26**	**172**
Daily Cost (Cost/Sortie)	**$ 622.15**	**$ 2,110.18**	**$ 541.25**	**$ 1,418.84**	**$ 666.67**	**$ 2,754.22**	**$ 490,439.17**

3. Daily Lift Maximization Model Results

The results of our daily lift maximization model are contained in Table 3. As with the daily cost minimization model, the first row contains the number of sorties required for one day of HA/DR operations, and the second row contains the average number of sorties accomplished by each aircraft per day, based on the Monte Carlo simulations we ran. The third row denotes the total number of aircraft required by type. Of special note, the daily lift maximization model elects to dispatch all 60 UH-1 aircraft available as the highest utility aircraft within the given budget constraint. The last row contains the 95th percentile weight limit for each aircraft. In other words, we assume for the purpose of our maximization model that each aircraft will carry up to the 95th percentile of its weight limit in cargo for each sortie dispatched. The total lift capacity delivered for one day of total sorties is 2,196,184.2 lb.

Table 3. Daily Lift Maximization Model Results

	MH60S	CH53E	UH-1	MV-22 Short	MH-60R	MV-22 Long	**Total**
Number of Sorties	223	1	192	97	0	57	**570**
Number of Sorties/Day	3.16	2.9	3.2	4.94	3.01	2.06	-
Number of Aircraft	**71**	**0**	**60**	**20**	**0**	**28**	**178**
95th Percentile Capacity	**3,100.0**	**8,357.0**	**2,861.6**	**6,150.0**	**1,500.0**	**6,150.0**	**2,196,184.2**

B. RISK ANALYSIS

We used Monte Carlo simulation to model risk analysis utilizing Crystal Ball. The simulation ran 100,000 trials, with each trial representing total capacity for one day in terms of pounds of goods delivered. The aircraft used are a result of the optimal vertical lift mix as previously determined by the linear programming model for both cost minimizing and capacity maximizing optimization. We evaluate the risk to capacity that can be delivered for both optimizations (cost and capacity) with a 95% certainty as well as the median capacity aggregated over all aircraft. These certainties are tailorable to the level of risk a commander may choose to incur for a given mission. We also present some of the error introduced while taking data from one aircraft, multiplying it by a determined factor, and running all aircraft individually.

1. Risk Analysis (Cost Optimization Model)

The cost optimization model utilized 75 MH-60S, 57 UH-1Y, and 39 V-22. Note that 26 of these V-22 were of the long-range type. Figure 9 represents the capacity of 1,643,406 lb that can be delivered with a 95% certainty. In terms of capacity risk, this value represents our estimate of the minimum amount that can be delivered at least 95% of the time. Figure 10 is representative of median capacity of 1,678,337 lb, or the capacity that can be expected on an average day.

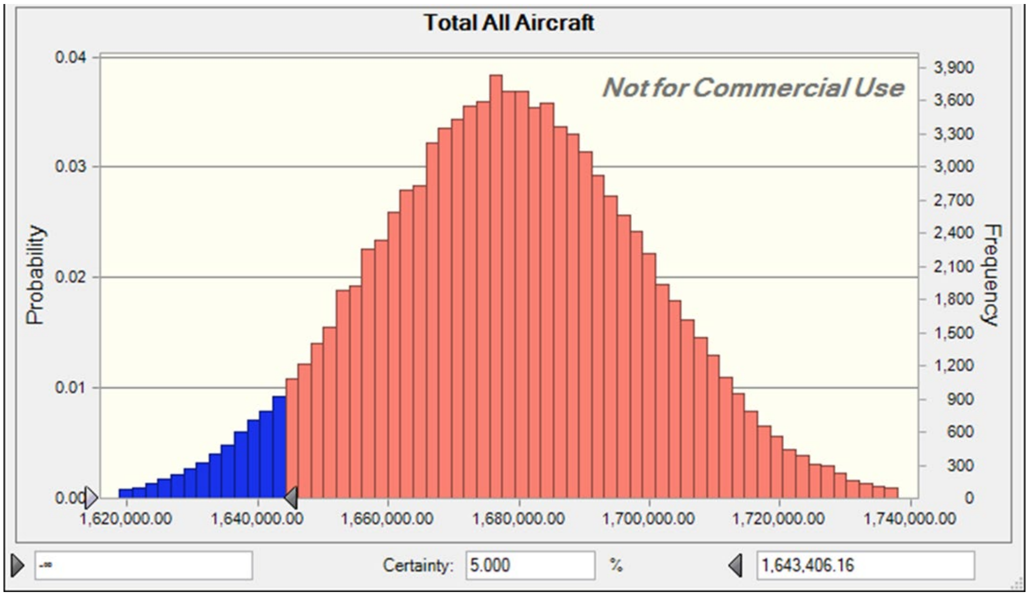


Figure 9. Total Aircraft Daily Capacity with 95% Certainty

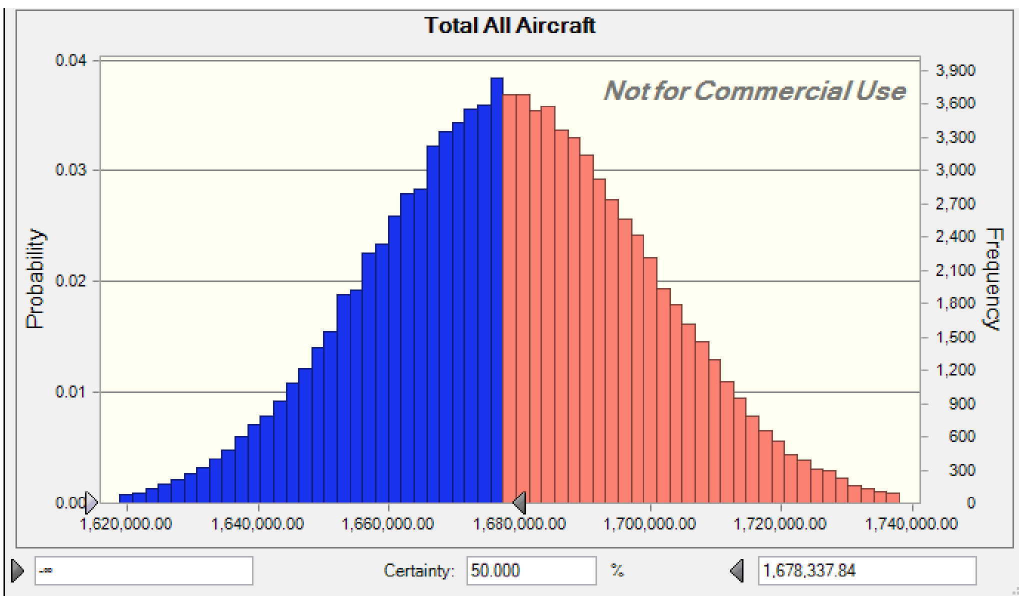


Figure 10. Total Aircraft Daily Capacity with 50% Certainty

2. Risk Analysis (Capacity Optimization Model)

The capacity optimization model utilized 71 MH-60S, 60 UH-1Y, and 48 V-22. Note that 28 of these were of the long-range type. The risk simulation for this model took on a similar distribution, trending towards normal. Figure 11 represents the capacity delivered with 95% certainty, 1,811,749 lb, and Figure 12 represents the average daily capacity of 1,848,115 lb, or a 50% certainty solution. Like the other risk model, the variance in the amount delivered, between 95% and the median, is minimal.

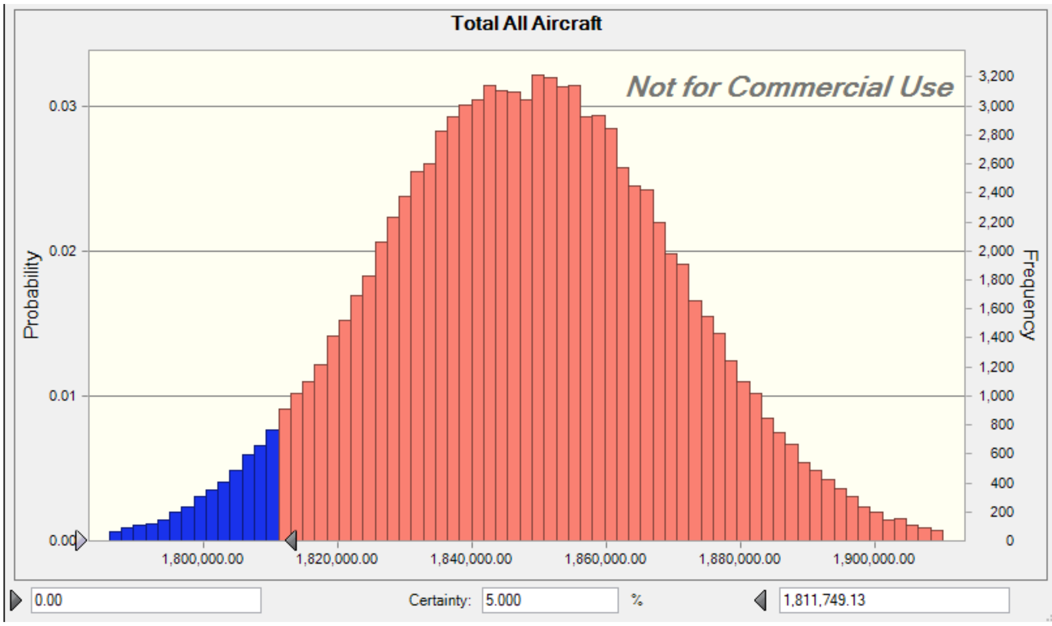


Figure 11. Total Aircraft Daily Capacity with 95% Certainty

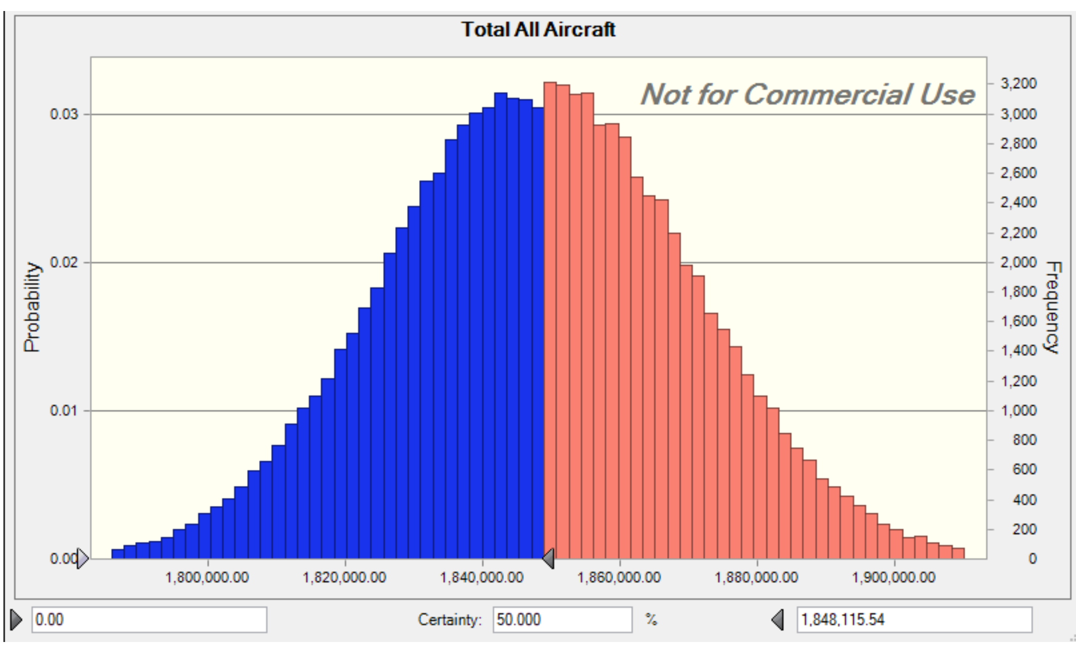


Figure 12. Total Aircraft Daily Capacity with 50% Certainty

3. Evaluating Single Aircraft versus All Aircraft of the Same Type

During our risk simulation, we had the decision of building the model for one aircraft and giving it a multiplication factor or building the model to analyze each aircraft individually. For example, the cost optimization model called for the employment of 57 UH-1 helicopters. Figure 13 shows a portion of that run, only indicating three of the 57 aircraft evaluated in total; however, among those three, we see a drastic difference in overall capacity for that day. Consider the difference between Aircraft 54 and Aircraft 55, where there is a 5,640 lb difference in goods delivered. If we then multiply these two results by a factor of 57, our daily capacity results vary drastically from 306,261 lb to 627,684 lb. The results of evaluating each aircraft independently and then summing the totals given by each aircraft resulted in an amount of 481,623 lb. The significance of this finding is that there is a large amount of volatility from one aircraft to another due to the variability in the distances to the LZs and the differences in capacity per sortie. Evaluating each aircraft individually produces a distribution that reduces this volatility.

Aircraft	Sortie	Fuel/Load (min)	Dist. to LZ (NM)	Enroute Time (minute	Unloading time (min)	Return to hub (Min)	Sortie Time	Minutes	Hours	Sorties Executed	Capacity
53	1	30	97.12819219	43.49023531	30	43.49023531	2.44967451	146.980471	2.45	1	2329.54339
	2	30	52.0469368	23.30459857	30	23.30459857	1.77681995	253.589668	4.226	1	2282.232908
	3	30	33.73685123	15.10605279	30	15.10605279	1.50353509	343.801773	5.73	1	2049.524476
	4	30	92.02140532	41.20361432	30	41.20361432	2.37345381	486.209002	8.103	1	2422.653317
	5	30	93.88854171	42.03964554	30	42.03964554	2.40132152	630.288293	10.5	0	2599.46[illegible]
							2.10096098			4	9083.954091

Aircraft	Sortie	Fuel/Load (min)	Dist. to LZ (NM)	Enroute Time (minute	Unloading time (min)	Return to hub (Min)	Sortie Time	Minutes	Hours	Sorties Executed	Capacity
54	1	30	106.0250427	47.47389973	30	47.47389973	2.58246332	154.947799	2.582	1	1790.770816
	2	30	94.60055442	42.3584572	30	42.3584572	2.41194857	299.664714	4.994	1	1557.595387
	3	30	48.30534541	21.62925914	30	21.62925914	1.7209753	402.923232	6.715	1	2025.522205
	4	30	101.8453588	45.60239946	30	45.60239946	2.52007998	554.128031	9.235	0	2974.181761
	5	30	117.2756681	52.51149317	30	52.51149317	2.75038311	719.151017	11.99	0	2390.3986[illegible]
							2.39717006			3	5373.888408

Aircraft	Sortie	Fuel/Load (min)	Dist. to LZ (NM)	Enroute Time (minute	Unloading time (min)	Return to hub (Min)	Sortie Time	Minutes	Hours	Sorties Executed	Capacity
55	1	30	17.77916094	7.960818332	30	7.960818332	1.26536061	75.9216367	1.265	1	2149.939976
	2	30	63.08172602	28.24554897	30	28.24554897	1.9415183	192.412735	3.207	1	2288.78126
	3	30	49.41377496	22.12557088	30	22.12557088	1.73751903	296.663876	4.944	1	2238.919665
	4	30	51.57781747	23.09454514	30	23.09454514	1.76981817	402.852967	6.714	1	2110.693248
	5	30	47.31264791	21.18476772	30	21.18476772	1.70615892	505.222502	8.42	1	2223.680[illegible]
							1.68407501			5	11012.01509

Figure 13. UH-1 Risk Simulation Model

Another finding is represented by the differences in the distributions created by evaluating one aircraft of a particular model over 100,000 trials and all aircraft of that same model over 100,000 trials. Figure 14 and Figure 15 visually depict these differences. In the single aircraft trial, the distribution appears to be multi-modal, whereas the distribution across all 57 UH-1 aircraft trends more towards a normal distribution.

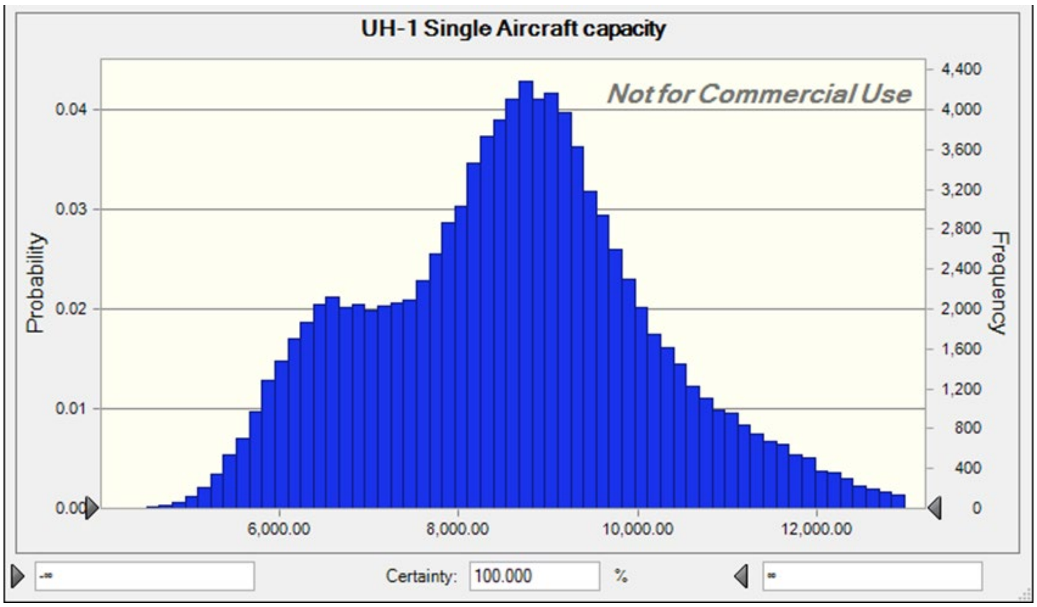


Figure 14. Distribution of a Single Aircraft

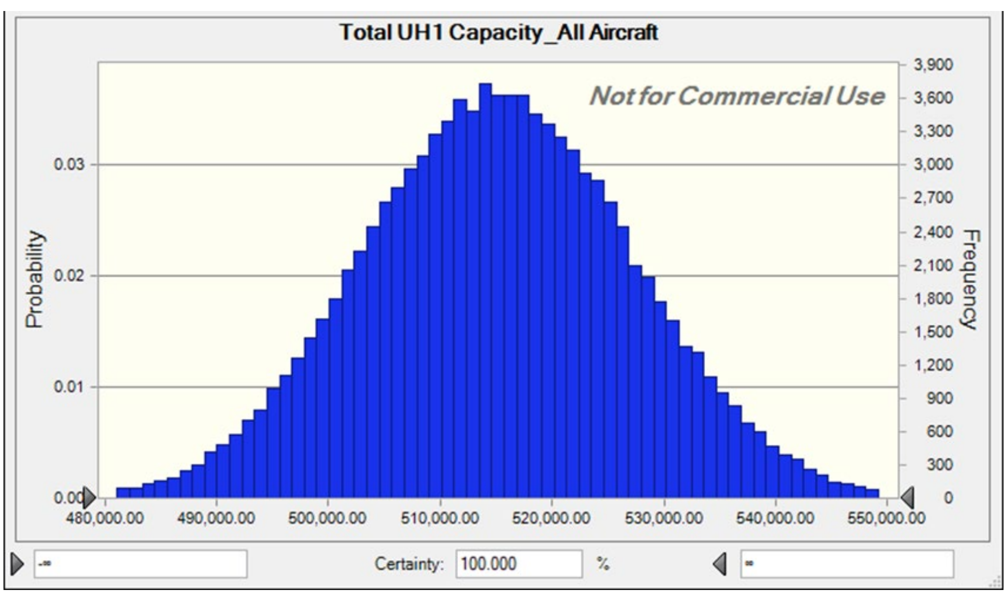


Figure 15. Distribution of All Aircraft of a Single Type

V. CONCLUSION

Our MBA project had two objectives. The first was to find an optimal mix of vertical lift aircraft that could be counted on to provide HA/DR, and the second was to find what is the likely daily capacity that can be counted on for that mix of aircraft. We developed two separate models to analyze these objectives. Given a situation where the number and type of aircraft are known, our models could accurately indicate which aircraft are most efficient in terms of both cost and capacity. Additionally, we could determine the risk to that capacity with a high degree of precision. Our models in this report provide results that are based on our assumptions of the number of aircraft we evaluated. As mentioned, they therefore provide scalability.

A. RESEARCH QUESTIONS ANSWERED

(1) What is the optimal allocation mix of U.S. Navy and USMC vertical lift capabilities in response to HA/DR operations?

The optimal product mix depends on the mathematical model and what is being optimized. The cost optimization model where the objective function sought to minimize cost chose to dispatch all 75 available MH-60S aircraft because of the MH-60S's higher relative cost efficiency compared to the other aircraft. The cost model then pulled 57 UH-1 aircraft and 39 V-22s to satisfy the total capacity constraint or theoretical daily demand. The cost optimization configuration can deliver 1,643,406 lb daily with a 95% reliability and a median of 1,678,337 lb on an average day. By contrast, the capacity model chose to dispatch all 60 UH-1 aircraft first because of their higher relative capacity efficiency. The capacity model then utilized a mix of 71 MH-60S and 48 V-22 to satisfy the rest of the model. The optimal mix for the capacity maximization model can expect to deliver 1,811,749 lb with 95% reliability and 1,848,115 lb on an average day. One important observation is that in both the models we utilized, the MH60R and the CH-53 aircraft were not part of the optimal mix. We interpret this conclusion to mean that both the CH-53 and the MH-60R, while capable, are relatively less efficient at HA/DR given our set of modeling constraints.

When we evaluated the risks to capacity being delivered from each aircraft, we found that the larger aircraft could reliably be counted on to deliver more goods in a given day than the smaller aircraft. For example, given a 95% certainty, a single V-22 could deliver 19,000 lb of goods, where a UH-1 could deliver 6,000 lb per day, representing a ratio greater than 3:1. When we compared the CH-53 and the V-22, which have a comparable load capacity, we found that the cruising speed of the V-22 gave an edge over the CH-53 because of the uniform distribution of the LZs.

(2) What are the strengths and weaknesses of each type of vertical lift capabilities designated for HA/DR?

Our Monte Carlo simulation modeled two different variables, distance to LZs and the capacity carried. We found that speed was probably the most important capability because of its relationship to time and distance, and it became increasingly more important the farther from the disaster area the LZs were. The V-22, because of its unique ability to fly as a fixed wing aircraft, allowed it to have the advantage of speed over all other assets. The second most important capability is related to the load capacity, or the ability to carry more resources on a single trip.

Another important capability for HA/DR response is aircraft availability. It seems obvious, but dedicating more aircraft to a mission increases the level of HA/DR support. The most theoretical variable within our project was the number of aircraft we selected, which equated to the entire fleet of aircraft within the Pacific Fleet area of responsibility. We understood as researchers the impracticability of this assumption, but it was necessary given the amount of aid needed for many major disasters. The takeaway from this capability is that U.S. vertical lift assets alone are insufficient to respond to natural disasters.

In the Risk Analysis section of this paper, we saw that variance to capacity delivered was small, equating to a 7% difference between 95% certainty and the median delivery capacity. From a decision-maker's point of view, this variance is almost inconsequential in terms of risk; however, it is important to note that much of this variance, or lack thereof, has to do with the simplicity of the risk model itself. In reality, there is an infinite number of variables that could be incorporated into this model. For example, loading, unloading, and fueling times, while held constant for our model, would also present some additional variability and thus create greater variance. Additionally, we are assuming perfect sortie completion (free of aircraft malfunction) and perfect LZ information, meaning isolated personnel are precisely in the location where the aircraft are landing. We mention these variables only to highlight that although our modeling variance is low, the potential variance, in reality would be much greater.

B. FOLLOW-ON RESEARCH

1. Application of Models to Real-World Example

The next step in our research project is to specifically adapt both our optimization and risk models to a real-world scenario modeled from a past disaster to capture a more realistic idea of aircraft mix and daily capacity. Often in the real world, commanders are not given the choice of what assets are available for employment to a disaster. However, there may be an event when the U.S. Navy can pre-select its vertical lift assets for HA/DR responses and desires to either minimize its costs or maximize its lift delivery performance. HA/DR coordinators can gather disaster-specific parameters, including the estimated distances to the LZ and relief demand based on the number of displaced persons. Using these parameters combined with the Navy's parameters, including potential aircraft available and budget, the HA/DR coordinator can use our model to determine the optimal mix of vertical lift assets for the present disaster. Our risk analysis model inputted with the scenario-specific parameters and the amount and type of vertical lift assets employed would provide the HA/DR coordinator the projected reliability of cargo delivery. If this analysis can be used and subsequently communicated across international partners, each party can better plan how their assets will contribute to the overall relief demand.

2. Other-Than-U.S. Assets

In HA/DR, the U.S. Navy is one of many entities providing relief. Many other nations' navies (including, in our scenario, the Japanese Maritime Self Defense Force) significantly contribute to relief efforts. Resultantly, HA/DR consists of teamwork between all parties to communicate the location and number of displaced persons, assess the amount of demand for all types of relief cargo, and track the completion of aid missions. Our research did not include the assets of other nations and non-governmental organizations in the delivery of goods and services (food, water, SAR). We assumed in our scenario that the U.S. Navy would be the sole entity providing relief for all displaced persons. Realistically, the U.S. Navy would not shoulder the entirety of operations. Analyses of other countries' or organizations' HA/DR assets could provide a better picture of the total capacity currently available.

3. Multi-criteria Analysis

Another potential area for research lies in evaluating trade-offs to force employment relative to each HA/DR response. Specifically, the cost/benefit to each additional asset for HA/DR support could more accurately evaluated. As decision-makers face the reality of finite resources, multi-criteria analysis will assist in efficient and effective resource allocation.

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