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Analysis of Traditional Aerial Systems and Fuel-Efficient Unmanned Aerial Vehicles (UAV) in Support of Spare Parts Delivery of Ships at Sea

June 2025

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ABSTRACT

This project conducts cost analysis of traditional aerial delivery systems using the MH-60S Seahawk and CMV-22B Osprey, against emerging fuel-efficient hybrid vertical takeoff and landing (HVTOL) unmanned aerial vehicles (UAVs), like Unmanned Aerospace's GH-4 Gyrocopter. Spare parts are essential for maintaining operational readiness of the Department of Defense (DoD) ships. A lack of spare parts can result in excessive downtime and inability to support the mission. When a part is unavailable, it must be flown in from shore or another vessel, typically using rotary-wing or tiltrotor aircraft like the MH-60S and CMV-22B. These expensive delivery methods can limit aircraft availability for other critical missions.

With the emergence of fuel-efficient UAVs, it is important to investigate their potential as a feasible and cost-effective solution to deliver spare parts to ships at sea. This study evaluates the acquisition and operational costs associated with both types of systems, considering multiple factors. It finds that UAVs, particularly the Kargo UAV, provide a cost-saving advantage over traditional aerial logistics platforms like the MH-60S Seahawk and CMV-22B Osprey. Therefore, it recommends that the Department of the Navy (DON) conduct pilot programs to further assess the performance, reliability, and interoperability of UAVs in logistical roles.

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ABOUT THE AUTHORS

Kylie Ball is a lead systems engineer at the Naval Surface Warfare Center Philadelphia Division, supporting the Columbia-class submarine program. She began her career as a contractor in 2012 after earning a Bachelor of Science in nuclear engineering from Rensselaer Polytechnic Institute. Early roles included supporting aircraft carrier habitability modification packages and leading design teams.

In 2015, Ball transitioned to the electric plant test facility for the Columbia-class submarine, first as a contractor and later as a Department of the Navy civilian. Since 2018, she has served as lead systems engineer for test readiness certification, ensuring technical requirements are satisfied and documented before testing begins. She also supports the program's technical director as deputy, helping resolve engineering challenges and enhance test facility performance.

Guillermo Juarez is a test engineer at the Naval Surface Warfare Center Philadelphia Division, where he supports electric plant and propulsion system testing for the Columbia-class submarine. Juarez began his career in the U.S. Navy in 2001, serving as an electronics technician aboard fast-attack submarine. He separated from the Navy in 2009 and earned a Bachelor of Science in electrical engineering from Temple University in 2014.

He began his civilian government service at U.S. Army Futures Command, developing and testing systems to ensure reliable position, navigation and timing in contested environments. He earned a Level III DAWIA certification in engineering in 2019 and a Master of Science in electrical and computer engineering from the University of Delaware in 2022.

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Special thanks to the Naval Postgraduate School for providing the necessary resources to conduct this research. The support from the staff and administration has been greatly appreciated.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEM	anion exchange membrane
ADDS	airborne deployable delivery system
AGL	above ground level
AMO	Air and Marine Operations
BVLOS	beyond visual line of sight
CBA	cost benefit analysis
CBP	Customs and Border Protection
CLS	contractor logistics support
CNO	Chief of Naval Operations
CONOPS	concept of operations
DLA	Defense Logistics Agency
DLR	depot level repair
DoD	Department of Defense
DON	Department of the Navy
DOTMLPF-P	doctrine, organization, training, materiel, leadership and education, personnel, facility and policy
EU	European Union
eVTOL	electric vertical takeoff and landing
FAA	Federal Aviation Administration
FHP	flight hour program
FOS	forward operating site
FY	fiscal year
GNSS	global navigation satellite system
HALE	high altitude long endurance
HFC	hydrogen fuel cell
HVTOL	hybrid vertical takeoff and landing
ISR	intelligence surveillance reconnaissance
MALE	medium altitude long endurance

MARV-EL	medium aerial resupply vehicle-expeditionary logistics
MSL	mean sea level
NPS	Naval Postgraduate School
OHCA	out of hospital cardiac arrest
O&M	operations and maintenance
OP-20	operational plan 20
RPM	revolutions per minute
SOUTHCOM	United States Southern Command
TRUAS	tactical resupply unmanned aerial system
UALS	unmanned aerial logistics systems
UAV	unmanned aerial vehicle
UAS	unmanned aerial system
USCG	United States Coast Guard
VLOS	visual line of sight
VTOL	vertical takeoff and landing

EXECUTIVE SUMMARY

A. INTRODUCTION

The U.S. Navy relies on an expansive logistics system to maintain operational readiness. One critical aspect of this system is delivering spare parts to ships at sea. Traditionally, this task has been accomplished using manned rotary-wing and tiltrotor aircraft, such as the MH-60S Seahawk and CMV-22B Osprey. However, these methods are costly and can be inefficient for small payloads. This research evaluates the feasibility of integrating HVTOL UAVs into the Navy's logistics framework as a cost-effective and sustainable alternative.

B. PROBLEM STATEMENT

Current aerial delivery methods for spare parts are expensive and reduce the availability of manned aircraft for mission-critical operations. As the DoD seeks to optimize logistics and improve operational efficiency, UAVs present a promising alternative. This study explores the costs of traditional aerial delivery systems compared to emerging UAV technologies, with a focus on enhancing readiness and aligning with broader DoD strategic objectives.

C. RESEARCH OBJECTIVES

This study explores the cost and mission effectiveness of routine resupply missions using Group 3 HVTOL UAVs, powered by hydrogen or electric propulsion.

The key research question includes:

1. How does the adoption of UAVs affect operational costs per flight hour compared to manned aircraft for part delivery at sea?

D. METHODOLOGY

The study uses a cost-based analysis approach, comparing procurement, operational, and maintenance costs of traditional helicopters and UAVs. The analysis leverages primary data from subject matter experts and secondary data from relevant DoD reports and industry case studies. Sensitivity analyses are performed to evaluate cost variability under a range of operational conditions.

E. FINDINGS

As depicted in Figure 1, the analysis shows that UAVs, particularly the Kargo UAV, provide a cost advantage over manned platforms. By reducing fuel consumption, maintenance needs, and manpower expenses, UAVs present a more economical solution for delivering small payloads. Use of UAVs brings limitations regarding payload, range and multi-mission support. However, advancements in UAV technology can contribute to supporting the Navy's strategic goals by enhancing logistical efficiency and enabling innovative operational capabilities.

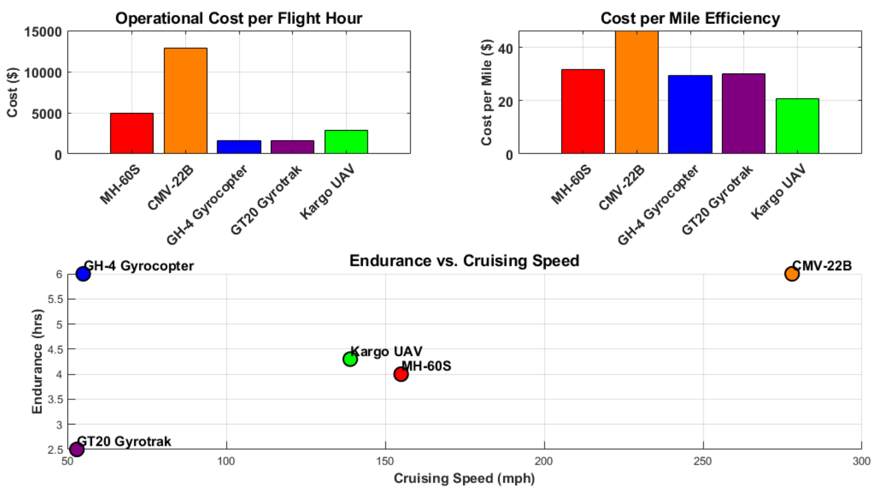

Figure 1. Weapon System Cost Comparison

While helicopters like the MH-60S offer greater payload capacities, UAVs can support optimizing Navy logistics, allowing for frequent, small-payload deliveries at a lower cost. Their rapid deployment capability, when appropriate, can ensures timely resupply without diverting high-value assets from mission-critical operations.

1. Recommendations

As the strategic landscape evolves, the integration of Group 3 HVTOL UAVs into the U.S. Navy's logistics framework can present a cost-effective and efficient alternative to traditional aerial resupply assets, such as the MH-60S and CMV-22B. This study demonstrates that UAVs, particularly those powered by electricity and hydrogen fuel, can offer significant operational cost reductions while preserving the availability of critical warfighting platforms.

Through cost-based analysis and sensitivity analyses, the findings show that UAVs provide savings in delivering small payloads to ships at sea, due to lower fuel consumption, reduced maintenance, and reduced personnel for flight operations. However, challenges such as refining UAV endurance, payload capacities, and integration within naval command structures must be addressed. Additionally, infrastructure improvements, including shipboard UAV refueling and recharging stations, are needed to support sustained operations in distributed maritime environments.

It is recommended that the DON conduct pilot programs to assess UAV performance, reliability, and interoperability while exploring policy adaptations for seamless integration within naval aviation frameworks. Ultimately, the adoption of UAV-based resupply solutions supports the U.S. Navy's strategic priorities, enhances sustainability, and optimizes resource allocation for future operations.

2. Conclusion

The goal of this thesis is to conduct a cost-based analysis to evaluate the feasibility and suitability of implementing UAVs for delivering spare parts to ships at sea in support of Naval logistics operations. As this analysis shows, there are not only procurement cost advantages to implementing UAVs in this manner but also decreased fuel costs. This research highlights the potential of vertical takeoff and landing (VTOL) UAVs to enhance mission availability by offloading routine delivery tasks from traditional platforms, like the MH-60S and CMV-22B, allowing those assets to focus on missions that require manned capabilities. Although UAVs face limitations in terms of range, speed, infrastructure support, and performance under adverse weather conditions, they represent a feasible option for shipboard logistics and warrant further research and development to exploit their operational utility within the Navy.

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I. INTRODUCTION

While rarely considered glamorous, the unsung hero of fleet readiness is its logistical support. Logistics and supportability enable the fleet to maintain its systems and keep equipment operating to achieve a greater mission. Without this support, the most advanced technology in the world may also sit on a shelf if it won't work when needed. Supportability covers many facets of support, but the key piece that this thesis focuses on is how spare parts make it out to ships that are deployed at sea and how this transportation process can be made more cost-effective while ensuring a timely delivery to minimize any potential system downtime.

A. PROBLEM STATEMENT

The purpose of this study is to conduct a cost-based analysis comparing fossil-fueled rotary wing or tiltrotor aircraft against Unmanned Aerial Vehicles (UAVs) to deliver critical parts and supplies to ships at sea. The U.S. Navy determined in a fleet logistics study that 70% of routine resupply deliveries weighed less than 15 pounds and 90% weighed less than 60 pounds, making low-weight cargo delivery with capital warfighting platforms such as the MH-60 or V-22 fiscally expensive (Naval Air Systems Command [NAVAIR], 2024). This project focuses on the use of Group 3 Heavy Vertical Takeoff and Landing (HVTOL) UAVs that are fully electric and/or powered by hydrogen fuel to reduce the U.S. Navy's costs and warfighting resources in the delivery of small payloads.

B. RESEARCH OBJECTIVES

In comparing the use of helicopters and HVTOL UAVs for delivering small payloads, such as repair parts, to ships underway, a cost-based analysis is critical to justify funding these types of systems. While the current concept of operations (CONOPS) relies on helicopters like MH-60s and CMV-22s, the transition to HVTOL UAVs presents notable advantages. These UAVs offer compelling cost-saving potential compared to helicopters, primarily due to reduced fuel consumption, lower labor requirements for crewing, decreased procurement costs, and reduced maintenance demands. The operational frequency of payload delivery with HVTOL UAVs allows for optimization, minimizing unnecessary flights and maximizing resource allocation. However, managing the average travel distance (range) covered by spare parts deliveries remains essential, considering UAVs' limited range capability. The research questions to achieve these objectives are as follows:

1. Primary Research Questions

How does the adoption of next-generation Group 3 UAV platforms, powered by alternative fuel, affect the fiscal and sustainability of routine resupply missions for the U.S. Navy compared to traditional fossil-fueled rotary wing or tiltrotor aircraft, and are HVTOL UAVs a feasible and cost-effective alternative for spare parts delivery to ships at sea?

C. METHODOLOGY

The research uses a quantitative cost analysis to evaluate the feasibility of transitioning from traditional rotary or tiltrotor aircraft to next-generation Group 3 HVTOL UAVs for spare parts delivery to ships at sea. Data is collected through direct engagement with subject matter experts, including Unmanned Aerospace and U.S. Southern Command (SOUTHCOM) leaders. Additional insights are drawn from relevant DoD documents and industry publications to support the analysis.

A cost analysis is used to compare the acquisition, operational, and maintenance costs of rotary-wing and tiltrotor aircraft like the MH-60S and CMV-22B against HVTOL UAVs. This includes an evaluation of fuel consumption metrics and the potential benefits of transitioning to alternative propulsion technologies, such as hydrogen and electric-powered systems. The analysis focuses on logistical performance and overall operational efficiency to inform future capability planning.

The research also includes an examination of the operational feasibility of UAVs by analyzing their range, payload capacity, and reliability compared to current spare parts delivery systems. Maintenance requirements, mission capabilities, and the frequency of small payload deliveries are also evaluated.

Finally, this study provides recommendations to improve cost efficiency and sustainability for spare parts delivery while maintaining operational readiness. This comprehensive approach, which includes a literature review, cost-based analysis, and use case modeling, provides Department of Defense (DoD) organizations with insights to optimize their logistical strategies and enhance mission support capabilities.

D. SCOPE AND LIMITATIONS

The scope of this research is limited to Group 3 UAVs as an alternative to traditional rotor and fixed-wing aircraft for delivering low-weight cargo (e.g., spare parts) to ships deployed at sea or remote land-based locations.

This study focuses primarily on small cargo deliveries based on the typical weight of spare parts and does not extend to larger or more complex logistics needs. The analysis is constrained to current and emerging technologies relevant to Group 3 UAVs and traditional aircraft. Additionally, the research relies on a quantitative methodology but does not explicitly incorporate empirical field testing, which could provide further validation. The reliance on expert consultations and secondary data sources introduces a dependency on the accuracy and availability of these inputs. Moreover, the project's findings are generalized for U.S. Navy operations, potentially limiting broader applicability to other military or civilian contexts.

Lastly, this study is limited to a cost analysis for the various options. It does not evaluate those costs against the measures of effectiveness for the options presented.

E. ORGANIZATION

Chapter I introduces the key challenges driving this research, outlines the research objectives and corresponding questions, details the methodology employed to achieve these objectives, and defines the scope and limitations of the study.

Chapter II presents relevant background information on UAVs, explores potential applications for UAV-based delivery of lightweight cargo to ships at sea and remote land-based locations, and discusses the rationale that forms the specific objectives of this research.

Chapter III provides a review of the literature addressing the operational and economic challenges associated with current aerial delivery systems, such as the MH-60 and CMV-22B. Additionally, the chapter presents an exploration of challenges such as range limitations and the complexities of integrating UAVs into existing logistical frameworks.

Chapter IV outlines methodology used to develop a cost-based analysis comparing traditional aerial delivery systems with emerging UAV technologies. It identifies key cost drivers, including Operational Plan 20 (OP-20) and the Flight Hour Program (FHP), acquisition and sustainment costs over the system's service life.

Chapters V and VI present a cost-based analysis comparing UAVs and traditional logistics resources using a structured nine-step approach. It evaluates cost factors by identifying relevant stakeholders, selecting alternatives, measuring and predicting impacts, monetizing costs, discounting for present value, and performing sensitivity analysis. Additionally, data on vehicle capabilities, OP-20 FHP, acquisition and sustainment costs, and sensitivity analysis are examined to determine the most cost-effective solution.

Chapter VII summarizes the key findings from the cost-effectiveness analysis, highlighting the comparative effectiveness of UAVs and traditional logistics resources. It provides recommendations based on cost savings, operational efficiency, and alignment with DoD objectives. Additionally, it identifies areas for further research to enhance future logistics and delivery solutions.

II. BACKGROUND

UAVs have emerged as transformative technologies revolutionizing various military applications. These platforms deliver tactical capabilities for strategic missions by collecting adversarial intelligence in remote or inaccessible terrain. These systems also provide strategic advantages in environments with a high risk of life loss and hazardous flight environments. Because of UAVs' versatility, their use in military operations has expanded to include routine tasks such as infrastructure inspection, remote cargo delivery, and logistics support. As technological advancements continue to refine their capabilities and accessibility, the integration of UAVs across the DoD promises to reshape the approach to various challenges and opportunities faced by the U.S. military.

A. PURPOSE

This chapter provides relevant background information about UAVs, including definitions, and their use in logistical applications with varying propulsion systems and flight configurations. It establishes the basis for addressing the identified research gaps, including vertical takeoff and landing (VTOL)-capable UAVs powered by hydrogen and batteries for last-mile delivery of spare parts to ships at sea.

B. BACKGROUND

Spare parts are critical to maintaining the availability of DoD systems on at-sea ships. A lack of required spare parts can result in excessive downtime and inability to support the mission. When a spare is available, it can be flown in from shore or another nearby vessel. These deliveries are currently made by rotary wing or tiltrotor aircraft like the MH-60S and CMV-22. However, using these platforms for small payload deliveries is increasingly expensive and limits their availability for higher-priority mission roles. As a result, there is a need to explore alternative delivery methods that are more cost-effective and operationally efficient.

In addition, the Chief of Naval Operations (CNO) Navigation Plan 2024, which outlines strategic direction and goals for the U.S. Navy, emphasizes the strategic priorities in modern warfare, where technological advancements and complexity are shaping the need for multi-domain operations and the integration of manned and autonomous systems. In response to these challenges, the CNO is focusing the Navy's strategy on distributed maritime operations and the development of a hybrid fleet, underscoring the importance of adapting legacy systems while scaling innovative capabilities to address operational readiness in contested global environments (Franchetti, 2024, p. 14).

C. RESEARCH RATIONALE

In January 2024, CNO released their Navigation plan for the Navy, with a list of seven areas of targeted focus called "Project 33" chosen to enhance readiness for the possibility of war with China and to improve the Navy's long-term advantage (Franchetti, 2024, p. III). Of the seven targeted areas, the second priority noted in the Navigation plan is the integration of robotic and autonomous systems for routine use (Franchetti, 2024, p. III). As the CNO states, "pursuing long-lead experimentation that will define the future's hybrid fleet. We know that robotic and autonomous systems, augmenting the multi-mission conventional force, will provide opportunities for us to expand the reach, resilience, and lethality of the combined manned-unmanned Navy team" (Franchetti, 2024, p. 9). To align with these focus areas, these authors sought to better understand the potential contributions of UAVs supporting Naval logistics, focusing on how this technology can be leveraged to reduce operational costs, improve response times, and support overall DoD sustainment goals.

With the continued emergence of fuel-efficient UAVs, it's important to investigate whether they can offer a feasible and cost-effective solution to deliver spare parts to ships at sea. This research will evaluate acquisition and operational costs associated with these systems, considering initial procurement expenses, maintenance, and operation costs, including fuel consumption and efficiency metrics. Through a cost-effectiveness analysis, the project aims to offer valuable insights into the financial impact of adopting alternative delivery systems for organizations like SOUTHCOM, supporting informed decisions on funding allocation and resource optimization. The project aims to evaluate and compare the most cost-effective and efficient aerial delivery solutions suitable for spare parts delivery.

D. UNMANNED AERIAL VEHICLES

A UAV consists of components and sub-systems integrated to perform specific tasks, like covert military missions or cargo delivery. Together, these components and sub-systems form a complete unmanned aerial system (UAS), including the air vehicle, propulsion system, navigation system, communications system, and payload system. It's important to note that the terms UAV and UAS will be used interchangeably throughout the document. Still, the focus will be on the complete UAV system configuration required for low-weight cargo delivery.

The earliest known UAV dates to the late 1800s when an anemometer was mounted on a kite to measure wind speed and direction at altitudes as high as 1,200 feet (Fahlstrom et al., 2012, p. 4). Though crude and low-tech, this UAV proved effective in measuring wind speed and pressure at altitudes that were not easily reached during that period. Similarly, in our modern era, UAVs operate in hazardous environments, remote locations, or challenging-to-reach areas that restrict ground movement. Technological advances have led to the expansion of UAVs in the military, making their use common throughout DoD. They offer a cost-effective alternative to traditional rotor and fixed-wing aircraft, requiring trained pilots and crew.

The integration of UAVs into military logistics is still evolving, and further work is needed to determine whether unmanned transport can reduce reliance on manned aircraft, leading to increased efficiency in logistical operations. Ergene's (2016) Naval Postgraduate School (NPS) graduate thesis titled *Analysis of Unmanned Systems in Military Logistics*, examines unmanned systems, specifically for military supply chain applications. The study draws on case studies and historical trends that explore how unmanned systems were integrated into existing logistics frameworks, focusing on their ability to enhance operational flexibility while mitigating risks with human-operated aircraft. Based on these findings the use of UAVs supporting military logistics operations is substantiated and supports our research, further expanding the use of UAVs in military logistics.

Additionally, UAV system information was used from *Introduction to UAV Systems* (Fahlstrom & Gleason, 2012) and *Unmanned Aircraft Systems* (Austin, 2010), both of which provide relevant background information about UAVs and their systems, which is presented in the following sections of this study.

1. The UAV as a System

a. Air Vehicle

The air vehicle serves as the backbone of the platform, directly affecting the stability and performance of the UAS. Its design is critically important to the system's aerodynamics of the system and integrates key components such as the payload, propulsion, and communications systems. The air vehicle can be a fixed-winged aircraft or, a rotary wing helicopter (Fahlstrom et al., 2012, p. 8).

(1) Fixed Wing

As depicted in Figure 1, a fixed-winged UAV resembles a traditional airplane in terms of design and function but on a smaller scale. Fixed main wings, fuselage, and rear wings are used to develop lift and serve as the controlling surfaces for the aircraft. Large, Group 3, Fixed-winged UAVs require conventional horizontal takeoffs and landings with wheels on a runway at high speed. These aircraft perform well in long-range, long-endurance missions operating at high altitudes with reduced wind turbulence. They are most appropriate for medium-altitude long endurance (MALE) and high-altitude long endurance (HALE) operations (Austin, 2010, p. 35).

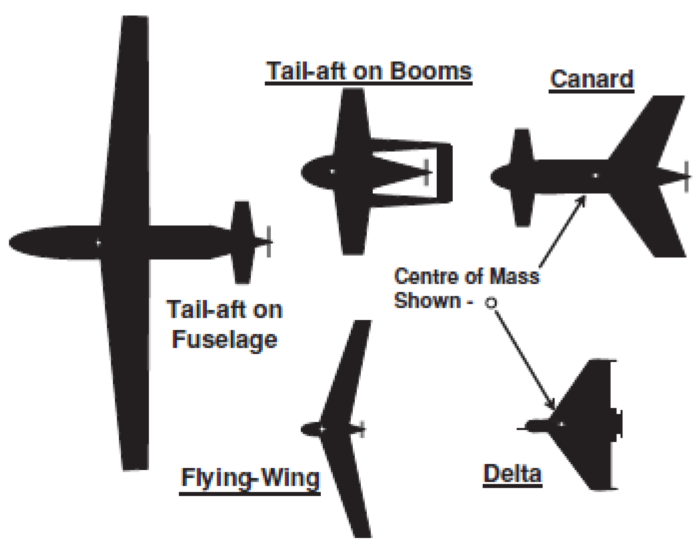

Figure 1. Fixed-wing UAV Configurations. Source: Austin (2010).

While fixed-winged UAVs are effective for MALE and HALE missions, they are not suited for lightweight cargo delivery in maritime operations. Their requirement for conventional horizontal takeoffs and landings limits their deployment from ships or other confined areas. Additionally, this UAV configuration lacks VTOL capabilities, making it unsuitable for delivering cargo to vessels or locations without established infrastructure. The design of these UAVs prioritizes endurance and altitude over maneuverability and accessibility, which are critical for last-mile delivery tasks to ships at sea.

(2) Single Rotor

As depicted in Figure 2, single-rotor UAVs function like traditional helicopters with the main rotor spinning, providing VTOL capability. The torque generated by the rotor causes the fuselage to rotate in the opposite direction, which is counteracted by a tail rotor that provides lateral opposing thrust (Austin, 2010, p. 37). Additionally, this configuration uses rotor head control systems to adjust blade pitch, adding complexity to the system. Single rotor UAVs perform well in short-range missions operating at lower cruising speeds and altitudes.

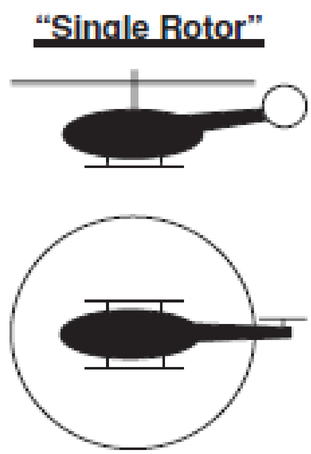

Figure 2. Single-rotor UAV Configuration. Source: Austin (2010).

A single-rotor UAV is well-suited for lightweight cargo delivery due to its VTOL capability, allowing it to operate without a runway. This UAV configuration excels in short-range missions at lower speeds and altitudes, making it ideal for delivering small cargo to remote or restricted locations, such as ships at sea.

(3) Multi-Rotor

As depicted in Figure 3, multi-rotor UAVs, such as quadrotors, use four fixed-pitched blades, each individually driven by electric motors mounted to each rotor head. This configuration simplifies the system by eliminating the complex single-rotor head control for aircraft pitch adjustments. Forward movement is achieved by increasing the speed of the two rear rotors, causing the aircraft nose to pitch downward and producing a forward thrust vector (Austin, 2010, p. 40). Like the single-rotor configuration, quadrotor UAVs provide VTOL capability and perform well in short-range missions operating at lower cruising speeds and altitudes.

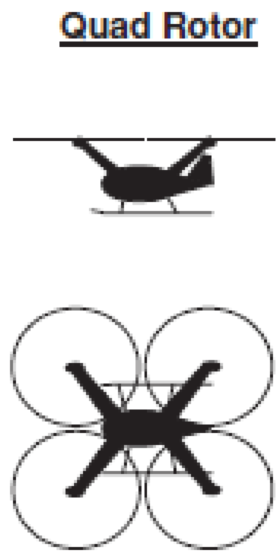

Figure 3. Quad Rotor UAV Configuration. Source: Austin (2010).

These features make multi-rotor UAVs efficient for short-range logistical tasks involving lighter cargo than single-rotor designs, which are more suitable for transporting heavier payloads over longer distances.

(4) Gyrocopter

As depicted in Figure 4, the gyrocopter UAV is a rotorcraft configuration that uses an unpowered main rotor in free autorotation, creating lift and side or rear thrusters powered by an engine or battery, spinning propellers to move the aircraft forward. Gyrocopter UAVs traditionally require conventional horizontal takeoffs and landings with wheels on a runway. However, modifications can be made to the traditional design, providing VTOL capability. Like the other rotorcraft configurations, the gyrocopter performs well in short-range missions operating at lower cruising speeds and altitudes.

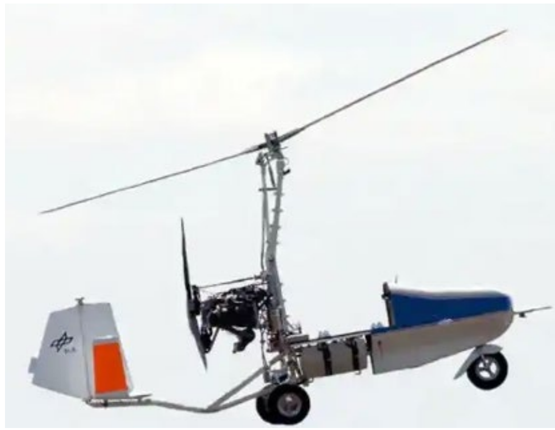

Figure 4. Gyrocopter UAV Configuration. Source: Szondy (2019).

The idea of fixed-wing and single or multi-rotor UAVs is not new, and their uses are well-documented in commercial and military applications. Similarly, the gyrocopter, which closely resembles a helicopter, combines fixed and rotary-wing aircraft characteristics to increase flight safety and reduce the system complexity of a helicopter, using the autorotation principle to develop lift from the unpowered top rotor. The gyrocopter was invented in 1920 by aeronautical engineer Juan de la Cierva and is widely used in European countries, so its operating and flight dynamics are well understood (Niki Rotor Aviation, 2022). However, using a gyrocopter design for unmanned, autonomous applications is a novel concept that the UAV industry or military has not widely implemented. This represents a gap in UAV configurations that our study seeks to address, contributing insights to this topic of study.

b. Propulsion System / Propellant

The propulsion system of UAVs is critically important because it generates lift and thrust to propel the aircraft and sustain flight. The propulsion system is tailored to meet specific mission requirements and flight characteristics based on user needs. In this chapter, three variants of fuel for UAV propulsion systems are discussed and compared.

(1) Jet Propellant

Jet Propellant (JP) is a traditional fossil fuel commonly used in combustion engines. These engines burn fuel to power a crankshaft, which turns a propeller or rotor, creating thrust. This fuel provides longer flight times and higher cargo capacity than hydrogen and electric UAV systems. Kerosene-based fuels JP-5 and JP-8 are used in rotary and tiltrotor aircraft and require periodic maintenance and generate significant noise during operation.

(2) Battery

Batteries supply electrical power to the UAV payloads and propulsion system. This system uses electrical energy from batteries to power electric motors, driving propellers or rotors to generate thrust. This option provides emission-free power, low maintenance, and quiet operation. However, capabilities are limited due to battery capacity and overall aircraft weight. The higher power density of this technology increases the system's maneuverability and provides power during periods of high demand, which includes VTOL and hovering.

(3) Hydrogen Fuel Cells (HFCs)

Emerging technology, HFCs produce electricity through a chemical reaction between hydrogen and oxygen, providing electrical power to the UAV payloads and propulsion system. This system uses electrical energy from this chemical reaction to power electric motors, driving propellers or rotors to generate thrust. This option can provide emission-free power if the source for generation is not driven by fossil fuel. Additional benefits include reduced maintenance requirements and quiet operation. The higher energy density of this technology increases endurance capabilities compared to all-electric battery-operated systems, still, challenges such as cost, and hydrogen refueling are limiting factors for use in UAV systems.

(4) Battery and Hydrogen (Hybrid)

As described in the Coelho et al. (2022) conference proceeding "Design of a tactical eVTOL UAV with a hydrogen Fuel Cell," using HFCs in the aeronautical market is not new, however, its implementation requires further studies and analysis (p. 95). Still, it is emerging as a possible energy source capable of replacing internal combustion engines that use fossil fuels. Their study explores the integration of HFCs into UAVs specifically designed for VTOL and fixed-wing operations, aligning well with the systems being investigated in this study. Their article highlights the limitations of battery-powered systems, such as low energy density and long recharge times, while emphasizing hydrogen's potential as an alternative that increases flight endurance. The authors work with the Portuguese Air Force to design an optimized UAV that can be used for tactical operations and validate it using advanced methodologies. Their results demonstrate improvements in flight endurance, structural integrity, and aerodynamic efficiency, achieving over three hours of flight time. Their work underscores the feasibility of HFCs for use in VTOL UAVs and supports their use for long-duration missions.

Similarly, An et al. (2022) journal article "Advanced Sizing Methodology for a Multi-Mode eVTOL UAV Powered by a Hydrogen Fuel Cell and Battery" power density and endurance limitations of conventional battery-powered UAVs are discussed with the solution of addressing this challenge through a hybrid system that combines battery and HFCs for UAV propulsion (p. 1). Their study presents a methodology that validates the design for a 25-kilogram UAV with a six-hour endurance through modeling techniques and empirical data, showing a less than 10% deviation between predicted and actual design outcomes. Further validating the feasibility of hydrogen coupled with batteries can be used to increase the performance of VTOL UAVs for use in long-duration missions.

c. Navigation System

UAV navigation systems integrate a global navigation satellite system (GNSS) and inertial measurement units, which work together to guide the system to a designated location. The navigation system maintains the attitude, altitude, and ground track of the UAV and is controlled manually by a trained operator or by autopilot software, which provides autonomous capabilities.

d. Communication System

Communication is facilitated through the data link, a subsystem of the UAV. This link enables two-way communication, either continuously or on demand. The uplink, typically operating at a few kilohertz, is used to control the flight trajectory of the UAV and its equipped sensors. The downlink includes two channels: a low data-rate channel for command acknowledgments and status updates, and a high data-rate channel for transmitting sensor data, such as video and radar (Fahlstrom et al., 2012, p. 10). Satellite communications are the preferred method for establishing data links, allowing for deployment in a large operational area and supporting autonomous control beyond visual line of sight (BVLOS).

e. Payload System

The type and performance of the payload system are determined by the requirements of the operational task (Austin, 2010, p. 10). Consisting of sensors or modules of sensors, the payload system gathers, processes, and delivers data to the user to support successful mission execution. This research will focus on delivering lightweight cargo-like repair parts. Additionally, cameras with scanning equipment may be mounted to the UAV to provide expanded functionality, supporting inspection of vessel infrastructure or scouting missions.

Weber et al.'s (2015) conference proceeding titled "Gyrocopter-based remote sensing platform," supports the idea that a gyrocopter can be a platform used for remote sensing and scanning. Their research presents a modular airborne sensor system, including high-resolution digital single-lens reflex cameras, a hyperspectral imager, and a thermal imaging system that collects data across various spectral bands. The gyrocopter's cost-effectiveness and flexibility make it suitable for medium-scale survey or scanning and highlight this aircraft's potential to conduct advanced remote sensing missions. However, since this research was conducted using a manned gyrocopter, further studies are needed to evaluate whether these capabilities can adapt to an unmanned gyrocopter of a smaller scale, operating with a less powerful power system.

f. Launch and Recovery

VTOL is the preferred launch and recovery method for UAVs, allowing UASs to operate from diverse terrains and military platforms without the need for additional equipment. This launch and recovery method is unaffected by wind and allows the aircraft to be deployed quickly after arriving on-site (Austin, 2010, p. 176). Similarly, the ability to hover during landing allows the UAV to descend slowly and accurately in confined or complex spaces, like a ship deck.

g. Control System

(1) Visual Line of Sight (VLOS)

The operation of a UAV using VLOS control requires a remote pilot and unaided visual contract with the unmanned aircraft while it's in operation. The remote pilot is required to maintain the trajectory, course, and altitude of the UAV while in flight, avoiding any obstacles or potential dangers in the surrounding airspace. Though this control system is less complex than others, it places the onus on the remote pilot who can become fatigued in prolonged operations. This method of controlling UAVs is not suitable for lightweight cargo delivery for ships at sea because the operational area is limited to the remote pilot's visibility. However, in the case of vessel infrastructure scanning or ship-to-ship delivery, where the operational area is localized to the vicinity of the ship, VLOS control can be a useful tool.

(2) BVLOS

Contrary to VLOS control, BVLOS UAV control does not require direct visual contact by a remote pilot, extending the operational area to the flight endurance and range capabilities of the UAV. However, a remote pilot may be needed to make minor course adjustments and monitor sensor systems, and UAV health as it navigates to its intended destination.

h. Supporting Systems

The supporting system will include a cargo delivery and retrieval system attached to the UAV air vehicle that efficiently transports and recovers cargo payloads in various environments. Ideally, the system will be modular, constructed of lightweight, durable material, and able to accommodate a range of cargo sizes and weights of up to 15 pounds.

2. Rules and Regulations for UAVs

As the use of UAVs proliferates in the public, private, and military sectors, the development of UAV rules and regulations continues to evolve. Originating in the 20th century, the International Civil Aviation Organization set foundational aviation principles, beginning in 1944, with subsequent national frameworks like the U.S. Federal Aviation Administration (FAA) and European Union (EU) regulations emerging to guide UAV integration into national airspaces (Garg, 2021, p. 233). These regulations address issues like restricted airspace, altitude limits, licensing, and insurance requirements, which ensure safe and ethical UAV operations. However, the regulatory approaches of specific countries, such as the United States, EU, and China vary widely, complicating UAV use in the global market. For example, a standard definition of due regard does not exist among countries, which is critically important to UAV use in military operations. The principle of due regard will be discussed further in the next section of the paper.

a. Controlled Airspace

In the United States, controlled airspace is defined by the Federal Aviation Administration (FAA) as airspace where air traffic control (ATC) service is provided and instrument flight rules (IFR) and visual flight rules (VFR) are met, often requiring pilots to obtain clearance from ATC before operating the aircraft in coastal or international airspace (Federal Aviation Administration [FAA], 2024, Chapter 3: Section 2). Therefore, when UAVs operate in controlled airspace, they must adhere to the same requirements as manned aircraft. This presents a challenge when operating UAVs because they are unmanned and do not have a human pilot onboard monitoring flight instruments or maintaining visual line of sight to avoid collision with other aircraft in the area.

b. Instrument Flight Rules (IFR)

IFRs are a set of regulations developed by the FAA that allows pilots to operate aircraft using onboard instruments when conditions, such as rain, fog, or night, cause poor visibility and prevent the use of visual aids. This requires that all aircraft be fitted with an instrument package capable of communicating and continuously monitoring ATC message traffic, ensuring safe navigation in conditions of reduced visibility. Additionally, pilots must file an IFR flight plan and receive ATC clearance when operating in controlled airspace (FAA, 2024, Chapter 3: Section 2). This presents a significant challenge to UAV operations because additional electrical payloads are needed to meet this requirement, which increases weight and power consumption, thereby reducing the performance capability of smaller Group 3 UAVs. Furthermore, to meet this requirement, UAVs must be able to autonomously detect and avoid obstacles and/or other aircraft operating in flight to avoid collision, which would require a software package that would have to be rigorously tested and validated.

c. Visual Flight Rules (VFR)

VFRs are regulations developed by the FAA that allow pilots to navigate aircraft using visual aids to prevent collision with other aircraft or obstacles. This requires good atmospheric conditions with clear visibility enabling the pilot to act in scenarios where a hazard is encountered during flight. In UAV operation, there is no onboard pilot to meet this requirement, relying on remotely monitored surveillance sensors, software to automatically maneuver the UAV to safety, and remote ATC communications, which may not be enough to meet FAA safety regulations.

d. Uncontrolled Airspace

Uncontrolled airspace is the opposite of controlled airspace. In this environment, ATC does not provide service, and the safe operation of the aircraft is left to the pilot. UAVs operating BVLOS or in uncontrolled airspace remove the ability of human intervention, making it harder to avoid collision and keep a safe distance from other aircraft. This complicates the reliable detection and avoidance of UAVs because if human intervention is removed, software (i.e., algorithms and artificial intelligence) must be integrated into UAVs to meet this requirement. These systems require extensive testing and validation to prove they can effectively replace human decision-making in dynamic airspace environments.

3. Issues and Concerns

a. Battery Technology

The primary concern with "battery-powered eVTOL UAVs is their limited range and endurance" (An et al., 2022, p. 1). This is especially true for UAVs that provide VTOL and hovering capabilities because these modes of operation require large bursts of electrical power. Batteries offer high power density, the maximum power they can deliver per unit of mass, making them ideal for meeting fast, high-power releases required in UAVs (Brun, 2018, p. 1). However, the energy density of batteries, the amount of energy they can store based on volume or weight, is lower in UAVs due to the system's weight constraints, limiting sustained VTOL and hovering maneuvers and reducing flight endurance (Brun, 2018, p. 71). For example, "lithium-ion is one of the most common battery chemistries sold commercially. Current commercial lithium-ion chemistries have an energy density ranging from 100 Watt-hours/kilogram to 265 Watt-hours/kilogram" (Littell et al., 2023, p. 2). This provides an average endurance of 15–60 minutes for VTOL UAVs.

b. Hydrogen Fuel Cells

Contrary to batteries, HFCs offer high energy density capability, providing longer flight times for UAVs, but lower power density, limiting their use for VTOL and hovering maneuvers. Hydrogen has an energy density of 33,410 Watt-hours/kilogram, offering significant potential for increasing endurance. Advancements in fuel cell and hydrogen storage technology can extend the endurance of VTOL UAV to more than three times that of traditional battery-powered systems. HFCs provide the same operational advantages as batteries, including safety and quiet operation, but are more complex and costly to implement (Brun, 2018). As described in Brun's (2018) University of Stavanger thesis titled "*Preliminary Design of a Fuel Cell-Battery Hybrid Propulsion System for a Small VTOL UAV,"* polymer electrolyte membrane HFCs paired with battery-powered systems are used to overcome the endurance limitations of traditional lithium-polymer batteries UAV systems (p. 17).

Storage and handling of hydrogen present challenges, particularly aboard a U.S. Navy vessel. While hydrogen's explosive potential is a cause for concern, the actual risk in UAV applications is minimal due to the small quantities involved. Furthermore, the possible explosion risk is reduced by producing hydrogen on demand for UAV operations rather than storing it in large amounts. For example, Enapter is a German-based company that commercially manufactures the EL 4.1, a patented anion exchange membrane (AEM) electrolyser that is standardized, stackable, and capable of producing hydrogen on-site The EL 4.1 AEM electrolyser is powered using a stand 240 volts alternating current (VAC)/60Hz power source and can produce up to 1.0785 kilograms of hydrogen in 24 hours (Enapter, 2024, p. 2). This approach aligns with current advances in hydrogen fuel systems, where innovations focus on safe, efficient, and compact production methods to address concerns around storage and handling.

c. Adverse Weather Conditions

Adverse weather conditions present challenges for UAVs during resupply missions and affect their performance, reliability, and safety. Contrary to manned aircraft, UAVs are vulnerable to extreme weather conditions because they lack the complex systems and human control used in traditional aircraft to overcome adverse weather challenges. High winds can disrupt their stability and control, causing erratic flight paths and mission failure. Heavy rain or dense cloud coverage can degrade the performance of sensor payloads and GNSS systems, leading to an inability to navigate to delivery locations. Extreme temperatures, whether hot or cold, can decrease the efficiency of batteries and HFCs, limiting cargo capacity and resulting in a loss of propulsion. Additionally, weather-related challenges complicate mission planning and can cause delays or cancellations of package deliveries. Weather in the open ocean is unpredictable and can change rapidly, further complicating the timely delivery of critical supplies and increasing the risk of UAV loss.

d. UAV Infrastructure

UAV infrastructure considerations are critical because these systems require specialized support for efficient and reliable operation. Like conventional aircraft used for resupply, UAVs depend on a network of physical infrastructure that must be established and maintained for continued operation. For example, organizations deciding to implement UAVs for resupply missions must strategically place VTOL platforms in locations that support their range and endurance capabilities, ensuring deployed UAVs can reach their delivery zones. Additionally, organizations must consider power infrastructure because UAVs using batteries and/or HFCs require frequent batteries or hydrogen bottle recharging, dictating the need for portable charging stations if a permanent solution is not developed. This may be particularly challenging in forward operating sites (FOS) located in remote locations with rough terrain or limited access to power resources.

Moreover, UAVs are complex machines with sensitive electronic equipment and mechanical components that require routine maintenance to ensure the system remains operationally available. This drives the need for repair and maintenance facilities with spare parts, diagnostic tools, and trained personnel capable of servicing damaged or malfunctioning UAVs as needed.

Finally, UAVs stored abroad U. S. Navy vessels require integration into existing ship infrastructure, which demands an upfront investment, and careful planning. These systems will require the installation of UAV-specific systems into the limited physical space available on ships. Additionally, ships must retrofit their power systems to support UAV operations without causing interference with existing ship systems, including battery and hydrogen recharging stations.

4. UAV Groups

Denevan's (2014) NPS graduate thesis titled "*Cost-based analysis of unmanned aerial vehicles/unmanned aerial systems in filling the role of logistical support*," investigated the use of UAS filling the role of logistical support and conducted research identifying and classifying UAV groups which has been leveraged to provide background information in this section of our study. Based on these findings and the performance characteristics outlined in each UAV group, Group 3 UAVs have emerged as the prime candidate for this research and will be the primary focus.

For completeness, we will include a larger-sized Group 4 UAV powered by JP-5 in our discussion. While this UAV relies on a traditional fuel source and a combustion engine, its unmanned, autonomous capability offers improved cargo delivery over helicopters and tiltrotor aircraft, such as the MH-60 and CMV-22B.

UAVs have emerged as invaluable assets within the DoD, showcasing their versatility across a wide spectrum of military operations, from intelligence, surveillance, and reconnaissance (ISR) missions to precise targeting and executing weapon strikes. As technology continues to advance, UAVs have transitioned into a multifaceted tool, enabling the DoD to execute missions efficiently while reducing the risk to human life. To streamline their management and regulation, the DoD has categorized UAVs into five groups, guided by their size, weight, and capabilities. In this discussion, we look at the various classifications of UAVs, exploring differences in design, functionality, and intended use. By understanding these classifications, we can better appreciate the evolving landscape of unmanned aerial systems and their implications across DoD sectors. The characteristics of each UAV group are shown in Table 1.

(1) Groups 1–2

Groups 1 and 2 consist of the smallest and lightest UAS, weighing from less than 20 pounds to 55 pounds. They provide restricted flight endurance at low altitudes of less than 3500 feet above ground level (AGL) at speeds of less than 250 knots and are best suited for ISR missions, target identification and acquisition, and battle damage assessment. These aircraft are compact in size with a payload capacity not exceeding 10 lbs. and a maximum range of approximately 124 miles (108 nautical miles) at speeds less than 100 knots. However, as they do not meet the minimum performance thresholds for this research, they are excluded from further discussion.

(2) Group 3

Group 3 UAVs are larger and more sophisticated in comparison to Groups 1 and 2 unmanned systems. Weighing between 55 and 1320 pounds, they offer extended endurance capabilities, greater payload capacity, and enhanced range, suitable for various missions such as ISR, logistics support, and weapon strike operations. Operating at medium altitudes for prolonged periods, these aircraft offer a payload capacity of up to 400 pounds and can cover distances of approximately 1150 miles (1000 nautical miles) at speeds below 250 knots. Given these performance capabilities, Group 3 UAVs will be the central focus of research for this project.

(3) Group 4

Group 4 comprises larger UASs, exceeding 1320 pounds in weight. They offer extended endurance, higher payload capacity, and longer-range capabilities compared to Group 3 systems, making them suitable for prolonged ISR missions and weapon strike operations. With a minimum payload capacity of 400 pounds and a range of approximately 1150 miles (1000 nautical miles), these aircraft require JP-8 fuel, akin to traditional rotor and tilt-wing aircraft using JP-5 fuel. Despite this, their fuel capacity remains relatively small, in the tens of pounds rather than the hundreds typically seen on the larger rotor and tilt-wing aircraft. Given these performance attributes, smaller Group 4 UAVs warrant further discussion in this research.

(4) Group 5

Group 5 represents the largest and heaviest UASs, weighing more than 1320 pounds. They offer extended endurance, higher payload capacity, and longer-range capabilities compared to Group 3 and 4 systems, making them suitable for extended ISR missions and weapon strike operations. These aircraft have a payload capacity ranging from 401 pounds to more than 1000 pounds, with a range exceeding 1150 miles (1000 nautical miles). However, their increased weight and extended range require a large fuel capacity of JP-8 fuel, comparable to the JP-5 fuel used in traditional rotor and tilt-wing aircraft. Given these performance attributes, Group 5 UAVs are excluded from further discussions in this research.

Table 1. DoD UAS Groups. Source: Army Unmanned Aircraft Systems Center of Excellence (n.d.).

<table>
<tr><th>UAS Groups</th><th>Size</th><th>Max Gross Takeoff Weight</th><th>Normal Operating Altitude (ft)</th><th>Airspeed</th></tr>
<tr><td>1</td><td>Small</td><td>< 20 lbs.</td><td>< 1200 AGL</td><td><100 knots</td></tr>
<tr><td>2</td><td>Medium</td><td>21-55 lbs.</td><td>< 3500 AGL</td><td rowspan="2">< 250 knots</td></tr>
<tr><td>3</td><td>Large</td><td>< 1320 lbs.</td><td rowspan="2">< 1800 mean sea level (MSL)</td></tr>
<tr><td>4</td><td>Larger</td><td rowspan="2">>1320 lbs.</td><td rowspan="2">Any Airspeed</td></tr>
<tr><td>5</td><td>Largest</td><td>> 1800 MSL</td></tr>
</table>

5. Variation of UAVs – Group 3

a. Unmanned Aerospace GH-4 Gyrocopter (Hydrogen/Electric Hybrid)

According to Gad Shaanan (personal communication, February 21, 2024), the Unmanned Aerospace GH-4 Gyrocopter, as depicted in Figure 5, represents a UAV design, integrating a hybrid power system comprised of HFCs and battery technologies. This combination not only enhances its operational efficiency but also extends its flight endurance and range significantly. Employing the principle of autorotation, the GH-4 Gyrocopter achieves lift during forward motion without direct motor power to its top rotor. Sustaining a near 0-degree angle post-takeoff, the rotor spins within the range of 350–450 revolutions per minute (RPM), using the relative airflow on the blades to generate lift. The gyrocopter also features VTOL capabilities, facilitated by patented technology. Using an electric motor, powered by the battery, the rotor accelerates above 600 RPM, automatically adjusting the blade angle to enable vertical ascent or hovering, ensuring seamless transitions between flight modes. In flight, the battery-powered motor disengages from the rotor, and the battery load is reduced, only powering installed payloads, while the HFCs provide power to the side thrusters. This configuration gives the GH-4 flight endurance of up to 4 hours with an operational range of 150–180 miles across varying mission profiles. Additionally, its VTOL capabilities enable it to access remote areas and maintain hover for approximately 30 minutes, facilitating mission execution. Unmanned Aerospace engineered the GH-4 Gyrocopter to accommodate payloads weighing up to 15 pounds, making it suitable for various logistical applications, including spare parts delivery and support operations for maritime vessels. Its design emphasizes sustainability, leveraging hydrogen and emission-free battery power to maximize performance and mission effectiveness. The Unmanned Aerospace GH-4 Gyrocopter characteristics and performance capabilities are shown in Table 2.

Figure 5. Unmanned Aerospace GH-4 Gyrocopter. Source: Unmanned Aerospace (n.d.).

Table 2. Characteristics and Performance of GH-4 Gyrocopter. Source: Unmanned Aerospace (n.d.).

Unmanned Aerospace GH-4 Gyrocopter			
Length	11.4 ft	**Wingspan**	11.4 ft
Gross Weight	95 lbs.	**Payload Capacity**	15 lbs.
Fuel Capacity	700 g	**Fuel Type**	Hydrogen / Electric
Data Link(s)	LOS BVLOS	**Frequency**	UHF SATCOM
Endurance	4 hrs.	**Max / Cruise Speeds**	85 / 55 mph
Ceiling	8000 ft	**Radius**	150 - 330 miles
Takeoff Means	Vertical	**Landing Means**	Hover

b. Airial Robotics GT20 Gyrotrak (Electric)

As depicted in Figure 6, the Airial Robotics GT20, also known as the Gyrotrak, is a battery-powered UAV solution engineered for optimal flight time, payload capacity, range, and speed performance. Serving as a hybrid gyrocopter/helicopter UAV, it introduces operational enhancements for increased efficiency and effectiveness. A notable advantage of the GT20 lies in its safety and efficiency derived from its gyrocopter design. Unlike traditional rotorcraft, its top rotor remains unpowered during flight, relying on autorotation for lift, while thrust is generated by forward-facing side propellers, eliminating the need to tilt forward during flight. This results in improved efficiency and stability. With flight endurance exceeding two hours and a range of up to 93 miles, the GT20 is designed for prolonged missions requiring aerial transit. Additionally, the GT20 features VTOL capabilities for seamless transitions between regular flight and hovering. The top rotor of the GT20 is a helicopter system that includes a swash plate assembly and control rods that tilt the rotor blades to produce the lift required for VTOL. Designed to accommodate payloads weighing up to 20 pounds, it is suitable for various logistical applications, including spare parts delivery and support operations for maritime vessels (Airial Robotics, 2024). Specifically tailored for BVLOS operations with manned aviation integration, the GT20 offers inherent safety features, night flight capabilities, and all-weather performance, ensuring adaptability across diverse applications while maintaining operational readiness. Its design ensures efficient and stable flight, while the battery-powered propulsion system delivers smooth and quiet operation, minimizing both noise pollution. The Airial Robotics GT20 Gyrotrak characteristics and performance capabilities are shown in Table 3.

Figure 6. Airial Robotics GT20 Gyrotrak. Source: Airial Robotics (2024).

Table 3. Characteristics and Performance of GT20. Source: Airial Robotics (2024).

Airial Robotics GT-20 Gyrotrak			
Length	5 ft	**Wingspan**	4.7 ft
Gross Weight	25 lbs.	**Payload Capacity**	8 lbs.
Battery	CFK Monocoque 12S15P	**Fuel Type**	Electric
Data Link(s)	LOS BVLOS	**Frequency**	UHF SATCOM
Endurance	2.5 hrs.	**Max/Cruise Speeds**	93 / 53 mph
Ceiling	16000 ft	**Radius**	93 - 132 miles
Takeoff Means	Vertical	**Landing Means**	Hover

c. Kaman Kargo (JP)

As depicted in Figure 7, the Kaman KARGO UAV is designed for efficient cargo delivery operations. It features a quadcopter configuration and is powered by Rolls-Royce 300 turbine engines, offering reliability and versatility. With flight endurance of 4.3 hours, achieved through JP power, it supports extended missions. Its VTOL capabilities enable maneuvering in confined spaces and accessing remote locations without needing a traditional runway. The KARGO UAV provides two payload delivery options: a belly cargo pod or sling load capability, facilitating transportation over distances of up to 500 miles. With a payload capacity of 800 pounds, it competes strongly in the cargo delivery drone sector. Piloting capabilities include onboard autonomy software developed by Near Earth Autonomy, allowing for remote or fully autonomous operation, and enhancing adaptability to different scenarios (Kaman Air Vehicles, 2024). Selected by the U.S. Marine Corps in October 2022, Kaman Air Vehicles is tasked with constructing a funded military logistics UAS prototype based on the KARGO UAV platform. The Kaman Kargo UAV characteristics and performance capabilities are shown in Table 4.

Figure 7. Kaman Kargo UAV. Source: Kaman Air Vehicles (2024).

Table 4. Characteristics and performance of Kargo Kaman UAV. Source: Kaman Air Vehicles (2024).

Kaman Kargo UAV			
Length	19.3 ft	**Rotors Extended**	24.4 ft
Gross Weight	2140 lbs.	**Payload Capacity**	800 lbs.
Fuel Capacity	50 lbs.	**Fuel Type**	JP-5 / JP-8
Engine Make	Turbine Engine	**Power**	300 hp
Data Link(s)	LOS BLOS	**Frequency**	UHF SATCOM
Endurance	4.3 hrs.	**Max / Cruise Speeds**	139 / 139 mph
Ceiling	10000 ft	**Radius**	575 miles
Takeoff Means	Vertical	**Landing Means**	Hover

E. TRADITIONAL LOGISTIC RESOURCES

The U.S. Navy uses traditional fixed-wing and rotor aircraft to deliver spare parts or urgent cargo to deployed ships at sea due to their versatility, speed, and payload capabilities. The MH-60S Seahawk is a short-range transport helicopter that can hoover and land in confined spaces, making it ideal for procession missions, such as delivery to naval vessels. The CMV-22B Osprey is a tiltrotor aircraft that combines VTOL capabilities with the speed and range of a fixed-wing aircraft. This hybrid design enables the CMV-22B to perform medium-to-long-range logistics missions, transporting heavier payloads faster and farther than a traditional helicopter.

1. NAVY MH-60 SEAHAWK

As depicted in Figure 8, the Sikorsky MH-60S Seahawk helicopter is a multi-mission aircraft designed to meet the U.S. Navy’s diverse operational demands. Building on the legacy of the UH-60 Black Hawk and the SH-60B Seahawk, the MH-60S features an adaptable cabin, allowing for easy reconfiguration across various missions. Equipped with advanced avionics, integrated sensors, and enhanced safety features, the MH-60S performs a range of roles, including logistics support, troop transport, search and rescue, and mine countermeasures (Aviators Database, 2006). The MH-60 Seahawk characteristics and performance capabilities are shown in Table 5.

Figure 8. Sikorsky MH-60 Seahawk Helicopter. Source: Aviators Database (2006).

Table 5. Characteristics and performance of MH-60 Seahawk. Source: Aviators Database (2006).

Navy MH-60 Seahawk			
Length	64.8 ft	**Rotors Extended**	N/A
Gross Weight	15201 lbs.	**Payload Capacity**	2600 lbs.
Fuel Capacity		**Fuel Type**	JP-5 / JP-8
Engine Make	Turbine Engine	**Power**	6200 hp
Data Link(s)	N/A	**Frequency**	N/A
Endurance	N/A	**Cruise Speed**	166 mph
Ceiling	18996 ft	**Radius**	518 miles
Takeoff Means	Vertical	**Landing Means**	Hover

2. NAVY CMV-22B OSPREY

As depicted in Figure 9, the CMV-22B Osprey is a tilt-rotor aircraft used by the U.S. Navy that provides long-range, medium-lift capabilities in aerial logistics operations. It supports critical logistical needs of the Joint Force Maritime Component Commander (JFMCC) by transporting cargo between forward operating sites to its primary operating sea base (NAVAIR, 2024). The Bell Boeing CMV-22B characteristics and performance capabilities are shown in Table 6.

Figure 9. Bell Boeing CMV-22B Osprey. Source: Office of the Director, Operational Test and Evaluation (2024).

Table 6. Characteristics and performance of CMV-22B Osprey. Source: Director Operational Test and Evaluation (2024).

Navy CMV-22B Osprey			
Length	57.3 ft	**Rotors Extended**	83.8 ft
Gross Weight	52600 lbs.	**Payload Capacity**	20000 lbs.
Fuel Capacity		**Fuel Type**	JP-5 / JP-8
Engine Make	Turbine Engine	**Power**	6200 hp
Data Link(s)	N/A	**Frequency**	N/A
Endurance	N/A	**Cruise Speed**	278 mph
Ceiling	25000 ft	**Radius**	1010 miles
Takeoff Means	Vertical	**Landing Means**	Hover

3. Airborne Deployable Delivery System

Customs and Border Protection (CBP) and Air and Marine Operations (AMO) collaborated with federal partners to implement the airborne deployable delivery system (ADDS), as depicted in Figure 10. ADDS facilitates transporting cargo and equipment weighing up to 150 pounds to U.S. Coast Guard (USCG) crews via parachute, enabling them to stay operational without needing to return to port for supplies or spare parts. Each ADDS operation saves roughly five days of transit time for USCG Cutters, amounting to approximately $1 million in savings per resupply due to the vessels' average daily operation cost of $200,000 (Public Affairs CBP AMO, 2024). Since March 2022, AMO air crews have conducted multiple aerial resupply missions in coordination with the USCG and other federal partners. These resupply missions have enabled USCG crews to remain on-station for approximately 75 additional days, eliminating the need for frequent port trips to complete logistical supply runs.

Figure 10. Airborne Deployable Delivery System. Source: Public Affairs CBP AMO (2024).

Though the ADDS reduces costs through delivery of cargo and equipment to USCG ships at sea, it is very much dependent on the coastal patrol schedule of CBP. The CBP performs these patrol missions using large fixed-wing aircraft such as the Lockheed P-3 Orion and the USCG piggybacks on these missions, on a not to interfere with basis, to coordinate package drops to a pre-determined location. The ADDS operations work well, or in cases where urgency is not required.

F. SCENARIOS

UAV integration into naval logistics and maintenance operations can enhance efficiency by offering safer and more cost-effective solutions for critical tasks. By comparing the capabilities of traditional aircraft and UAVs, various scenarios have been developed to illustrate specific instances where UAVs would provide logistical advantages to naval vessels. Additionally, these scenarios demonstrate UAVs' versatility in multi-purpose operations, further highlighting their value as a strategic asset to the Navy.

1. Forward Operation Site to Ship Cargo Delivery

Using UAVs for resupply missions from FOSs to ships at sea offers increased efficiency and transformative capability for naval logistics. In this case, UAVs deliver critical supplies, such as spare parts, from FOSs to vessels operating within a 300 nautical mile radius of the coastline. This capability eliminates the need for ships to return to port and deploy manned aircraft for resupply or parts delivery, enhancing mission efficiency. This capability also ensures a continuous supply line that keeps ships mission-ready and minimizes downtime due to logistical constraints. Furthermore, UAV resupply operations lower the risks associated with manned missions, particularly in contested or remote maritime environments, where threats may be high.

2. Ship to Ship Cargo Delivery

Emergency part delivery using a UAV between vessels offers a quick and efficient solution to unexpected equipment failures during deployed operations. In this case, when a deployed ship is at sea and experiences critical equipment failure, a UAV that natively resides on a vessel can be used to get the required part from its inventory and deliver it to the affected ship. This approach eliminates the need for complex and resource-consuming ship-to-ship mooring operations, involving logistical planning and increased operational risk. Avoiding the need for vessels to rendezvous ensures minimal disruption to the ship's mission and maintains tactical positioning. Additionally, UAV delivery offers the fastest response for equipment restoration compared to deploying helicopters or rerouting ships.

3. Ship to Shore Cargo Delivery

Using UAVs for parts delivery to maritime detachments deployed in littoral zones or stationed at FOSs near the shoreline enhances the operational effectiveness of these units. In this case, UAVs provide a quick and efficient way to deliver critical parts or supplies from larger offshore vessels to littoral zones, ensuring uninterrupted operations and eliminating the need for smaller vessels to return to their support ships. This capability increases mission endurance and duration and eliminates the complexities and delays associated with traditional shore-to-vessel logistics in infrastructure-limited regions. A flexible and sustainable resupply solution, UAVs allow for quickly adapting to operational demand and maintaining readiness and effectiveness in coastal environments.

4. Hull Integrity Inspection/Infrastructure Scanning

Using UAVs for hull integrity inspections and ship infrastructure scanning leverages advanced technology and improves efficiency, safety, and data accuracy. UAVs can be deployed for routine maintenance to eliminate the need for manual surveys, divers, or scaffolding, typically required while performing hull integrity inspections and infrastructure scanning, which are time-consuming and dangerous. UAVs are equipped with sensors like high-resolution cameras, LiDAR, thermal imaging, and ultrasonic devices that can capture detailed imagery and detect structural deformities or hull corrosion.

G. CHAPTER SUMMARY

This chapter discusses current and proposed technologies to deliver spare parts to ships at sea. It provides an overview of the different UAV groups, key systems and components required for their operation, rules and regulations to follow for their use, and current issues and concerns regarding their practical implementation. It provides key characteristics, for example, UAVs and traditional logistics resources like the MH-60S and CMV-22B, including cruising speeds, payload capabilities, fuel type, and endurance limitations. This chapter also includes a discussion of different operational scenarios to be considered for UAV implementation. Building on this foundation, the next chapter will provide an overview of the past research on the practicalities and feasibility of UAV adoption within the DoD and private industry.

III. LITERATURE REVIEW

The following chapter offers an overview of prior research and key advancements made in the application of UAVs and hydrogen fuel technologies. For better comprehension of what has been studied, this section is divided into three subsections: (a) UAV logistics applications within the DoD, which examines past and present programs within the DoD to improve upon operational readiness across the Services, (b) UAV logistics applications within industry, which examines corporate and academic research into how UAVs can improve logistics across non-defense related industry, and (c) the use of hydrogen as a fuel source, which examines the studies previously conducted on the practicality and safety of using hydrogen as a primary fuel compared to conventional fossil fuels.

1. UAV Logistics Applications within the DoD

Historical data from U.S. Navy casualty reports indicate that warships often experience reduced mission readiness due to logistical delays in receiving electronic parts or assemblies, "90% of which weigh less than 50 pounds" (NAVAIR, 2020, para. 5). Given this data, it becomes imperative for the U.S. Navy to minimize this lead time as much as possible. As the current CONOPs use helicopters like the MH-60 or V-22, which are costly and traditionally do not deliver parts as soon as they are needed, the DoD is seeking alternative methods to reduce costs and improve lead time, both in academic research areas and in practical applications.

Cost plays a significant role in the direction of DoD programs and policies, including logistics applications. When considering alternative solutions, like substituting traditional assets like helicopters with UAVs, any solution should provide cost savings and at least the same—if not increased—performance for the mission under evaluation. A cost–benefit analysis (CBA) is a clear way to capture the costs and benefits of any potential course of action. Denevan (2014) performs this analysis in his master's thesis by examining the costs associated with using UASs compared to traditional delivery systems to support resupply missions. He begins by looking at UASs currently in the DoD inventory and current aircraft used to perform these missions, and then uses:

> A cost-based or cost-effectiveness analysis, as a special case of a CBA model comparing the costs of operating UAVs with the costs of operating traditional sources as an alternative resource to provide the sustainment and replenishment of critical aircraft components to deployed operational flying squadrons (Denevan 2014, p. 2).

Denevan's (2014) CBA follows the nine stages laid out by Boardman et al. (2006), to identify if there are opportunities to use alternative solutions to support logistics operations in the Marine Corps and save on cost (Denevan 2014, p. 2). He notes that costs are "based on what is known as the cost per flight hour program (FHP). Cost data is collected and then calculated by the Naval Air Systems Command and derived from the Department of the Navy, Naval Comptroller's office" (Denevan 2014, p. 31), and the analysis provides the cost analysis on a per-flight-hour basis and a per-known-distance basis ranging from 25 to 15,000 miles. One standout in the analysis is Denevan's (2014) decision to negate the benefits portion of the CBA and focus on the cost analysis. He claims that regardless of methodology, the benefits remain the same, which are to "provide users with material in a cost-effective and timely manner" (Denevan 2014, p. 31). It should be noted that the use of certain power sources in logistics solutions may introduce additional operational or external costs that affect the overall assessment. However, Denevan (2014) does not appear to consider alternative fuels when surveying potential UAS solutions, likely due to the state of technology at the time. Denevan (2014) instead focuses on the two identified primary cost drivers when conducting his CBA: the cost of flight operations budgets and the costs tied to the loss of human life. The author ultimately concludes that employing Boardman et al.'s. (2006) nine-step approach, there are "considerable costs saving provided in the use of UAVs. The K-MAX, with its lower cost estimate, provides a significant saving over the MV-22 and the CH-53E option if the K-MAX's maximum speed can be increased thus reducing its flight time" (Denevan, 2014, p. 49). He identifies other UAV options as well but highlights that they fall short in payload capability when compared to the K-MAX. He also points out the cost-effectiveness of the traditional aircraft delivery system, the KC-130J, which Denevan (2014) considers ideal for large payloads (p. 50). He notes that redirecting ISR UAVs is not in the DoD's best interest, given the United States' current operating environment, and states that using UAVs to conduct logistics roles would only make sense if additional UAVs were available and not needed elsewhere (Denevan, 2014, p. 50).

Ergene (2016) builds on Denevan's (2014) CBA in his master's thesis. He sets out to examine applications of UASs, with a focus on unmanned aerial delivery methods, based on applications in the civilian sector and military logistical challenges (Ergene, 2016, p. 25). Ergene (2016) highlights the positive and negative impacts of using UAVs, including the cost and time savings that could be realized (p. 59) and the vulnerability to cyber-attacks and safety issues (p. 65). He leverages two primary studies to define the cost drivers and differences between current cargo delivery methods and cargo UAVs, those of Denevan (2014) and Peterson and Staley (2011), concluding that both studies show the potential for significant cost savings and reduced lead-time if cargo UAVs are deployed (Ergene, 2016, p. 64). He provides recommendations to improve the use of UAVs in military logistics, including the continuation of research and development with respect to military logistics applications and looking to civilian applications and improvements in the use of unmanned systems (Ergene, 2016, p. 73).

In 2020, the Naval Air Warfare Center Aircraft Division acquired a prototype UAV, called the Blue Water Maritime Logistics UAS, to demonstrate ship-to-ship and ship-to-shore cargo transport operations based out of Naval Air Station Patuxent River (NAVAIR, 2020). This UAS was purchased in response to the Military Sealift Command tasking Naval Air Warfare Center Aircraft Division to demonstrate that a UAV could fly a 20-pound payload to a moving ship 25 miles away without the need to refuel (DLA, 2020). Of the 65 UAVs that were analyzed, only two were deemed to be technologically advanced enough to partially meet requirements. Ultimately, the Blue Water Maritime Logistics UAS by Skyways was selected (Mesta, 2023). The Blue Water UAS runs on both electricity and JP-5 fuel, making it a hybrid-electric Group 3 UAV (DLA, 2020). According to Skyways (n.d.), the V2.6 Hybrid-Electric Unmanned Cargo Aircraft has a maximum range of 500 miles and can carry a maximum useful load of 30 pounds. Successful test flights were performed in June 2023 to test the UAS's ability to transport material to the USNS Patuxent (T-AO 201) while at sea in the Atlantic Ocean (Mesta, 2023). Testing consisted of two drones, including Skyways V2.6B, conducting five test flights: three flights from the USNS Patuxent to Marines operating in an expeditionary environment in North Carolina and two flights from the Marines back to the USNS Patuxent. The UAS "successfully made two autonomous flights transporting simulated cargo from the Marines ashore to the fleet replenishment oiler at-sea" (Mesta, 2023, para. 5).

In his thesis, Frank C. Smeeks (2022) uses the process outlined by Buede (1999) in his book *The Engineering Design of Systems: Models and Methods* to determine if there are operational scenarios in which hydrogen-powered UAVs may be leveraged to provide an advantage to the U.S. Navy. Ultimately, he identifies 10 use cases or operational scenarios in which hydrogen-powered UAVs could potentially be used, including Operational Scenario 7: Logistics/Re-Supply at Sea (F. C. Smeeks, 2022, p. 48). In this scenario, a hydrogen-powered UAV would transport supplies between a replenishment ship and the ship in need of replenishment (F. C. Smeeks, 2022, p. 49). F. C. Smeeks (2022) notes that the hydrogen-powered UAV offers a reduced risk to pilots as well as a potential increase in performance, as the use of the UAVs would reduce, if not eliminate, pilot error due to stress and fatigue (p. 51). He further notes that the barriers to implementing this operational scenario include inadequate hydrogen fueling and logistics infrastructure for U.S. Navy ships, a lack of hydrogen safety policies for shipboard use, and a lack of training for the crew regarding safe hydrogen use practices (F. C. Smeeks, 2022, p. 51). However, while this is a good look at the technical feasibility of implementing UAVs, F. C. Smeeks (2022) does not consider the financial implications associated with the potential benefits and how the technology aligns with the DoD's goals.

The U.S. Navy, however, is not the only service that is being assessed for the incorporation of UAVs to enhance its logistics support. In his 2020 master's thesis, Preston (2020) aims to develop requirements and design considerations for implementing an unmanned aerial logistics systems (UALSs) using a systems engineering approach (p. v), but due to limitations on information sharing, results instead in an exploration of doctrine, organization, training, materiel, leadership and education, personnel, facility and policy (DOTMLPF-P) implications that should be factored in when weighing the inclusion of UAVs into a logistical use case (p. 47). Preston (2020) notes that one of the biggest hindrances to implementing UAVs is that policies as currently written will "hinder the end product landing in the hands of the correct users," and recommends the system being owned by division logistics units instead of being treated like a traditional aircraft (p. 48). He further notes that policy should be adjusted such that the UALS be limited to conducting its primary mission, which is to support resupply runs, differing from the status quo where aircraft missions are re-prioritized and supplies go undelivered (Preston, 2020, p. 48). Preston (2020) also advocates for the education of all Marines on autonomy and UALS to overcome natural human resistance to innovation and to foster understanding and trust in any new UAV platform (p. 49). The author makes the case that by overcoming these two critical DOTMLPF-P hurdles, it will be easier to implement a resupply solution utilizing UAVs when the UAVs are ready for production and deployment. The costs of implementing these DOTMLPF-P recommendations should be factored into any CBA, as they may impact the overall recommendation when determining if a hydrogen-powered UAV is a viable replacement for the current CONOPs, which is the aim of this paper.

The Marines are not unaware of the potential of UAVs to enhance logistics support; Preston (2020) takes note of their interest in UAVs, best exemplified in the cases of the Tactical Resupply Unmanned Aerial System (TRUAS) and Medium Aerial Resupply Vehicle – Expeditionary Logistics (MARV-EL). In September 2019, Navy and Marine Corps Small Tactical Unmanned Aircraft Systems Program Office, PMA-263 held a prize competition to demonstrate the capabilities of commercial UAV prototypes to carry a 60-pound minimum payload with a minimum distance of 10 kilometers (Preston, 2020, p. 8). SURVICE Engineering's TRV-150c took home the first-place prize (Preston, 2020, p. 8) and would later be awarded the contract for the TRUAS (Davis, 2023). The TRUAS is ultimately intended to carry payloads of up to 120 pounds over a maximum range of 7.5 miles (Davis, 2023, para. 12) and "will be operated by logistics Marines rather than relying on aviation units," with the hope of increasing operational efficiency (Davis, 2023, para. 16). The initial operational capability of the TRUAS was announced in October 2023, and, as noted by Colonel Aaron Angell, the Logistics Combat Element Division director,

> The contested logistics environment challenges the ability of our Marines to distribute necessary supplies to the right place at the time of need.

> TRUAS gives a logistics unit the organic ability to immediately respond with a precision ground-launched air delivery system. This is leap-ahead technology that we will learn to continue to shape future unmanned aerial logistics platforms (NAVAIR, 2023, para. 8).

Another program under assessment by PMA-263 is the MARV-EL UAV program, which seeks to provide the Marine Corps with a ship-based capability to transport heavier loads (300–600 pounds) at a distance of 100 miles (Davis, 2023, para. 15). Following a call for white papers from potential vendors in February 2022 (NAVAIR, 2024, para. 5), other transaction agreements were awarded to both Kaman Aerospace and Leidos in January 2023 to deliver a prototype UAV to demonstrate the required capabilities (NAVAIR, 2024, para. 6). Kaman Aerospace submitted a design for the KARGO UAV (Kaman, 2024, para. 4), while Leidos partnered with Elroy Air (2024) to submit Elroy's Chaparral system to meet requirements (para. 3). The performance evaluation of these two systems was conducted July 8–26, 2024 (NAVAIR, 2024, para. 1).

Meanwhile, the Air Force is exploring the potential of electric rotorcraft to decrease fuel logistics and improve resupply capabilities under a program it calls Agility Prime (OUSD(A&S), 2023, p. 10). The program seeks prototypes to "help the government assess the transformative vertical flight market and applicable hybrid or electric vertical takeoff and landing aircraft technologies" (OUSD(A&S), 2023, p. 10). Agility Prime aims to provide the Air Force with a small, unmanned logistics system–air to carry payloads of 60–150 pounds "to provide emergent and routine distribution of supplies between neighboring ground units" (Head, 2020, para. 8). In 2022, the Air Force released a report to Congress noting the progress made in the program, including the successful remotely piloted flight of the eVTOL aircraft in December 2021 (Electric VTOL News, 2022, para. 1). As of 2022, the program was anticipating the award of a Fiscal Year (FY) 2023 procurement contract for 24 aircraft for early use, operational use, and developmental testing (Electric VTOL News, 2022, para. 17).

2. UAV Logistics Applications within Industry

While the consequences of longer delivery lead times are not as critical as those experienced by the military, private companies and corporations are also looking at ways to reduce logistics lead times. In a world where two-day shipping is expected, the faster a company can deliver its products to customers, the better. To remain competitive, companies like Google and Amazon are charting courses for implementing UAVs within their business models to achieve faster delivery times and promote customer satisfaction.

In 2019, Wing became the first drone delivery company to receive Federal Aviation Administration (FAA) approval to receive an air carrier certificate, allowing it to begin delivery trials in the United States (McFarland, 2019, para. 1). Wing, a subsidiary of Alphabet (the parent company of Google), reports over 3,000 deliveries, including food, to homes in Australia (McFarland, 2019, para. 5). This new delivery system is expected to "lower the costs of delivery for retail, logistics, and healthcare organizations" to as little as 30 minutes (Wing, n.d., para. 1). While the test program was small in scale, results from Australia showed average delivery times of approximately seven minutes, including package preparation time (McFarland, 2019, para. 8), a fraction of the goal set forth by Wing. The removal of delivery drivers and pilots would also likely have financial benefits for Wing, but without a full cost–effectiveness analysis, this remains speculation.

Over ten years after Amazon founder Jeff Bezos announced plans for the company to pursue drone delivery (McFarland, 2020, para. 4), the FAA granted Amazon approval to begin flying its MK30 drone in support of its Prime Air project (Palmer, 2024, para. 3). Like Wing, Prime Air's goal is to deliver packages via drone in 30 minutes or less (McFarland, 2020, para. 4), and the project's FAA approval marks a significant step toward the company beginning drone delivery in the United States, starting in College Station, Texas, and West Valley in the Phoenix, Arizona, metro area (Amazon, n.d., para. 5.). While Prime Air's current capabilities are limited to one item weighing up to five pounds, delivery is expected within an hour during daylight hours in favorable weather conditions (Amazon, n.d., para. 3), significantly cutting down on package lead time and, one can assume, boosting customer satisfaction. Implementation of Prime Air will also reduce carbon emissions, as its fleet of drones is fully electric and produces zero emissions during flight, in line with its goal of reaching net zero emissions by 2040 (Amazon, n.d., para. 2).

Large corporations are not the only ones studying how UAVs could be leveraged to improve their logistics; academic researchers are also studying the effects of how drones can be used to improve other industry applications. Claesson et al.'s primary argument in their 2016 research paper is that survival rates following an out-of-hospital cardiac arrest (OHCA) may be improved by using UAVs to deliver automated external defibrillator, thus shortening the time between collapse and first shock compared to waiting on first responders to arrive. The authors detail the background of the problem (response time for OCHAs), as well as the methodology used to simulate UAV-delivered automated external defibrillator delivery time. They also provide data on the average time for first responders to arrive on the scene following a report of an OCHA to support the claims that UAVs may improve delivery time and subsequently improve survival rates in patients experiencing OHCA. Claesson et al. (2016) ultimately conclude that the use of a drone-delivered UAV may reduce the time from collapse to first shock in OHCA cases, particularly with regard to rural areas. While this paper doesn't focus on the costs associated with each method, the study highlights the time advantage that can be realized, which has implications not only in the medical community but also in other applications where time is a critical factor of mission success.

Li et al. (2022), on the other hand, focus more on the sustainability side of logistics in their study. In their research, they perform a review of 36 other studies between 2021 –2022 pertaining to the use of UAVs in logistics applications. They break down the studies into three categories: theoretical models, application scenarios, and other issues (Li et al., 2022, p. 1). While their study and those they review pertain mostly to the comparison between UAV use and ground transportation (e.g., trucks), Li et al. (2022) conclude that drones offer logistical advantages, as they can fly more direct routes than commercial ground transportation options, which can reduce delivery times (p. 9). Regardless of the means of transportation being replaced, these logistical benefits offered by drones appear to be a consistent finding across the research published in the field.

Eun et al. (2019) similarly aimed to evaluate the efficiency of UAV-based delivery logistics in comparison to traditional ground vehicle delivery methods (p. 1). To do this, the authors developed a mathematical model to obtain delivery schedules for both UAVs and ground vehicles that optimize delivery routes while accounting for each system's limitations and restrictions. Using this model, they assess performance based on factors such as travel distance and vehicle speed (Eun et al., 2019, p. 2). Based on the optimal delivery determined by their mathematical model, Eun et al. (2019) conclude that UAV-only delivery significantly outperforms ground vehicle–only delivery across all tested ranges and speeds (p. 11).

3. Use of Hydrogen as a Fuel Source

While interest seems to have increased recently, hydrogen fuels have been studied for decades, and for good reason: Hydrogen has the highest energy content of any available fuel and is the only fuel that is carbon-free (Nikolaidis & Poullikkas, 2017).

In 1974, Carhart et al. examined the potential viability of using hydrogen as a fuel for naval applications compared to conventional fossil fuels like gasoline and JP-5. The authors noted that while hydrogen has about three times the energy per unit weight compared to gasoline, at the time of writing, the amount of hydrogen needed to completely replace fossil fuels would be enormous (p. 1). Fuel cell applications improve the comparison but were not competitive at the time, leading the authors to concede that development of cheap fuel cells may improve the competition with conventional fuels (Carhart et al., 1974, p. 1). While the authors concluded that hydrogen was not a suitable fuel to propel ships at that time, certain missions like small submersibles and long-range planes used for transport and patrol could benefit from the use of hydrogen as a fuel (Carhart et al., 1974, p. 24). It should also be noted that advancements in technology have made hydrogen a more viable option for use as a fuel.

Hydrogen itself is not a readily available fuel source and must be derived from other sources, which can be costly, resulting in manufacturers often choosing the least expensive means of production (Carhart et al., 1974, p. 12). There are multiple means of producing hydrogen, with each differing in the costs per kilogram produced. The Department of Energy (n.d.) breaks down these methods into four general categories: natural gas reforming, biomass gasification, biomass-derived liquid reforming, and solar thermochemical hydrogen (para. 2).

In their paper, Nikolaidis and Poullikkas (2017) provide a comparison of the 14 methods that can be used to produce hydrogen. These methods encompass the use of both conventional and alternative fuels as a primary source, and the paper provides a total cost of hydrogen in dollars per kilogram for comparison, ranging from $1.34/kilogram for coal gasification without carbon dioxide capture and storage in 2005 dollars to $23.27/kilogram for solar photo-voltaic electrolysis in 2007 dollars (Nikolaidis & Poullikkas, 2017, p. 609). That said, Nikolaidis and Poullikkas (2017) conclude that of the 14 methods studied, steam methane reforming is currently the most cost-effective means of producing hydrogen, followed by coal gasification (p. 610). It should also be noted that Nikolaidis and Poullikkas (2017) present the costs in varying FY dollars rather than baselined against a standard year, making direct comparison difficult without additional analysis. However, the data provided serves as a useful data point for calculating the cost of hydrogen production, which factors into the CBA presented in Chapter V.

The next issue to consider is the feasibility of producing hydrogen, but luckily, this is not one of the problems facing the DoD. There are multiple options available to the government, including one of its own patents. From a conceptual level, "hydrogen can be made onboard the vessel where the electrolysis of water produces hydrogen for fuel and oxygen for breathing underwater" (F. C. Smeeks, 2022, p. 15). This was, in fact, demonstrated and later patented by the Naval Research Lab in 2016 through an apparatus that can "simultaneously extract carbon dioxide and hydrogen from seawater. This single process provides all the raw materials necessary to produce synthetic liquid hydrocarbon fuels" (Parry, 2016, p. 2). The apparatus includes "an ion exchange, cathode and anode electrode compartments and cation-permeable membranes that separate the electrode compartments from the ion exchange compartment" (DiMascio et al., 2016). While the by-products of the apparatus are currently geared toward the generation of feedstock for fuels like JP-5 (Parry, 2016), the hydrogen produced could potentially be used to fuel a hydrogen-powered or hybrid UAV.

However, while the patent is convenient, it is by no means the only solution for producing hydrogen. As F. C. Smeeks (2022) points out, the Massachusetts Institute of Technology has developed a hydrogen tactical refueling point, which can generate hydrogen in situ (p. 15). A hydrogen tactical refueling point leverages a chemical reaction using aluminum and any source of water, including seawater, river water, and urine, to generate hydrogen gas and steam (Hochenberg, 2022). Using this process, hydrogen fuel can be stored and transported as an inert solid, making it far safer than attempting to store it in liquid gas form (Hochenberg, 2022).

F. C. Smeeks (2022) further notes the possibility of using the Refueling and Support Package to Enable Communications and Situational Awareness, under development by the Office of Naval Research (p. 16). The Refueling and Support Package to Enable Communications and Situational Awareness aims to generate hydrogen and oxygen in the space of a single shipping container from only potable water and 440 VAC (F. C. Smeeks, 2022, p. 16). This in situ production could then be used to deliver hydrogen in support of fueling unmanned vehicles (F. C. Smeeks, 2022, p. 16).

Regardless of the technology used to produce hydrogen, looming over the technology is the concern for hydrogen safety. Mention hydrogen, and many minds will conjure up images of the famous Hindenburg disaster of 1937. However, in terms of implementation, the real issues holding back hydrogen production seem to be more on the logistics side, including how to store it, policies to guide its implementation, and how to train on it. F. C. Smeeks (2022) notes this in his master's thesis, stating that major barriers to implementation of hydrogen-powered UAVs to support DoD logistics include "a lack of policy and guidance from higher authority, safety concerns stemming from hydrogen safety misconceptions, a lack of hydrogen fuel usage training, and a lack of current infrastructure on ships and installations to support the use of hydrogen fuel" (p. xiv). Among those concerns lie the risk of hydrogen leaking within its enclosed storage space and how to properly combat a hydrogen fire aboard a ship (F. C. Smeeks, 2022, p. 16). As Najjar (2013) notes in his review of hydrogen safety in energy applications, hydrogen hazards fall into one of three categories: physiological (asphyxiation, thermal burns), physical (embrittlement, component failure), and chemical (burning, explosions), which need to be considered when weighing the use of hydrogen as a fuel source (p. 10720). Examining the objections noted by F. C. Smeeks (2022), most of the concerns are related to the storage and potential leaking of hydrogen, which could lead to ignition—one of the chemical hazards noted by Najjar (2013). While hydrogen ignition is a serious hazard, the likelihood of this risk is diminished due to hydrogen's ability to rise and disperse rapidly, and "unless the escape is in an enclosed, unventilated area, it is unlikely to be serious" (Najjar, 2013, p. 10717). To further mitigate the risk, the use of hydrogen sensors can be implemented to provide early leak detections (Najjar, 2013, p. 10724). This type of mitigation strategy is already underway in the U.S. Navy, with the service looking to procure hydrogen sensors to support normal operational use as well as firefighting (C. Smeeks & Pollman, 2023). Najjar (2013) ultimately concludes that before any significant progress can be made toward the applications of hydrogen fuel, a high degree of safety is necessary, and designs need to be accounted for the properties of hydrogen to mitigate the hazards associated with the production, storage, transportation, and use of this fuel (p. 10725).

4. Chapter Summary

This literature review examines the past and current work being performed to assess the practicalities of implementing UAVs and alternative power generation technologies across the DoD and within industry. Within the DoD, UAV research seems to fall into one of two categories: potential use cases for UAV applications, and the potential impact of UAV implementation with respect to cost and delivery lead times. While most studies are concluding potential benefits exist for the DoD, research appears to still be in the earlier stages of field testing and pilot programs with respect to the implementation of UAVs within the Services. Industry, too, has been researching the potential benefits of UAV implementation. From medical equipment to package delivery, companies are investing time and money to reduce costs and delivery time, and similar to that of the DoD, are seeing potential savings that can impact their bottom line. Additional studies into the feasibility of using hydrogen to power UAVs are also examined. While most research has shown that potential benefits exist for implementing hydrogen powered technology, there are still barriers to its widespread use, including storage and safety concerns.

IV. METHODOLOGY AND DATA

This chapter outlines the methodology used to conduct a cost-based analysis evaluating the integration of Group 3 HVTOL UAVs into U.S. Navy logistics for spare parts delivery at sea. It compares the procurement, operational, and sustainment costs of traditional aircraft (e.g., MH-60S Seahawk and CMV-22B Osprey) with emerging UAVs like the GH-4 Gyrocopter and Kargo UAV. Using data from DoD reports, subject matter experts, and industry sources, the analysis examines cost per flight hour, payload, endurance, and responsiveness to identify the most efficient and feasible resupply solution.

A. COST-BASED ANALYSIS

This study uses the nine steps of CBA outlined in the Office of Management and Budget (OMB, 1992) Circular A-94 and Boardman et al. (2006). However, traditional aircraft and UAVs serve the same purpose, delivering spare parts to ships at sea, so the core benefit for the end user remains unchanged. As a result, a direct comparison of their benefits was not performed in this study, as the primary distinction lies in cost, efficiency, and operational impact.

The primary area of interest in this study is the resupply of ships at sea, specifically, repair parts or small cargo delivered to end users in a cost-effective and timely manner. As such, the focus is on cost differences between the traditional systems and alternatives, making it a cost-based analysis. While the principles of CBA and the guidance in OMB Circular A-94 still apply, the monetary benefits of the end user are excluded from consideration in this study because they are the same across all systems.

Boardman et al. (2006) outlined nine stages of CBA, highlighting how this structured process supports informed decision-making. The steps are as follows:

1. Decide whose costs count.
2. Select a portfolio of alternatives.
3. Catalog potential impacts and measure indicators.
4. Predict quantitative impacts over the life of the project.
5. Monetize all impacts.
6. Discount for time to present value.

7. Sum all costs.
8. Perform sensitivity analysis.
9. Recommend the alternative with the largest cost savings. (Boardman et al., 2006, pp. 6–14)

When considering the cost of UAVs, the analysis began with Step 1 and considering who has standing in this situation. *Standing* refers to whose benefits and costs should be included in the analysis, including all relevant stakeholders affected by or involved in the decision-making process. In this study, the U.S. Navy and ship's crews have standing as they define the operational needs as end users, along with taxpayers, who provide the funding supporting military aviation assets, including traditional and UAV aircraft.

In the second step, comparisons are made between the status quo and a similar alternative. The status quo consists of traditional aerial delivery systems, whereas the alternatives are fuel-efficient HVTOL UAVs for resupply operations. Additionally, varying mission scenarios are used for the comparisons and analysis of resupply operations. These scenarios are based on the endurance of each delivery system and the distance required for delivery of small cargo requirements.

The third step includes an analysis of causes and potential outcomes. This is conducted by applying key indicators for measurement. In this study, the outcome indicators are the cost per flight hour required to operate traditional aircraft and UAVs delivery systems, which will determine the system results in the lowest cost.

The fourth step involves a cost estimation, which are the processes used to identify quantitative life-cycle costs and the qualitative ecological impacts of each system.

To monetize all impacts as required by the fifth step, the costs of alternatives are converted into monetary terms, allowing for a direct comparison. In this study, all costs are normalized to FY2024 dollars.

The cost values must be consistently defined to conduct an accurate comparison in a cost-effectiveness assessment. The value of money changes over time due to inflation. For example, the worth of $1 in 2000 is not equivalent to $1 in 2024. Therefore, in the sixth step, a standard reference is established to ensure consistency across data collected in different years, a process known as normalization. In this study, all costs are normalized to FY2024 dollars.

Step seven combines the collected and standardized indicators to compute and present a result.

The eighth step serves to strengthen the credibility of the study by performing a sensitivity analysis to assess how variations in one or more input variables impact the study's outcomes. In this case, the sensitivity analysis focuses on operational cost based on varying cost per hour and speed.

Finally, the ninth step provides any final conclusions that can be drawn from the data.

This study examines the feasibility of using UAVs to deliver small cargo to Navy vessels at sea as an alternative to traditional aviation resources. UAVs offer a potential benefit of reducing operational costs. The study compares the costs of traditional delivery methods to those of UAVs and seeks to determine whether UAVs can provide the same level of reliable parts delivery while achieving cost savings.

B. COST DRIVERS

Two primary cost drivers are used to determine the estimated costs within the cost-based analysis presented in this study. These include the U.S. Navy's flight hour budget, known as the OP-20, and the acquisition and sustainment costs calculated per flight hour over the life of each system.

1. OP-20 and FHP

The FHP encompasses the OP-20 (FHP budget exhibit), which is the Navy's budgeting tool to allocate funding for the flying hours of naval aircraft. This provides a means to develop and maintain the Navy's tactical air forces, which require proficient crews executing military flying tasks (Heivilin, 1989). The OP-20 sets the funding levels for each aircraft system and includes consumables, contractor logistics support (CLS), depot-level repairs (DLR), and fuel. The OP-20 is part of the president's budget, released every year following the State of the Union address, and serves as a request to Congress for yearly operations and maintenance (O&M) funding for naval aircraft. As with most budgets, the FHP OP-20 is not exact and is developed using historical data and budget forecasts, which can lead to cost overruns or underutilization. Therefore, our research assumes the CMV-22B and MH-60S FHP budget has been fully executed per funded flying hours in the OP-20 for FY2024.

The three UAV alternatives discussed in this study are in the early stages of development and are not programs of record; therefore, they are not budgeted for in the U.S. Navy OP-20 FHP. To determine O&M funding for these systems, direct vendor data from each manufacturer and/or openly available data from public sources has been used to estimate costs, based on 200 flight hours per FY. In discussions with subject matter experts and UAV vendors, a mission goal of 200 flight hours per FY was deemed reasonable and achievable for these aircraft. This target aligns with their potential operational life span of 10 years, during which they can accumulate up to 2,000 flight hours.

2. Acquisition: Cost per Flight Hour over the Life of the System

Acquisition and sustainment costs combine the system's initial procurement costs with the O&M costs required to operate and maintain each aircraft throughout its life cycle. The cost per flight hour over the system's life is calculated by dividing the total acquisition and sustainment costs by the system's designed service life flight hours.

a. MH-60S Seahawk

The program acquisition unit cost for a U.S. Navy MH-60S Seahawk's program acquisition unit cost is $23.5 million per aircraft in FY2015 (DoD, 2014, p. 23). Its useful service life was initially estimated to be 10,000 flight hours based on selected acquisition reports published by the DoD (DoD, 2014, p. 32). However, in April 2003, Naval Air Systems Command (NAVAIR, 2003) cleared the in-service U.S. Navy MH-60S Seahawk fleet to increase their service life flying hours to 12,000 flight hours (NAVIR, 2003). The airframe cost per flight hour for the MH-60S Seahawk is determined by dividing the procurement cost by the total service life flight hours, resulting in $1,961 per flight hour, as detailed in Table 7.

Table 7. MH-60S Seahawk Airframe Cost per Flight Hour. Adapted from DoD (2014) and NAVAIR (2003).

Service Life Flight Hours	12,000
Procurement Cost of MH-60S Seahawk	$23,533,000
Airframe Cost per Flight Hour	$1,961

b. CMV-22B Osprey

The program acquisition unit cost for a U.S. Navy CMV-22B Osprey's program acquisition unit is $110 million per aircraft in FY2018 (DoD, 2018, p. 53). Its useful service life is assumed to be 10,000 flight hours based on selected acquisition reports published by the DoD (2018, p. 67). The airframe cost per flight hour for the CMV-22B Osprey is determined by dividing the procurement cost by the total service life flight hours, resulting in $11,000 per flight hour, as detailed in Table 8.

Table 8. CMV-22B Osprey Airframe Cost per Flight Hour. Source: DoD (2018).

Service Life Flight Hours	10,000
Procurement Cost of CMV-22B Osprey	$110,000,000
Airframe Cost per Flight Hour	$11,000

c. Unmanned Aerospace GH-4 Gyrocopter

The Unmanned Aerospace GH-4 Gyrocopter UAV is still in its early stages of development, but the company's CEO, Gad Shannan, has provided initial procurement cost estimates. Through this communication, we confirmed assumptions of the GH-4 procurement cost and service life flight hours, which are $395,000 and 2,000 flight hours, respectively (G. Shaanan, personal communication, February 24, 2024). The airframe cost per flight hour for the GH-4 Gyrocopter is determined by dividing the procurement cost by the total service life flight hours, resulting in $198 per flight hour, as detailed in Table 9.

Table 9. GH-4 Gyrocopter Airframe Cost per Flight Hour. Source: G. Shaanan (email to author, February 24, 2024).

Service Life Flight Hours	2,000
Procurement Cost of GH-4 Gyrocopter	$395,000
Airframe Cost per Flight Hour	$198

d. Airial Robotics GT20 Gyrotrak

The procurement costs and service life hours for the Airial Robotics GT20 Gyrotrak are not publicly available. However, since the technology of this UAV is like that of the Unmanned Aerospace GH-4, we have assumed the procurement cost and service life hours to be comparable. Therefore, the airframe procurement cost for the GH-4 will be used as a baseline for the GT20 Gyrotrack. Performance specification will be a differentiating factor in deciding which system meets the user needs. The airframe costs per flight hour for the GT 20 Gyrotrak are detailed in Table 10.

Table 10. Assumed GT20 Gyrotrak Airframe Cost per Flight Hour

Service Life Flight Hours	2,000
Procurement Cost of GT20 Gyrotrak	$395,000
Airframe Cost per Flight Hour	$198

e. Kaman Kargo UAV

The KARGO UAV is currently competing in the MARV-EL program, managed by NAVAIR PMA-263, and culminates in a fly-off scheduled for July 2024 (Kaman Air Vehicles, 2024). The procurement costs for the Kaman Kargo UAV are not publicly available. However, in 2023 the Marines awarded a contract to tech company Leidos to develop a single prototype drone called the SeaOnyx. It was valued at approximately $14 million and included 18 months of development and testing (Lawrence, 2023). Since the Kaman Kargo Corporation has already developed and tested a prototype, the development efforts should be minimal, and all that is required is operational testing through a DoD organization. Therefore, the procurement cost of the Kman Kargo UAV is estimated to be no less than $2 million, resulting in $1,000 per flight hour based on 2,000 service life flight hours, as detailed in Table 11.

Table 11. Assumed Kargo UAV Airframe Cost per Flight Hour

Service Life Flight Hours	2,000
Procurement Cost of Kaman Kargo	$2,000,000
Airframe Cost per Flight Hour	$1,000

C. CHAPTER SUMMARY

This chapter provides the steps performed to conduct the cost-based analysis performed in this study. It details the decisions made when determining relevant costs and provides the cost drivers that were leveraged for the calculations, including the flight hour budget and the acquisition and sustainment costs for each of the systems examined. It calculates the baseline costs per flight hour for all the options under consideration. The next chapter evaluates the costs associated with the life cycle costs of each option and highlights the trade-offs to be considered for UAV adoption.

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V. COST-BASED ANALYSIS OF UAVS AND TRADITIONAL LOGISTICS RESOURCES

This chapter provides a cost-based analysis comparing traditional platforms, such as the MH-60S Seahawk and CMV-22B Osprey, with Group 3 HVTOL UAVs like the GH-4 Gyrocopter, GT20 Gyrotrak, and Kargo UAV. Using a nine-step framework and data from the Navy's OP-20 FHP and industry sources, the analysis evaluates life cycle costs and highlights the financial and operational trade-offs of UAV adoption for small-payload resupply at sea.

A. COST-BASED ANALYSIS

In this chapter, Boardman et al.'s (2006) nine-step framework was again deployed to determine the cost effectiveness of the logistics resources. The steps are outlined in Chapter IV of this paper.

When considering the primary stakeholders for Step 1 of this analysis, the study includes the U.S. Navy, DoD, and ship crews who rely on offshore and cost-effective resupply methods. Secondary stakeholders include American taxpayers, UAV manufacturers, and DoD policy-makers concerned with operational efficiency and sustainability of DoD systems.

For Step 2, the study evaluates the use of traditional rotary-wing and tiltrotor aircraft for spare parts delivery, including the MH-60S Seahawk and the CMV-22B Osprey, against next-generation UAVs—specifically, the GH-4 Gyrocopter, GT20 Gyrotrak, and the Kaman Kargo UAV. These UAV alternatives were selected based on key cost and performance indicators, including O&M and sustainment expenses.

Step 3 considers the impacts of both traditional rotary-wing and tiltrotor aircraft, which require significant fuel consumption, maintenance, and onboard crew, and UAVs, which offer a fuel-efficient autonomous solution.

To quantify the long-term impact of these alternatives for Step 4, the study estimates operational costs over the life cycle of each system. Rotary-wing and tiltrotor aircraft incur higher expenses due to their reliance on jet propellant fuel, substantial manpower requirements, and frequent maintenance. In contrast, UAVs operate with lower fuel and maintenance costs, benefiting from hydrogen or electric propulsion systems and reduced personnel needs.

For Step 5, relevant costs are monetized, considering factors such as fuel expenses and personnel salaries. In this study, all costs are normalized to FY2024 dollars, and benefits are not considered.

To ensure accurate comparisons over time, Step 6 applies a real discount rate following OMB Circular A-94 guidelines, which allows for a fair evaluation of life cycle costs. In this study, all costs are normalized to FY2024 dollars.

The total costs of each system are summed in Step 7, revealing that though traditional aircraft have higher overall operational expenses, total cost savings are comparable to UAVs.

To validate these findings, Step 8 conducts a sensitivity analysis to test the impact of changing key cost drivers, which include varying operational costs, speed and efficiency, and endurance. This ensures the robustness of the results under different scenarios.

To complete step nine, the analysis suggests that fuel-efficient UAVs present a sustainable alternative for small-payload deliveries compared to traditional helicopters. Their adoption could lead to reduced fuel expenditure and lower maintenance costs. Further refining cost models and mission parameters will strengthen these conclusions and support decision-making for future procurement and deployment strategies.

B. DATA ANALYSIS

The Navy uses aircraft to deliver supplies to ships at sea, and this requires an understanding of cost, performance, and mission needs. The MH-60S Seahawk and CMV-22B Osprey are two systems currently in use, each with specific roles and operating costs. This analysis reviews flight hours and cost data to determine the cost per flight hour for each system. It also includes unmanned systems such as the GH-4 Gyrocopter, GT20 Gyrotrak, and Kargo UAV to explore other options for completing the same missions. By comparing costs, crew needs, and flight range, the analysis provides information to support decisions about which systems are best suited for different mission types.

1. OP-20 FHP

The MH-60S Seahawk is a multipurpose rotor aircraft capable of delivering parts to ships at sea, but its O&M costs are high. The average funded flying hours for the MH-60S Seahawk is calculated using flying hours funded from the OP-20, shown in Table 12, starting in FY2024 through FY2028, which is equal to 308 hours per aircraft. The average budgeted cost to operate and maintain this system, also taken from the OP-20, includes the sum of consumables, CLS, DLR, and fuel and is averaged from FY2024 through FY2028, which is equal to $382,000 per aircraft. Taking these numbers and dividing the average budgeted cost by the average flying hours, the average cost per flight hour is calculated to be $1,240.

Table 12. OP-20 FHP Budget Data for MH-60S Seahawk. Source: Director of Cost Assessment and Program Evaluation (CAPE) (2024, p. 53).

MH-60S Seahawk					
	FY2024	**FY2025**	**FY2026**	**FY2027**	**FY2028**
Quantity	170	170	170	170	170
Flying Hours Funded	362	287	295	297	300
Consumables	$57,669	$83,874	$87,187	$90,121	$93,344
CLS	$48,615	$56,934	$54,785	$56,205	$54,413
DLR	$231,235	$202,588	$215,108	$220,041	$227,953
Fuel	$31,673	$24,228	$24,509	$25,270	$26,032
Total per Aircraft	$369,192	$367,624	$381,589	$391,637	$401,742
Total per Fleet	$62,762,640	$62,496,080	$64,870,130	$66,578,290	$68,296,140

Similarly, the CMV-22B Osprey is a versatile tiltrotor capable of delivering parts to ships at sea, but the cost of O&M of this aircraft is also high. The average funded flying hours for the CMV-22B Osprey is calculated using flying hours funded from the OP-20, shown in Table 13, starting in FY2024 through FY2028, which is equal to 346 hours per aircraft. The average budgeted cost to operate and maintain this system, also taken from the OP-20, includes the sum of consumables, CLS, DLR, and fuel and is averaged from FY2024 through FY2028, which is equal to $218,000 per aircraft. Taking these numbers and dividing the average budgeted cost by the average flight hours, the average cost per flight hour is calculated to be $630.

Table 13. OP-20 FHP Budget Data for CMV-22B Osprey. Source: CAPE (2024, p. 9).

CMV-22B Osprey					
	FY2024	**FY2025**	**FY2026**	**FY2027**	**FY2028**
Quantity	36	37	37	37	37
Flying Hours Funded	247	349	391	349	396
Consumables	$29,924	$45,792	$58,307	$59,332	$75,479
CLS	$8,283	$7,989	$8,284	$2,010	$2,065
DLR	$59,789	$105,329	$135,716	$138,584	$176,353
Fuel	$15,836	$23,986	$26,539	$24,141	$28,073
Total per Aircraft	$113,832	$183,096	$228,846	$224,067	$281,970
Total per Fleet	$4,097,952	$6,774,552	$8,467,30	$8,290,47	$10,432,890

2. Acquisition and Sustainment Costs

The airframe procurement and O&M costs were calculated in previous sections. Now, we determine the hourly cost of operating the system with operational crews. Based on each system's crewing requirements, this cost is calculated using the FY2024 DoD military personnel composite standard pay and reimbursable rates for the U.S. Navy. The total crew hourly pay is then added to the previously calculated airframe and O&M costs to derive the cost per flight hour for each system.

The DoD composite standard pay rates for each crew member's rank were taken from the Under Secretary of Defense (Comptroller) reports and used to calculate the total crew hourly pay. The combined pay of all crew members is divided by the average FY flight hours budgeted in OP-20.

a. MH-60S Seahawk

The MH-60S Seahawk helicopter operates with a crew of three: a pilot, copilot, and tactical aircrewman. The pilot is responsible for safely flying the aircraft and avoiding collisions. The copilot manages airborne tactical operations, while the tactical aircrewman operates the aircraft's sensors. The MH-60S total cost per flight hour breakdown, including crew, is shown in Table 14.

Table 14. MH-60S Seahawk Total Cost per Flight Hour Breakdown. Adapted from CAPE (2024) and McAndrew (2023, p. 3).

Navy MH-60S Seahawk	
Lifetime Flight Hours (LFH)	12,000
Cost of MH-60S	$23,533,000
Operations	
Airframe	$1,961
O&M (OP-20)	$1,241
Crew	
O-2 (Pilot)	$149,901
O-2 (Copilot)	$149,901
E-6	$127,272
Total Crew Yearly Pay	$427,074
Total Crew Hourly Pay	$1,387
Average FY Flight Hours	308
Total Cost per FH	$4,589

b. CMV-22B Osprey

The CMV-22B Osprey operates with a minimum crew of three: a pilot, copilot, and a loadmaster. The pilots are responsible for safely flying the aircraft and avoiding collisions, while the loadmaster manages the transport of personnel and cargo. The CMV-22B total cost per flight hour breakdown, including crew, is shown in Table 15.

Table 15. CMV-22B Osprey Total Cost per Flight Hour Breakdown. Adapted from CAPE (2024) and McAndrew (2023, p. 3).

CMV-22B Osprey	
Lifetime Flight Hours (LFH)	10,000
Cost of CMV-22B	$110,000,000
Operations	
Airframe	$11,000
O&M (OP-20)	$630
Crew	
O-2 (Pilot)	$149,901
O-2 (Copilot)	$149,901
E-6	$127,272
Total Crew Yearly Pay	$427,074
Total Crew Hourly Pay	$1,234
Average FY Flight Hours	346
Total Cost per FH	$12,864

c. GH-4 Gyrocopter

Two crew members operate the GH-4 Gyrocopter, one pilot and a tactical aircrewman to communicate with ATC and monitor sensors at the ground station if operating BVLOS. The tactical aircrewman in the ground station is critical to BVLOS operation because when operating autonomously, these UAVS cannot detect and avoid collisions with other aircraft that may be operating in the same area. In these cases, the ground station contacts ATC and communicates with the pilot to take manual control of the UAV to make avoidance maneuvers to avoid collision. The GH-4 total cost per flight hour breakdown, including crew, is shown in Table 16.

Table 16. GH-4 Gyrocopter Total Cost per Flight Hour Breakdown. Adapted from G. Shaanan (email to author, February 24, 2024) and McAndrew (2023, p. 3).

GH-4 Gyrocopter	
Lifetime Flight Hours (LFH)	2,000
Cost of GH-4	$395,000
Operations	
Airframe	$198
O&M	$33
Crew	
O-2 (Pilot)	$149,901
E-6	$127,272
Total Crew Yearly Pay	$277,173
Total Crew Hourly Pay	$1,386
Average FY Flight Hours	200
Total Cost per FH	$1,617

d. GT20 Gyrotrak

Like the GH-4 Gyrocopter, only two crew members are needed to operate the GT20, one pilot and one tactical aircrewman to communicate with ATC and monitor sensors at the ground station, if operating BVLOS. The GT20 is equipped with an Automatic Dependent Surveillance-Broadcast (ADS-B) transceiver. It transmits the UAV’s position, speed, altitude, and flight vectors to other aircraft and ATC, enabling them to take necessary collision-avoidance measures. Additionally, it receives ADS-B signals from nearby aircraft, allowing the autopilot software or a ground station operator to maneuver the UAV and prevent potential collisions (Bots & Drones Europe, 2021). The tactical aircrewman in the ground station is critical to BVLOS operation because the ground station contacts ATC and communicates with the pilot to take manual control of the UAV to make avoidance maneuvers if needed to avoid collision. The GT20 total cost per flight hour breakdown, including crew, is shown in Table 17.

Table 17. GT20 Gyrotrak Total Cost per Flight Hour Breakdown. Source: McAndrew (2023, p. 3).

GT20 Gyrotrak	
Lifetime Flight Hours (LFH)	2,000
Cost of GH-4	$395,000
Operations	
Airframe	$198
O&M	$12
Crew	
O-2 (pilot)	$149,901
E-6	$127,272
Total Crew Yearly Pay	$277,173
Total Crew Hourly Pay	$1,386
Average FY Flight Hours	200
Total Cost per FH	$1,596

e. Kargo UAV

The Kargo UAV has the same crew requirements as the GH-4 and GT20, similarly requiring ground station communication while operating BVLOS to facilitate manual maneuvers to avoid in-flight collisions. The exact procurement cost of the Kargo UAV is not publicly available information; therefore, a $2 million procurement cost has been assumed, which is consistent with Group 4 UAVs with similar capabilities. The Kargo UAV total cost per flight hour breakdown, including crew, is shown in Table 18.

Table 18. Kargo UAV Total Cost per Flight Hour Breakdown. Source: McAndrew (2023, p. 3).

Kargo UAV	
Lifetime Flight Hours (LFH)	2,000
Cost of GH-4	$2,000,000
Operations	
Airframe	$1,000

Kargo UAV	
O&M	$430
Crew	
O-2 (Pilot)	$149,901
E-6	$127,272
Total Crew Yearly Pay	$277,173
Total Crew Hourly Pay	$1,386
Average FY Flight Hours	200
Fuel per hour	$86
Total Cost per FH	$2,902

3. Calculated System Performance

This section of the study presents a comparative analysis of each aircraft system, focusing on total cost per flight hour and cruising speed to assess the costs associated with resupply missions of varying lengths. The total cost per flight hour for each system was calculated in previous sections, while cruising speed was determined using the manufacturer's technical specifications or data sheets.

The procurement costs of the MH-60S Seahawk and CMV-22B Osprey are significantly higher than those of the identified Group 3 and Group 4 UAV solutions. However, their longer service life, factored alongside O&M expenses and crew costs, results in a total operation cost per flight hour comparable to the lower-cost UAV alternatives.

Additionally, the cruising speed of aircraft is an important factor to consider. Cruising speed is below the aircraft's maximum capability while maintaining efficient and economical performance. Based on operational data, this speed is chosen to optimize fuel consumption and overall efficiency during flight.

When comparing the five aircraft for 100, 200, and 300-mile missions, cost, speed, and endurance play an important role in determining efficiency, as shown in Table 19. The MH-60S is cost-effective for short-range missions, completing a 100-mile trip in 0.65 hours at $2,983. For a 200-mile mission, the MH-60S requires 1.29 hours, costing $5,920, while a 300-mile mission takes 1.94 hours at $8,903. However, with an endurance of 4 hours and a maximum operational radius of 518 miles, at 400 miles, the

MH-60S is past its round-trip operational limit, which would require refueling to get back to the original takeoff location.

The CMV-22B, the fastest option with a 278-mph cruising speed, covers 100 miles in 0.36 hours at $4,631, 200 miles in 0.72 hours at $9,262, 300 miles in 1.08 hours at $13,893, and 400 miles in 1.44 hours at $18,524. Although more expensive than the MH-60S per mile, the CMV-22B offers better endurance and faster mission completion, making it a good option for long-range missions.

In contrast, the GH-4 Gyrocopter is less efficient in mission competition time due to its slower cruising speed of 55 mph, but it offers a slightly better cost when compared to the MH-60S. The GH-4 requires 1.82 hours to cover 100 miles at $2,943, a 3.64-hour flight for 200 miles at $5,886, and 5.45 hours for 300 miles, bringing the mission cost to $8,813. While its 6-hour endurance allows for long-range flights, the high cost and slow speed make it impractical for time-sensitive missions. Additionally, the GH-4's maximum operational radius is approximately 330 miles, so a mission with a round-trip distance of over 150 miles would require refueling, which could be done at the original takeoff location or the final destination if the ship is equipped with hydrogen refueling capabilities. Therefore, the GH-4 is non–mission capable for missions exceeding 100 miles, as shown in Table 19. The red highlights indicate instances where the system's endurance falls short of the required mission flight time.

Similarly, the GT20 Gyrotrak flies at a cruising speed of 53 mph and has a 2.5-hour endurance. It can complete 100 miles in 1.89 hours at $3,016. However, at 100 miles, the GT20 approaches its operational limit, making it the least viable option compared to other solutions presented in this study. For missions that require flying over longer distances, the GT-20 would have to be refueled. Therefore, the GT20 is non–mission capable for missions exceeding 400 miles, as shown in Table 19. The red highlights indicate instances where the system's endurance falls short of the required mission flight time.

The KARGO UAV Quadcopter is the most cost-effective option, flying at a cruising speed of 139 mph and covering 100 miles in 0.72 hours at $2,089. It can complete a 200-mile mission in 1.44 hours at $4,179, and a 300-mile mission, which takes 2.16 hours, at $6,268. With an endurance of 4.3 hours, it can complete 400-mile (200-mile round-trip) missions but would need refueling for longer flights.

We estimate the cost to refuel UAVs such as the GH-4 Gyrocopter, GT20 Gyrotrak, and Kargo UAV Quadcopter by calculating their hourly operating costs using the mission data in Table 19. The GH-4 has an operating cost of $1,617 per flight hour; with an endurance of 6 hours, a full mission cycle costs $9,702. The GT20 Gyrotrak operates at $1,596 per hour; with a 2.5-hour endurance, its full mission cycle costs $3,990. The KARGO UAV operates at $2,902 per hour; with a 4.3-hour endurance, a full mission cycle costs $12,479.

Refueling becomes necessary when a mission's total flight time exceeds the UAV's endurance. For round-trip missions, both the outbound and return legs must be considered when determining whether a refueling stop is required. When refueling is needed, the cost is assumed to be equivalent to the full cost of one endurance cycle, based on the aircraft's hourly rate. For example, if the GH-4 is assigned a 600-mile round-trip mission, it would require 10.91 hours of flight time, exceeding its 6-hour endurance. This would require at least one refueling, adding $9,702 to the base operational cost of $17,641, bringing the total mission cost to approximately $27,343. This approach can similarly be applied to the GT20 and KARGO UAVs, using their respective endurance limits and hourly costs. This method provides a general estimation framework for evaluating refueling costs in UAV mission planning without the need for specific fuel consumption data.

Table 19. Comparison of Manned Aircraft and UAV Operational Costs at Cruising Speed for Missions of Varying Length

100 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$4,589	155	0.65	4	100	$2,983
CMV-22B	$12,864	278	0.36	6	100	$4,631
GH-4 Gyrocopter	$1,617	55	1.82	6	100	$2,943
GT20 Gyrotrak	$1,596	53	1.89	2.5	100	$3,016
Kargo UAV Quadcopter	$2,902	139	0.72	4.3	100	$2,089
200 Miles						

Weapon System Type	Total Cost Per Hour	Cruising Speed (mph)	Flying Time (hrs)	Endurance (hrs)	Range (miles)	Cost
MH-60S	$4,589	155	1.29	4	200	$5,920
CMV-22B	$12,864	278	0.72	6	200	$9,262
GH-4 Gyrocopter	$1,617	55	3.64	6	200	$5,886
GT20 Gyrotrak	$1,596	53	3.77	2.5	200	$6,017
Kargo UAV Quadcopter	$2,902	139	1.44	4.3	200	$4,179
300 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$4,589	155	1.94	4	300	$8,903
CMV-22B	$12,864	278	1.08	6	300	$13,893
GH-4 Gyrocopter	$1,617	55	5.45	6	300	$8,813
GT20 Gyrotrak	$1,596	53	5.66	2.5	300	$9,033
Kargo UAV Quadcopter	$2,902	139	2.16	4.3	300	$6,268
400 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$4,589	155	2.58	4	400	$11,840
CMV-22B	$12,864	278	1.44	6	400	$18,524
GH-4 Gyrocopter	$1,617	55	7.27	6	400	$11,756
GT20 Gyrotrak	$1,596	53	7.55	2.5	400	$12,050
Kargo UAV Quadcopter	$2,902	139	2.88	4.3	400	$8,358

The KARGO UAV is the most economical choice across all distances. For 200-mile missions, the MH-60S and CMV-22B remain competitive at approximately $5,920 and $9,262, respectively, with the CMV-22B’s higher speed potentially justifying its cost. For operations beyond 200 miles, the CMV-22B is the best option due to its speed and endurance, while the MH-60S remains a viable alternative.

In contrast, though cost-efficient, the GH-4 and GT20 gyrocopters are impractical for time-sensitive, long-range missions due to their slow speeds and endurance limitations. However, they offer a viable unmanned alternative for shorter missions up to 200 miles.

A comparison of systems over varying distances is presented in Figure 11. The data indicate that the cost differences between the MH-60S, GH-4 Gyrocopter, and GT20 Gyrotrak are relatively small, with the CMV-22B being the costliest across all distances and the Kargo UAV being the least costly across all distances. This highlights the need for a trade-off analysis to balance speed, endurance, and cost, ensuring the selection of the most suitable system based on mission requirements.

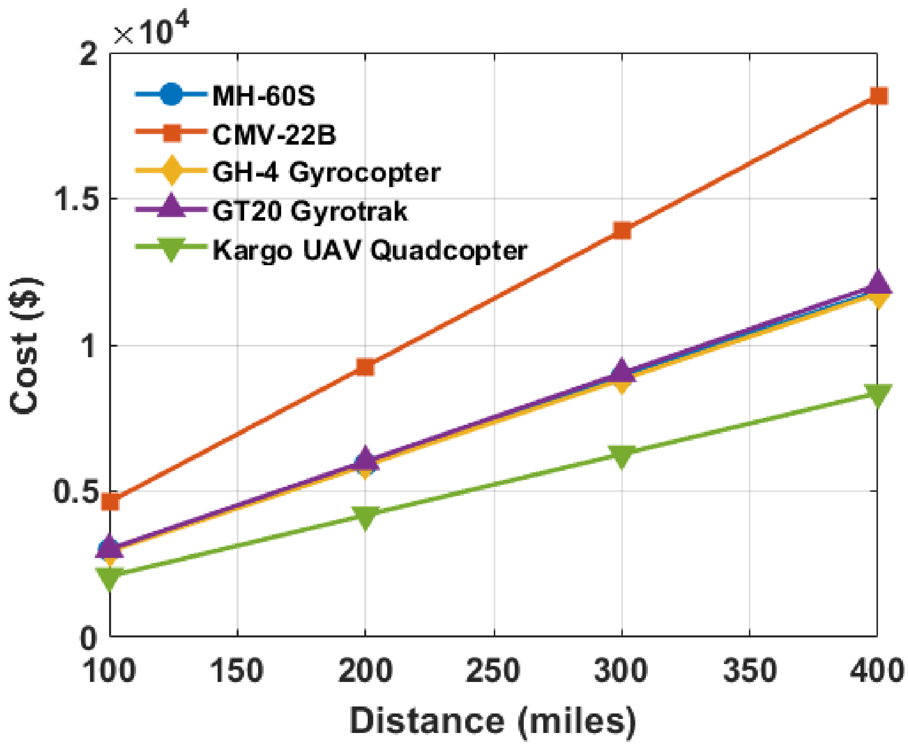

Figure 11. Cost Comparison of Systems for Varying Distances

4. Cost-based Analysis: Sensitivity Analysis Discussion

This section examines how changes in operational parameters affect the cost ranking of aircraft. The analysis evaluates the effect of these scenarios across mission distances and identifies which platforms remain lowest in cost under varying conditions.

a. Operational Variability

The hypothetical impact of operational variables, cost per hour and cruising speed, was evaluated to assess how cost rankings between these aircraft shift under different assumptions. To determine if these assumptions had a significant impact on the outcome, hypothetical parameters were used to conduct a sensitivity analysis.

Specifically, the cost per hour was varied by ±20%, while cruising speed was adjusted by ±10%. An analysis was conducted to determine whether these adjustments lead to any shifts in the rankings, compared to the outcomes derived using nominal operating values.

As shown in Table 20, the cost per hour increased by 120%, and the cruising speed was raised by 110%. Even with these adjusted values, the Kargo UAV remains the most cost-effective option across all distances, with the gyrocopter UAVs following close behind. In contrast, the traditional aircraft continues to be the more expensive alternative.

Table 20. Sensitivity Analysis: Cost 120% with Speed at 110%

100 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	171	0.58	4	100	$3,194
CMV-22B	$15,437	306	0.33	6	100	$5,094
GH-4 Gyrocopter	$1,940	61	1.64	6	100	$3,182
GT20 Gyrotrak	$1,915	58	1.72	2.5	100	$3,294
Kargo UAV Quadcopter	$3,482	153	0.65	4.3	100	$2,264
200 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	171	1.17	4	200	$6,443
CMV-22B	$15,437	306	0.65	6	200	$10,034
GH-4 Gyrocopter	$1,940	61	3.28	6	200	$6,365
GT20 Gyrotrak	$1,915	58	3.45	2.5	200	$6,607
Kargo UAV Quadcopter	$3,482	153	1.31	4.3	200	$4,562
300 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	171	1.75	4	300	$9,637
CMV-22B	$15,437	306	0.98	6	300	$15,128
GH-4 Gyrocopter	$1,940	61	4.92	6	300	$9,547
GT20 Gyrotrak	$1,915	58	5.17	2.5	300	$9,902
Kargo UAV Quadcopter	$3,482	153	1.96	4.3	300	$6,825

400 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	171	2.34	4	400	$12,886
CMV-22B	$15,437	306	1.31	6	400	$20,222
GH-4 Gyrocopter	$1,940	61	6.56	6	400	$12,729
GT20 Gyrotrak	$1,915	58	6.90	2.5	400	$13,215
Kargo UAV Quadcopter	$3,482	153	2.61	4.3	400	$9,089

As shown in Table 21, costs per hour remain at the higher value of 120%, but cruising speed is reduced to 90%. In this scenario, Kargo UAV continues to be the most cost-effective option. Despite having a higher procurement cost than the gyrocopters, the Kargo UAV's cruising speed is more than double that of the gyrocopters, enabling it to complete its mission in half the time. This results in a significant reduction in cost per hour compared to the slower gyrocopters. The MH-60S is relatively close to the UAVs, but it is still more expensive. The CMV-22B is significantly more expensive due to its higher procurement costs, making it the least favorable alternative.

Table 21. Sensitivity Analysis: Cost 120% with Speed at 90%

100 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	140	0.71	4	100	$3,910
CMV-22B	$15,437	250	0.40	6	100	$6,175
GH-4 Gyrocopter	$1,940	50	2.00	6	100	$3,881
GT20 Gyrotrak	$1,915	48	2.08	2.5	100	$3,984
Kargo UAV Quadcopter	$3,482	125	0.80	4.3	100	$2,786
200 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	140	1.43	4	200	$7,875
CMV-22B	$15,437	250	0.80	6	200	$12,349
GH-4 Gyrocopter	$1,940	50	4.00	6	200	$7,762
GT20 Gyrotrak	$1,915	48	4.17	2.5	200	$7,986

Kargo UAV Quadcopter	$3,482	125	1.60	4.3	200	$5,572
300 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	140	2.14	4	300	$11,785
CMV-22B	$15,437	250	1.20	6	300	$18,524
GH-4 Gyrocopter	$1,940	50	6.00	6	300	$11,642
GT20 Gyrotrak	$1,915	48	6.25	2.5	300	$11,970
Kargo UAV Quadcopter	$3,482	125	2.40	4.3	300	$8,358
400 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$5,507	140	2.86	4	400	$15,749
CMV-22B	$15,437	250	1.60	6	400	$24,699
GH-4 Gyrocopter	$1,940	50	8.00	6	400	$15,523
GT20 Gyrotrak	$1,915	48	8.33	2.5	400	$15,954
Kargo UAV Quadcopter	$3,482	125	3.20	4.3	400	$11,144

As shown in Table 22, costs per hour were reduced by 80%, and the cruising speed increased by 110%. The combination of a lower cost per hour and an increased cruising speed continues to favor the Kargo UAV. In this case, the MH-60S helicopter comes very close in total cost for each mission distance to the UAVs. However, the speed deficit between the Kargo UAV and MH-60S remains too large, meaning that the increased speed for the gyrocopters does not reduce the total cost per hour at each mission distance.

Table 22. Sensitivity Analysis: Cost 80% with Speed at 110%

100 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,671	171	0.58	4	100	$2,129
CMV-22B	$10,291	306	0.33	6	100	$3,396
GH-4 Gyrocopter	$1,294	61	1.64	6	100	$2,122
GT20 Gyrotrak	$1,277	58	1.72	2.5	100	$2,196

Kargo UAV Quadcopter	$2,322	153	0.65	4.3	100	$1,509
200 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,962	171	1.17	4	200	$4,295
CMV-22B	$11,874	306	0.65	6	200	$6,689
GH-4 Gyrocopter	$1,294	61	3.28	6	200	$4,243
GT20 Gyrotrak	$1,277	58	3.45	2.5	200	$4,405
Kargo UAV Quadcopter	$2,366	153	1.31	4.3	200	$3,041
300 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,962	171	1.75	4	300	$6,425
CMV-22B	$11,874	306	0.98	6	300	$10,085
GH-4 Gyrocopter	$1,294	61	4.92	6	300	$6,365
GT20 Gyrotrak	$1,277	58	5.17	2.5	300	$6,601
Kargo UAV Quadcopter	$2,366	153	1.96	4.3	300	$4,550
400 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,962	171	2.34	4	400	$8,591
CMV-22B	$11,874	306	1.31	6	400	$13,481
GH-4 Gyrocopter	$1,294	61	6.56	6	400	$8,486
GT20 Gyrotrak	$1,277	58	6.90	2.5	400	$8,810
Kargo UAV Quadcopter	$2,366	153	2.61	4.3	400	$6,059

As shown in Table 23, in the final iteration, the cost per hour remains reduced to 80%, while the cruising speed is lowered to 90%. As with the other previous scenarios, the Kargo UAV remains the most cost-effective option, with the MH-60S and gyrocopters being relatively close in cost. Varying aircraft speed has a greater impact on the gyrocopters than the higher procurement costs, as the slower an aircraft is, the longer it must remain airborne to complete its mission, which consequently increases its total operational costs.

Table 23. Sensitivity Analysis: Cost 80% with Speed at 90%

100 Miles						
Weapon System Type	Total Cost Per Hour	Cruising Speed (mph)	Flying Time (hrs)	Endurance (hrs)	Range (miles)	Cost
MH-60S	$3,671	140	0.71	4	100	$2,607
CMV-22B	$10,291	250	0.40	6	100	$4,116
GH-4 Gyrocopter	$1,294	50	2.00	6	100	$2,587
GT20 Gyrotrak	$1,277	48	2.08	2.5	100	$2,656
Kargo UAV Quadcopter	$2,322	125	0.80	4.3	100	$1,857
200 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,671	140	1.43	4	200	$5,250
CMV-22B	$10,291	250	0.80	6	200	$8,233
GH-4 Gyrocopter	$1,294	50	4.00	6	200	$5,174
GT20 Gyrotrak	$1,277	48	4.17	2.5	200	$5,324
Kargo UAV Quadcopter	$2,322	125	1.60	4.3	200	$3,715
300 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,671	140	2.14	4	300	$7,856
CMV-22B	$10,291	250	1.20	6	300	$12,349
GH-4 Gyrocopter	$1,294	50	6.00	6	300	$7,762
GT20 Gyrotrak	$1,277	48	6.25	2.5	300	$7,980
Kargo UAV Quadcopter	$2,322	125	2.40	4.3	300	$5,572
400 Miles						
Weapon System Type	**Total Cost Per Hour**	**Cruising Speed (mph)**	**Flying Time (hrs)**	**Endurance (hrs)**	**Range (miles)**	**Cost**
MH-60S	$3,671	140	2.86	4	400	$10,500
CMV-22B	$10,291	250	1.60	6	400	$16,466
GH-4 Gyrocopter	$1,294	50	8.00	6	400	$10,349
GT20 Gyrotrak	$1,277	48	8.33	2.5	400	$10,636
Kargo UAV Quadcopter	$2,322	125	3.20	4.3	400	$7,429

As shown in Figure 13, the sensitivity analysis reveals that the Kargo UAV consistently remains the most cost-effective option across all scenarios with the lowest cost-per-mile efficiency ratio, calculated by dividing cruising speed by cost per hour, despite variations in cost per hour and cruising speed. While both the MH-60S helicopter and gyrocopters come close in cost at times, the Kargo UAV's speed and overall efficiency allow it to maintain its advantage, particularly as the slower gyrocopters incur higher operational costs due to extended mission times. The analysis highlights the influence of speed on operational costs, with slower aircraft facing greater cost burdens. Ultimately, the Kargo UAV is the most reliable choice, even when factoring in different assumptions and operational adjustments.

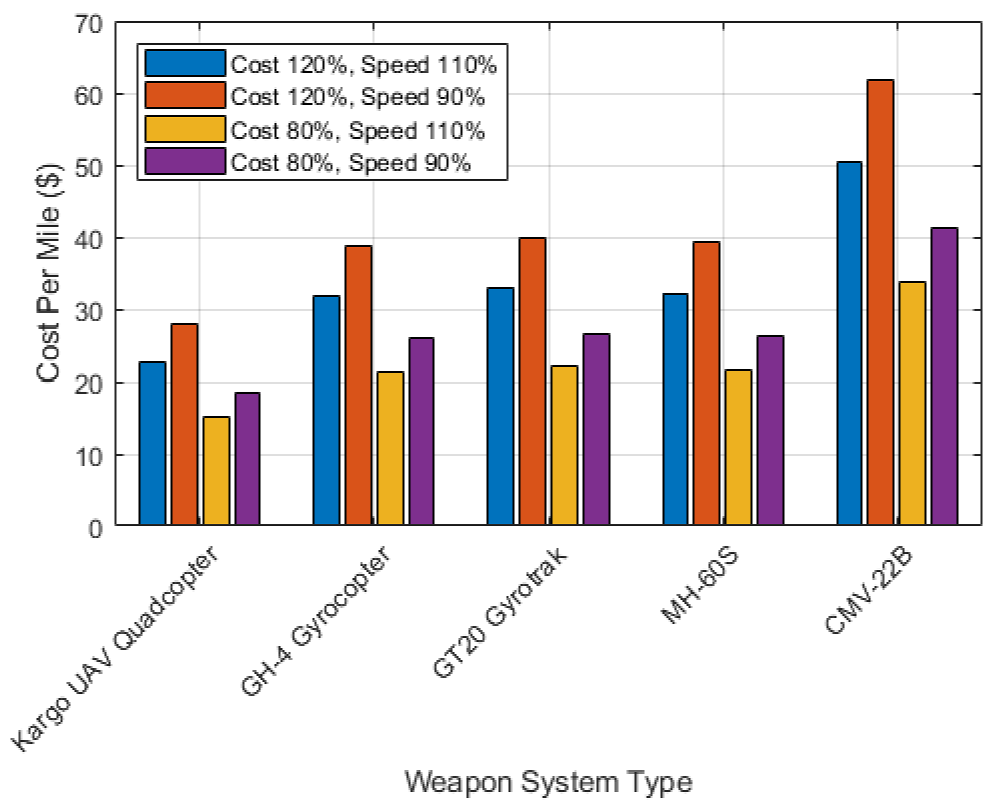

Figure 12. Cost Per Mile Efficiency of UAVs versus Helicopters

C. CHAPTER SUMMARY

This chapter evaluates the life cycle costs of UAV adoption for small-payload resupply at sea and highlights the financial and operational trade-offs. It discusses each step used to calculate the relevant costs and the factors considered. This section provides the total costs of each option considered in terms of flight hour, allowing a direct comparison between the different aircraft. A sensitivity analysis is performed to test the soundness of the results by applying hypothetical performance parameters to the model. This is to determine how the cost rankings shift as the parameters change. In this case, cruising speed and cost per hour were varied. As this chapter’s results show, even under varied assumptions, cost rankings remained consistent, with the Kargo UAV proving an alternative worthy of further consideration. The next chapter summarizes the key findings from this study and provides conclusions and the author’s recommendations for areas worthy of further study.

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VI. CONCLUSION

This study has analyzed the cost-effectiveness and feasibility of using fuel-efficient UAVs for spare parts delivery to Navy ships at sea. By comparing traditional aerial delivery systems, such as the MH-60S Seahawk and CMV-22B Osprey, with emerging UAV technologies, the findings highlight the potential for cost savings and increased operational efficiency. The research demonstrates that UAVs, particularly VTOL systems, can serve as a viable alternative while aligning with DoD's sustainability objectives. While challenges such as infrastructure requirements and adverse weather conditions remain, the benefits of UAV integration, which include lower fuel consumption and enhanced mission availability, highlight the need for further exploration and investment in these technologies.

A. SUMMARY OF FINDINGS

In this thesis, the goal was to address two research questions:

1. How the adoption of next-generation Group 3 UAV platforms, powered by alternative fuel, affects the fiscal effectiveness of routine resupply missions for the U.S. Navy compared to traditional fossil-fueled rotary wing or tiltrotor aircraft?
2. Are HVTOL UAVs a feasible and cost-effective alternative for spare parts delivery to ships at sea?

Based on the cost analysis conducted in this study, the findings highlight that UAVs, particularly the Kargo UAV, offer a cost-saving advantage over traditional aerial logistics platforms like the MH-60S Seahawk and CMV-22B Osprey. The study demonstrates that UAVs, especially those with HVTOL capabilities, can reduce operational costs through lower fuel consumption, reduced maintenance requirements, and decreased manpower needs. Sensitivity analysis indicates that even when key cost drivers fluctuate, UAVs remain the most economical choice for small-payload deliveries.

As shown in Figure 13, among the UAV options considered, the Kargo UAV consistently proves to be the most cost-effective, with its optimized speed and efficiency reducing overall mission expenses. While traditional aircraft such as the MH-60S and CMV-22B possess greater payload capacities, their higher operating costs make them less favorable for routine resupply missions.

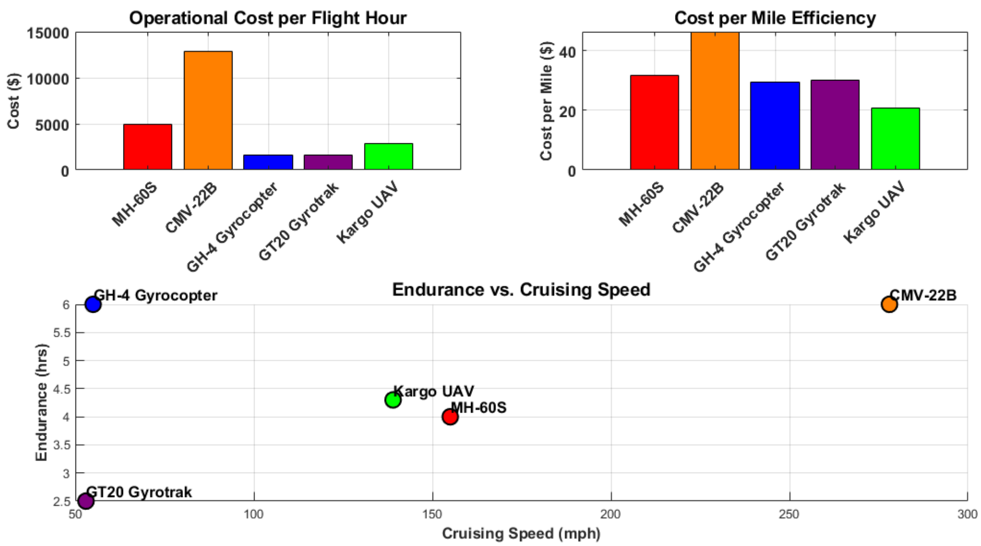

Figure 13. Weapon System Cost Comparison

Among the UAV options considered, the Kargo UAV consistently proves to be the most cost-effective, with its optimized speed and efficiency reducing overall mission expenses. While traditional aircraft such as the MH-60S and CMV-22B possess greater payload capacities, their higher operating costs make them less favorable for routine resupply missions.

Overall, the findings support the adoption of UAV technology to enhance logistical efficiency, reduce costs, and improve sustainability in Navy resupply operations.

B. RECOMMENDATIONS

Given the evolving strategic landscape, the integration of Group 3 HVTOL UAVs into the U.S. Navy's logistics framework offers a viable and cost-effective alternative to traditional aerial resupply assets such as the MH-60S and CMV-22B. The findings of this study suggest that UAVs, particularly those powered by electricity or hydrogen fuel, can significantly reduce operational costs while maintaining the availability of warfighting platforms for critical missions.

As demonstrated through cost-based and sensitivity analyses, UAVs provide substantial cost savings in delivering small payloads to ships at sea. These savings stem from lower fuel consumption, reduced maintenance requirements, and decreased reliance on personnel-intensive operations.

Despite these advantages, certain challenges must be addressed before full-scale adoption. The operational feasibility of UAV-based logistics depends on refining their endurance, payload capacities, and integration within existing naval command and control structures. Additionally, infrastructure enhancements, such as shipboard UAV refueling and recharging stations, must be developed to support sustained operations in distributed maritime environments.

Given these considerations, it is recommended that the DON conduct pilot programs to further evaluate the performance, reliability, and interoperability of UAVs in logistical roles. These programs should assess the impact of UAV logistics on mission readiness, cost-effectiveness, and operational flexibility. Furthermore, policy adaptations should be explored to ensure seamless integration of autonomous resupply missions within current naval aviation frameworks.

Ultimately, the adoption of UAV-based resupply solutions aligns with the U.S. Navy's strategic priorities, enhances sustainability, and optimizes resource allocation for future naval operations.

C. POSSIBLE IMPLICATIONS

As defense and logistics operations evolve to meet modern demands, organizations are exploring alternatives to traditional manned aircraft for routine resupply missions. One alternative is the adoption of Group 3 HVTOL UAV platforms. When considering the potential adoption, it is important to ask what the operational implications are of transitioning from fossil-fueled rotary wing or tiltrotor aircraft to Group 3 HVTOL UAV platforms for routine resupply missions regarding maintenance requirements, capability, and overall costs.

Transitioning from fossil-fueled rotary wing or tiltrotor aircraft to Group 3 HVTOL UAVs for routine resupply missions introduces several operational considerations. In terms of maintenance, Group 3 HVTOL UAVs are simpler systems with fewer moving parts, allowing for simplified and predictive maintenance practices based on usage hours. Their modular component designs and commercial off-the-shelf parts reduce maintenance downtime and the need for specialized labor.

From a capability perspective, Group 3 HVTOL UAVs provide VTOL capability in constrained environments, can be operated autonomously or remotely, and maintain consistent payload-to-range performance when transporting cargo weighing less than 15 pounds. These characteristics support use in repeated supply missions across varied environments. Additionally, the absence of onboard pilots eliminates risks to personnel, allowing for increased mission frequency and application across a range of logistics scenarios.

Regarding cost, these UAVs may reduce life cycle expenses through lower fuel usage, streamlined maintenance, and decreased personnel and support requirements. However, upfront costs related to acquisition, infrastructure, operator training, and integration with current logistics systems require further evaluation. Over time, the use of HVTOL UAVs has the potential to improve efficiency, cost control, and sustainment readiness.

D. AREAS OF FURTHER RESEARCH

UAVs remain an evolving technology, and despite their increasing integration into military logistics, significant gaps in data and operational experience persist. One of the primary challenges is the lack of comprehensive cost data, particularly for newer UAV models. While the DoD has started tracking UAV costs, its analysis is still in its early stages. A more definitive study should be conducted once a broader dataset is available, like what exists for traditional manned aircraft.

Next, it is recommended that additional analysis be performed to gain insight into which acquisition strategy would be most suitable for procuring next-generation Group 3 HVTOL UAVs. Given the advanced development and prototyping existing amongst UAVs, this analysis recommends implementing the rapid fielding pathway under DoD Instruction 5000.80 for procurement of any potential solution, while leveraging industry partnerships, which will allow for accelerated capability deployment for naval logistics and maintenance operations. By using commercial off-the-shelf technology, this fielding strategy allows for minimal modifications to be made and deployed to the field to meet operational capability within 5 years. Coupling this strategy with spiral development will allow for incremental capability improvements to be incorporated based on end user feedback, while maintaining cybersecurity, airworthiness, and interoperability standards. However, further study would likely reveal additional insights that could change the recommendation.

Beyond cost considerations, the DoD and the broader global defense community have yet to fully realize UAVs' potential. As these platforms evolve, further research should explore their expanding capabilities, including enhancements in endurance, payload efficiency, and autonomy.

Regulatory constraints also pose a significant challenge as advancements in UAV technology continue to outpace adoption and regulatory frameworks. Current UAV regulations struggle to keep up with the speed of technological innovation. Future research should examine how evolving policies, both domestic and international, impact the integration of UAVs into military operations. Addressing airspace restrictions, safety concerns, and interoperability with existing systems will be crucial for maximizing UAV utility in logistics.

Finally, additional studies should focus on the infrastructure requirements for UAV operations, particularly in maritime environments. The logistical feasibility of hydrogen-powered UAVs, onboard refueling solutions, and the integration of UAVs into naval vessels requires deeper exploration. Research in these areas will ensure that UAV-based delivery solutions align with operational readiness goals while maintaining cost efficiency and regulatory compliance.

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