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RESEARCH ON POTENTIAL UNMANNED AERIAL SYSTEMS CONOPS FOR USN AND USCG SHIPS

by

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June 2023

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The use of unmanned aerial systems (UAS) aboard United States Navy (USN) and United States Coast Guard (USCG) vessels is currently limited due to several factors including cost, capability, and policy and regulation. The primary goal of this analysis is to examine how Group 1–3 UAS impacts a surface ship's performance during intelligence, surveillance, and reconnaissance (ISR), search and rescue (SAR), and logistics missions and to consider what performance parameters of small UAS systems may be most meaningful to performing those missions. The data used in this research include publicly available UAS specifications, ship specifications and metrics, and previously conducted cost/budgeting analyses. This information is utilized to inform various models of potential missions, a tool that facilitates the selection of UAS for user requirements and a cost analysis. The results of these analyses indicate that UAS are beneficial to the missions they may perform—i.e., missions that can support their shorter operational times and ranges relative to other airborne assets. For ISR/SAR scenarios, the analysis shows UAS increase the number of targets identified when compared to a ship operating without an aerial asset and decrease the overall time to completely search an operational area. In logistical delivery scenarios—those where a UAS is used to retrieve a delivery from port—they are shown to reduce both the cost and time necessary to do so compared to a ship fully diverting to port.

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and Jacob A. VanWhy

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ABSTRACT

The use of unmanned aerial systems (UAS) aboard United States Navy (USN) and United States Coast Guard (USCG) vessels is currently limited due to several factors including cost, capability, and policy and regulation. The primary goal of this analysis is to examine how Group 1–3 UAS impacts a surface ship's performance during intelligence, surveillance, and reconnaissance (ISR), search and rescue (SAR), and logistics missions and to consider what performance parameters of small UAS systems may be most meaningful to performing those missions. The data used in this research include publicly available UAS specifications, ship specifications and metrics, and previously conducted cost/budgeting analyses. This information is utilized to inform various models of potential missions, a tool that facilitates the selection of UAS for user requirements and a cost analysis. The results of these analyses indicate that UAS are beneficial to the missions they may perform—i.e., missions that can support their shorter operational times and ranges relative to other airborne assets. For ISR/SAR scenarios, the analysis shows UAS increase the number of targets identified when compared to a ship operating without an aerial asset and decrease the overall time to completely search an operational area. In logistical delivery scenarios—those where a UAS is used to retrieve a delivery from port—they are shown to reduce both the cost and time necessary to do so compared to a ship fully diverting to port.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASW	anti-submarine warfare
BOE	back of the envelope
CG	Guided Missile Cruiser
CIVPAY	civilian pay
CNO	Chief of Naval Operations
CONOPS	concept of operations
COTS	commercial off the shelf
CSAR	combat search and rescue
CVN	Nuclear Carrier
D&C	detect and confirm
DDG FLT IA	Flight IA Guided Missile Destroyer
DDG FLT IIA	Flight IIA Guided Missile Destroyer
DOD	Department of Defense
DOE	design of experiments
EO/IR	electro-optical and infrared
GAO	Government Accountability Office
GCS	ground control station
GPS	global positioning system
Hr	hour
ICAO	International Civil Aviation Organization
ID	identification
ISR	intelligence, surveillance, and reconnaissance
Kts	knots

LCS-1	Freedom-Class Littoral Combat Ship
LCS-2	Independence-Class Littoral Combat Ship
MDA	maritime domain awareness
MILPERS	military pay
MOE	metric of evaluation
MUM-T	manned-unmanned teaming
NM	nautical miles
NSC	National Security Cutter
NumUAS	number of UAS
O&M	operation and maintenance
O&S	operations and sustainment
OPBOX	operational area
OPC	Offshore Patrol Cutter
OSD	Office of the Secretary of Defense
OTH	over the horizon
PH	per-hour
POI	point of interest
PROC	procurement
RDT&E	research, development, test, and evaluation
SAR	search and rescue
SARs	selected acquisition reports
SUW	surface warfare
SWAP-C	space, weight, power, and cooling
TOC	total ownership cost

TOI	target of interest
TW	track width
UAS	unmanned aerial systems
UNCLOS	United Nations Convention on the Law of the Sea
USCG	United States Coast Guard
USN	United States Navy
USNI	United States Naval Institute
VERTREP	vertical replenishment
VTOL	vertical takeoff and landing
WMEC	Alex Haley Class Medium Endurance Cutter
WPC	Fast Response Cutter

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EXECUTIVE SUMMARY

The Chief of Naval Operations' (CNO) 2021 NAVPLAN [1] includes a goal of achieving a hybrid fleet by the year 2045, though currently there is limited organic (i.e., launched and recovered from the vessel) Unmanned Aerial Systems (UAS) use on smaller surface ships in both the United States Coast Guard (USCG) and the United States Navy (USN) fleets. Many UAS assets are capable of intelligence, surveillance, and reconnaissance (ISR), search and rescue (SAR), and light-load resupply missions. Utilizing these systems in place of manned alternatives in suitable operations may save crucial time and effort in meeting mission goals. This research seeks to identify UAS parameters that improve performance for key missions performed by USN and USCG vessels, to model UAS behavior and impacts in contrast to alternatives currently employed, and to propose a methodology for early evaluation of UAS alternatives considered for integration into the surface fleet.

This research summarizes relevant literature on UAS usage both in general and in the maritime environment. The research also summarizes information collected on UAS systems and vessel types as well as their relevant parameters, specifications, and capabilities. The information collected is then synthesized into a "Drone Selector Tool," which analyzes the interaction of UAS requirements with ship-based constraints. This Excel-based tool considers:

- What generic UAS parameters are most valuable in an operating scenario.
- What capability specific UAS systems achieve on those parameters.
- What ships can support specific UAS systems.

This tool then calculates, for each ship type, which UAS can operate from it and the relative value of each UAS type. This tool is designed to be easily updated with real-world data for UAS systems, ship types, and stakeholder preferences. Stakeholders can use this tool to guide further research into specific UAS solutions.

Following the development of the Drone Selector Tool, the impact of UAS systems on operational scenarios is considered. This is accomplished through scenario development and modeling. First, notional operational scenarios are developed for ISR, SAR, and logistics missions. Then, relevant metrics of interest for each scenario are described (for example, mean time to search an area). Finally, back-of-the-envelope calculations as well as higher fidelity simulation modeling via ExtendSim [2] are presented. ExtendSim, created by Imagine That Incorporated, is a robust suite of simulation software that allows for continuous, discrete event, and other forms of simulation modeling [2]. These models are then used to consider how changes in various ship and UAS parameters (for example, UAS speed) impact mission performance evaluated via the metrics of interest.

For the ISR scenarios considered, the analysis shows that incorporating a UAS capability can significantly reduce mean time to search an area. This impact is larger for smaller areas as UAS aerial time is finite, while search time increases with the size of the search. The impact of UAS on reducing time also increases as the number of targets in the scenario increases. With respect to UAS parameters for the ISR mission, speed of the UAS is key—if the UAS speed is approaching the speed of the ship, UAS impact is reduced.

In the SAR analysis, UAS capability significantly reduces time to search the box when the UAS is used to increase sensor width. Here, the analysis shows that the total amount of UAS aerial time is a key factor, whether this is achieved with additional UAS systems or longer endurance time. UAS sensor width is also a key factor, with wider sensor ranges decreasing the time required to search the box. However, while UAS systems can be used to decrease time to search, the assumed probability of detection for the UAS is important. If the probability of detection is low, this usage pattern will likely lead to fewer overall detections.

A scenario in which the UAS is used to increase the overall probability of detection as opposed to increasing sensor width is also considered. In this scenario, the UAS systems has effectively no impact on scenario time. As in the previous SAR scenario, probability of detection is important—UAS impact on scenario non-detections is negligible or negative at the lower end of UAS probability of detections considered. At the higher end of the UAS probability of detections considered (a number similar to the assumed ship probability of detection) UAS positively impact the mean number of scenario non-detections (i.e., they decrease non-detections). Finally, UAS systems have negligible impact on non-detections for scenarios with fewer total targets to find, but their impact increases as targets are added.

Additionally, with respect to the impacts of adding UAS to the surface fleet for ISR and SAR missions, the following trends emerged:

- In the ISR case, UAS speed is key parameter.
- In general, more searching with high probability of detection decreases the number of non-detections in a scenario and more searching with low probability of detection increases the number of non-detections in a scenario. This implies that UAS sensors must be carefully considered when acquiring new systems.
- Counterintuitively, having UAS capability is more impactful to ISR and SAR mission metrics when smaller areas are searched. This is because larger searches take longer and UAS aerial time has a hard upper bound.

UAS Systems are more likely to be impactful when there are more targets to find or confirm in ISR and SAR environments. The cost implications of adding UAS systems into the surface fleet were also considered. The analysis suggests that smaller commercial off-the-shelf (COTS) UAS solutions are likely to be significantly lower cost per hour than traditional manned assets, even when procurement costs are included for the UAS systems. As the cost for the COTS UAS solutions increases, their per hour cost approaches the lower end of manned asset costs. This analysis is dependent on the number of UAS hours flown because fixed procurement costs are included. The more the UAS asset is flown, the lower its comparative per unit cost will be. This study also considered the number of flight hours at which UAS system costs breakeven, or the procurement investment for a single UAS has paid for itself by reducing the marginal cost of supporting the surface fleet. This analysis assumes that the hours flown by the UAS replace manned asset hours. Here, both lower and higher cost COTS UAS systems reach the breakeven point in terms of operating hours rapidly if it is assumed that all UAS hours are substitutes for manned asset hours.

However, for higher cost systems, this operating-hour breakeven point is highly dependent on the assumed substitution rate. For the notional higher-end COTS UAS system considered, if 50% of the single UAS system's hours are substitutes for manned asset hours, the number of flight hours to reach breakeven operating hour increased ~680% relative to the 100% substitution rate case

Ultimately, it is likely that incorporating UAS into the surface fleet, all else equal, will lead to improved performance for lone ships in ISR and SAR missions for the metrics considered. UAS integration into smaller surface ships will also provide increased flexibility to commanders to adapt to operational challenges. However, not all UAS systems have the right mix of speed, mission endurance, and avionics to provide meaningful capability. Those that do are likely to be larger and more expensive. This suggests that the UAS systems to be integrated must be selected with care.

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I. BACKGROUND AND CONCEPTS

A. INTRODUCTION

The Chief of Naval Operations' (CNO) 2021 NAVPLAN [1] includes a goal of achieving a hybrid fleet by the year 2045, though currently there is limited organic (i.e., launched and recovered from the vessel) Unmanned Aerial Systems (UAS) use on smaller surface ships in both the USCG and USN fleets. UAS are often quicker to launch, cheaper to operate and maintain, and more efficient to utilize than their manned counterparts such as helicopters, airplanes, or ground or sea surface-based systems. Therefore, investigating the integration of UAS into the United States Coast Guard (USCG) and U.S. Navy (USN) fleet is a crucial step towards maintaining maritime superiority, efficiency, and cost effectiveness.

Many UAS assets are capable of intelligence, surveillance, and reconnaissance (ISR) and light-load resupply missions. Utilizing these systems in place of manned alternatives in these suitable operations may save crucial time and effort in meeting mission goals. This research seeks to identify UAS parameters that improve performance for key missions performed by USN and USCG vessels and model UAS behavior and benefits in contrast to alternatives currently employed.

B. BACKGROUND

A UAS is an aircraft that is controlled remotely by an operator or is autonomously controlled internally. In general, UAS are divided into five categories [2] defined by their size, speed, and operational altitudes. Refer to Table 1 for these groups and their respective metrics.

Table 1. UAS Groups

UAS Group	Maximum Weight (lbs)	Normal Operating Altitude (ft)	Speed (kts)
Group 1	0-20	< 1,200 AGL	< 100
Group 2	21-55	< 3,500 AGL	< 250
Group 3	< 1320	< FL 18,000 MSL	< 250
Group 4	> 1320	< FL 18,000 MSL	Any Airspeed
Group 5	> 1320	> FL 18,000 MSL	Any Airspeed

This study focuses on Groups 1–3 due to their more compact storage requirements and more easily managed takeoff requirements. Heavyweight UAS (Groups 4 and 5) are utilized in military operations outside of Groups 1–3's capabilities but are too large for use on smaller vessels—such as the Coast Guard's Cutter—to be considered for organic support of missions.

The most obvious use case for UAS' is ISR for missions that require long-range visibility and coverage of large swaths of land and sea surface under search. Some lighter assets are also capable of having lightweight cargo affixed to them so that resupply of a vessel is possible within the system's flight and retrieval range.

For a mission that requires air-coverage, it is currently status quo for USCG and USN vessels without the capacity for onboard aerial assets to rely on land-based helicopter or fixed-wing support. The time required for the pilots to ready the craft, launch, and reach the point of interest (POI) can be considerable, depending on the crew's readiness and distance to the POI. This can hinder the effectiveness of search and rescue missions, tracking missions, and any other time-sensitive operation. A ship-based launch of a UAS requires far less time and can provide support nearly immediately during operations where time is paramount.

In recent years, advancements have been made in UAS technologies which greatly improve their range of operation, sensor quality, and various other characteristics [3]. Historically, smaller UAS have been limited in operational range, due both to battery and fuel capacities as well as radio-control ranges. While the smaller Groups 1–3 UAS are still somewhat limited with respect to energy capacity, the improvements in battery capacity, storage, and efficiency have relieved some of this limitation. These developments have improved UAS relevance in situations requiring ISR, time-intensive tracking or searching, and retrieval after the fact.

This study considers both battery and gas powered UAS. In general, the requirements for a UAS are minimal when compared to that of other aerial vessels. UAS' are often modularly constructed so that replacement of a faulty component is swift and inexpensive. Additionally, the maintenance requirements for helicopters far surpass those of a smaller craft such as a Group 1–3 UAS. Any larger UAS requires more expensive parts, more time and labor-intensive maintenance, and require longer downtimes to repair, given the added complexity of the overall system. Chapter IV of this study provides analysis of these differences and cost benefits.

C. OBJECTIVES

The goal of this study is to provide an analysis of meaningful benefits derived from the integration of Group 3 or smaller UAS systems on select USN and USCG ships and to identify and analyze critical constraints on maritime UAS operations. The current state of the USN and USCG surface fleets is such that the only vessels with organic aircraft capabilities (rotary or fixed wings) are those that have SWAP-C (Space, Weight, Power, and Cooling) to support a helicopter squadron, fixed-wing air wing, or a combination of the two.

1. Current State of USN

The only USN Battle Force ships that have organic aviation capability are the following: Nuclear Carriers (CVNs), Guided Missile Cruisers (CGs), Flight IIA Guided Missile Destroyers (DDG FLT IIAs), Freedom-Class Littoral Combat Ships (LCS-1s), Independence Class Littoral Combat Ships (LCS-2s), and L-Class Amphibious vessels. Each of these ship classes is equipped with a flight deck, aircraft handling equipment—including elevators and catapult systems on CVNs—aircraft hangar(s), and the requisite crew berthing space to house the maintainers, operators, and pilots of the squadron's aircraft. Each of these components is critical to achieving organic aircraft capability on an afloat platform.

Two noticeable exceptions to the list of USN surface vessels with organic aircraft capabilities are the initial two variants of the Arleigh Burke Guided Missile Destroyers (DDG Flt. Is and IIs). These vessels are equipped with a flight deck capable of landing helicopters, but they lack remaining critical components for housing, transferring, and maintaining organic aircraft. DDG Flight Is and IIs are capable of supporting helicopter flight operations that are limited to personnel transfer, helicopter refueling, and vertical replenishment (VERTREP).

Elevated sensors, whether they are rotary-wing, fixed-wing, or satellites, are vital components for successfully operating across the Competition Continuum as defined by the Joint Concept for Integrated Campaigning [4]. This continuum is a model designed to cover the spectrum of military operations starting with cooperation, progressing to competition below armed conflict, and ending at the end of the spectrum with armed conflict. Whether an aircraft is aiding the ship in establishing Maritime Domain Awareness (MDA) in peacetime or assisting in closing a kill chain in conflict, operating at sea without some type of organic air capability puts surface vessels at a disadvantage, both in lethality and survivability.

2. Current State of USCG

Organic aircraft capability is equally as important for USCG surface vessels as it is for USN vessels. While their missions may diverge in times of conflict, USN and USCG routinely conduct similar mission sets. Larger USCG vessels such as the National Security Cutters, High Endurance Cutters, Medium Endurance Cutters, Healy Class Icebreakers, and Polar Class Icebreakers all have organic aircraft capability. They have each of the requisite critical components necessary for conducting sustained, organic aircraft operations at sea.

Two USCG vessel classes where the integration of UAS may be of significant benefit are: the future Heritage-class Offshore Patrol Cutter (OPC) and the Sentinel class Fast Response Cutters (WPCs). The Heritage-Class OPCs are the highest investment priority for the USCG [4]. As of 01 December 2022, there are four OPCs under construction [5]. These vessels are intended to replace the Alex Haley Class Medium

Endurance Cutter (WMEC) and the Famous Class WMEC [6]. Each of these two classes have organic aircraft capability as well as the requisite critical systems and personnel requirements discussed previously. While ships without organic aircraft capability stand to benefit the most from their integration onboard, augmenting manned aircraft with UAS is a viable option being explored by numerous militaries around the globe [7]. As such, organic aircraft capability afloat should not preclude a vessel from UAS integration.

The WPC does not possess organic aircraft capabilities as the OPCs do. Additionally, unlike the Flights I and II DDGs that the USN currently operates, the WPCs do not have a flight deck of any kind. Although the Sentinel-Class cutters are at an operational disadvantage compared to the aircraft-capable-counterparts, they still conduct all the operational missions the OPCs and WMECs are responsible for including: ISR, SAR, national defense operations, and law enforcement operations [6]. The addition of UAS would ostensibly provide these vessels with the airborne ISR and SAR capabilities that their counterparts possess. Investigating the differences in operating with versus without a UAS asset is a foundational principle of this study.

3. Literature Context for Study

There is a large body of work that is relevant the topics that this study explores. Chapter II includes a discussion on the current state of the literature as it pertains to operationalizing UAS for roles such as ISR, SAR, and logistics. This discussion includes journal articles, conference papers, and reports which examine UAS in the context of these mission areas on a case-by-case basis; but there is little work that explores establishing a CONOPS (Concept of Operations), system architecture or framework that could fulfill multiple roles and missions of interest to the USN and USCG. This lack of research is especially true when transposed to the maritime domain. The vast body of work exploring the use of UAS for search and rescue is almost exclusively devoted to SAR operations conducted over land. The operating environment for maritime operations is harsher, and the areas to be searched are larger; however, conducting the search is much simpler. The same holds true for a preponderance of the unmanned logistics studies and papers.

Research is typically focused on delivering packages in an urban environment while using the logistics infrastructure of a multinational firm.

There are lessons that can be gleaned from the previous work that has been conducted, but the problem space that this study explores appears to be novel. The MUM-T (Manned-Unmanned Teaming) concept that is explored in two of the pieces of literature could prove to be directly applicable to covering large search areas in a smaller amount of time. While airborne MUM-T is out outside of the scope of this study, the concept is worth of exploring in future analysis. The MUM-T concept does not, however, provide an alternative to manned helicopters as is discussed in the initial project submitted by the stakeholders. Exploring the potential for taking the MUM-T concept and applying it to a CONOPS that may be used with or without an airborne helicopter has interesting potential for this study. In summary, this study examines a problem space that has novel applications for the USCG and USN. Analysis of relevant UAS parameters and CONOPS broadens the body of work exploring novel applications of UAS particularly in the Maritime Domain.

D. CONCEPTS OF OPERATIONS

This study focuses on incorporating Groups 1, 2, and 3 UAS on surface vessels with a wide array of capabilities and limitations. As previously stated, while vessels with and without organic aircraft capability may benefit form UAS integration, the primary benefactor of UAS integration are those ships that do not possess organic aircraft capability. This means that while they may possess one or two of the critical components necessary for airborne operations at sea, they do not possess all of them. As a result, the majority of vessels in this CONOPS are missing one or all the following aspects: flight deck, aircraft handling equipment, hangar, and SWAP-C for aircraft maintenance and crew habitability. These vessels include DDG Flight Is and IIs for the USN, and USCG OPCs and WPCs. There are a variety of vignettes this study utilizes to illustrate the various ways in which these potential CONOPS may be employed to meet the mission needs of the USN and USCG.

1. Intelligence Surveillance and Reconnaissance/Search and Rescue

UAS may be launched from a vessel at sea that may or may not have a flight deck. This limits the type of UAS that may be used in raw size, storage size, and takeoff and landing capability. Once a UAS is launched from the vessel, operators onboard confirm that the UAS has a positive connection with whatever control interface is applicable to the UAS in use. The next phase in UAS operation varies slightly with the mission it is being employed to accomplish, but in general, the operators stationed onboard the vessel control the UAS to patrol a sector of ocean surrounding the vessel for ISR and SAR operations. When employing the UAS for ISR operations, the UAS can be utilized to patrol an area around the ship that is not adequately covered by surface search radar. While maritime surface search radars allow shipboard operators to maintain situational awareness past the visual horizon, they do not provide a capability for target identification outside of general size, bearing, range, course, and speed. Airborne UAS allow shipboard operators to identify, classify, and track targets over the horizon (OTH) when otherwise they would be unable to. This allows the vessel to maintain a standoff distance from the target of interest (TOI). Shipboard UAS controllers are able vector the UAS to a TOI and use the onboard sensor suite, generally consisting of an electro-optical/infrared (EO/IR) sensor, camera, or both, to identify the TOI and relay the information to the ship. This delivers robust maritime surveillance capability to vessels steaming alone—capabilities that are generally reserved for ships with organic aircraft capability, or ships sailing in the vicinity of other vessels or land bases with aviation capabilities.

Utilizing UAS for SAR missions is similar in form to ISR missions. Much like ISR missions, there are different types of SAR missions. There could be a scenario where SAR units are given a last known position that must be searched, a scenario where UAS supporting the SAR mission are given an area of ocean to search, and UAS could also be vectored to radar contacts to confirm their identity and classification. While the end results of successfully completing the SAR mission are different from a successfully completed ISR mission, the methods by which the searching units execute said mission are extremely similar.

2. Logistics

This study also explores the potential benefits of employing UAS in a maritime logistics role. According to USNI, "most ships and aircraft taken out of mission-capable status while deployed, lack simple components like wires or electronic assemblies, 90% of which weigh less than 50 pounds" [8]. While a 50-pound payload capacity is well outside the lifting capability of most UAS today, this statistic illustrates the profound impact that UAS could have on parts resupply.

There is a significant number of mission-critical parts keeping a ship from being fully mission capable that could be delivered faster, more efficiently, and more effectively by UAS than having to pull into port or conduct a replenishment at sea. UAS could potentially make an outsized impact in the efficiency of logistics operations at sea as well introducing potential cost savings while increasing operational availability of deployed surface forces. The previous examples where the UAS are searching for an unlocated target or are sortied to search a given area of ocean, the maritime logistics scenario typically consists of launching a UAS and vectoring it to another unit either delivering part to or picking up apart from another unit either at sea or ashore.

There are two main differences between the maritime logistics scenario and the ISR/SAR scenarios. The first difference is the payload being carried by the UAS: rather than a robust sensor suite being carried by the UAS, the payload is a parcel for delivery either to or from a unit at sea. The second difference is the flight path of the UAS. The SAR/ISR missions could potentially cover an unknown range, in which case the mission length is a function of the fuel source of the UAS. The time that the UAS has to search is directly related to the battery life or fuel onboard. Generally speaking, before the UAS takes off from the ship for a logistics mission, the operators will know the start point, the endpoint, and the range that the UAS will need to cover to complete the mission. Therefore, successful mission completion criteria are determined by the payload lifting capabilities of the UAS, as well as the operational energy life of the UAS—be it fuel or battery power. It is possible to know whether a given type of UAS is capable of completing a particular mission before launching the UAS. This has implications for mission planning as well as for UAS selection, which is discussed in Section D.1 of this chapter and in Chapter III.

There exist multiple variations of the logistics mission for UAS attached to a ship at sea, but they can be generalized to the following scenario: a UAS is launched either from "own-ship" or a supply ship and proceed to travel to a supported or supporting ship for parts pickup or delivery. The same principals and standard operating procedures that apply to supply ships at sea may be applied to shore-based facilities for the purposes of modelling potential benefits derived from integrating UAS into the logistics mission. This modelling effort is discussed further in Chapter IV.

E. STUDY ORGANIZATION

1. Drone Selector Tool

This study collects and analyzes data on UAS, paired with a variety of surface vessels, to accomplish a given mission set as discussed in the previous sections. The result of this analysis is that of a Microsoft Excel-based mix-and-match drone selector tool. This tool is designed to ingest the type of ship conducting an operation, the available types of UAS, and the mission parameters that must be accomplished, in order to recommend specific UAS and ship pairs that provide increased mission capability. Each UAS has different performance specifications and capabilities which make certain UAS better suited than others for specific mission-ship pairing sets. Tables 2 and 3 show the various metrics and parameters that are considered to conduct the UAS-selection analysis as well as the motivation for using a given metric. Chapter III provides a comprehensive discussion of the Drone Selector Tool, the ways it may be implemented, and the methodology used to calculate the drone-ship-mission pairing rank.

Table 2. UAS Parameters for Drone Selector Tool

Characteristic	Reasoning
Operational Range	Determines if UAS can meet range requirements for mission
Speed	Determines how quickly the UAS is able to arrive at its area of operation/make a logistics delivery
Loiter Time	Determines the amount of time UAS can remain on station, search pattern/size determination
Sensor Type	Determines what type of sensors are standard on the UAS to facilitate operation in certain environments, such as infrared for nighttime operations
Sensor Quality	Determines how well the UAS is able to see/identify targets of interest and the clarity of that intelligence
Payload Capacity	Determines the ability of the UAS to conduct logistics delivery missions
Payload Swappable	Determines if the UAS is capable of utilizing alternate sensors to operate in a wider range of environments, such as at night
Storage Size	Determines if the UAS is too large to be stored aboard a particular vessel
Take-Off Method	Constraint for ship class requirement, i.e., a UAS requiring a runway cannot be launched from a vessel without a runway
Fuel Type	Determines ship compatibility, i.e., whether the ship is allowed to carry/store its fuel type whether gasoline or batteries

Table 3. Ship Parameters for Drone Selector Tool

Characteristic	Reasoning
Fuel type allowed	Determines what types of UAS may be operated aboard the ship, i.e., gasoline or battery storage allowed
Ship storage capacity	Determines if there is enough free space to store the UAS aboard the vessel
Runway length	Determines what types of UAS may be launched by the ship, i.e., those without runways cannot operate UAS that require them to launch
Launch area	Determines if there is enough free space aboard the vessel to launch a UAS, i.e., large UAS cannot be launched by a vessel without sufficient space to do so

2. Models

This study also utilizes the collected data to generate a series of models that detail the impacts of UAS inclusion in ISR, SAR, and logistics missions. These models are designed within the modeling software ExtendSim to generate results with base-case scenarios—that is, scenarios where the ship operates normally without a UAS—as well as scenarios with UAS inclusion. With these two sets of results, their differences are examined to identify the impact that UAS have on these missions and scenarios. The goal of these modeling efforts is to define these impacts as they pertain to the ship's ability to complete a certain mission set. These models, their key metrics, and the resulting impacts are presented in Chapter IV.

3. Study Limitations

There are currently limited requirements for small UAS to be operated onboard USN and USCG vessels. The UAS program for the USCG has focused on acquiring UAS capability onboard National Security Cutters (NSC). According to the USCG UAS program fact sheet, the USCG is operating eight NSCs with UAS onboard [9]. The USN, much like the USCG currently has limited UAS program footprint. The USN operates the MQ-8B and MQ-8C Fire Scout systems. Independence Class and Freedom Class LCSs are currently the only two USN battle force ships with requirements to operate a UAS as a part of regular shipboard operations [10]. However, the Navy has indicated that it will expand the MQ-8 System program to include the capability on the upcoming FFG-62 Class vessel; signaling their intent to integrate UAS on future platforms [11]. Integrating Groups 1–3 UAS USCG and USN ships will be an effort that must start from the ground up. The two services do not currently have a Program of Record for integrating UAS onboard on a diverse set of ships. Therefore, there are substantial costs associated with starting the effort along with robust training, test, and evaluation, and modeling efforts that must take place before surface ships are routinely operating at sea with UAS adding to their suite of capabilities.

This study is informed by the effort currently underway to incorporate Textron's Aersonde UAS onboard USN DDG Flight Is and IIs in the Seventh fleet area of operations (AOR) as well as U.S. 5th Fleet's Task Force 59. The latter being a manned-unmanned task force designed to test an experiment on emerging Unmanned and Artificial Intelligence technologies [12]. The details of the experiment are limited at the Unclassified level, but the USN successfully launching, recovering, and operating a Group 3 UAS from a DDG without organic aircraft support is a critical proof of concept that lays the groundwork for future efforts.

This study is a step towards analyzing performance and CONOPS for operating UAS on a variety of USCG and USN ships. With the development of multiple CONOPS for various missions, the construction of a diverse set of vignettes, and a mix-and-match drone selector tool, this study aims to provide the USCG and USN with concrete documentation that UAS have a place in the surface fleet. Though this effort is a step in the right direction, substantial modeling, testing, evaluation, and experimentation is critical to the successful integration of UAS in the surface fleet over the long run.

A significant constraint that currently exists on ships realizing the full potential of UAS integration are operational and policy requirements for maintaining "due regard to the safety and regularity of all other aircraft" [13]. Solving the "Due Regard" problem for operating UAS on surface ships is a subject of much concern—i.e., determining what capabilities must the UAS or the ship possess so that this requirement is sufficiently met.

This study briefly addresses due regard in Chapter II. It presents the current state of due regard policy in the U.S. DOD, and operating constraints presented by maintaining due regard. This study does not seek to answer the question of due regard for UAS on surface ships. However, the limitations presented by the current due regard policy is addressed, and assumptions implemented to develop a feasible CONOPS that addresses the current state of policy.

4. Chapter Outline

This study is divided into three phases in order to systematically address the problem posed by the USCG and USN. Phase One consists of data collection, Phase Two: Analysis, and Phase Three: Refinement and recommendations.

a. Data Collection

Phase One is guided by the following questions:

- What does the literature say about integrating UAS systems onboard ships?
- What do the USN and USCG documentation say about requirements and plans for integrating UAS on ships?
- What UAS systems can be launched from each vessel being examined?
- What missions can UAS platforms contribute to aboard USN and USCG ships?

Data is utilized from both independent research as well as the knowledge-base of this study's stakeholders. The data collected independently is integrated with the data provided by the stakeholders to address the key questions outlined above.

The data collection process and implications of said data are discussed in Chapter II. The data ranges from the operational parameters of ships and UAS to the programmatic state of UAS in the USCG and USN. Current policy with respect to Due Regard and its implications on the project are also be discussed in Chapter II.

b. Analysis

Phase Two seeks to answer the following questions:

- What roles may UAS systems realistically perform that manned aircraft currently assume?
- What UAS assets could be assigned to USN and USCG ships to replace manned aircraft?
- What future CONOPS and be identified and developed for UAS systems onboard ships?

Chapter III takes the data that was collected in Phase One of the project and discussed in Chapter II and apply it to a feasible concept of operations for surface ships. Chapter III develops UAS requirements for shipboard use and illustrates what parameters of UAS and ships are relevant to integration while highlighting which UAS are likely to provide the most value. The implications of the requirements and CONOPS used in the Drone Selector tool be used to inform scenario and vignette modeling. The modeling, analysis, and results from are discussed in Chapter IV.

c. Refinement and Recommendations

Phase Three seeks to answer the following questions:

- What gaps exist in meeting future requirements?
- What is the return on investment for integrating UAS into the fleet?
- What policy Changes would enable integrating UAS into the fleet?

These questions, the Cost/Benefit Analysis, and business case analysis are discussed in Chapter IV. Chapter V takes the holistic methodology employed throughout the study in order to make recommendations for the USCG and USN and suggestions for follow-on work.

II. UAS AND SHIPS

A. INTRODUCTION

Presented in this chapter are the current literature for afloat UAS operations, a brief summary of Due Regard, the general capabilities and requirements for the Group 1–3 UAS alternatives and introduce the requirements imposed by the USN and USCG stakeholders. Naturally, there are commonalities between various UAS alternatives, but there are also differences in key metrics, for example range and sensor capability. Choosing the correct UAS to fill a certain ship's requirements requires a careful balancing of tradeoffs. To achieve this balance, the stakeholders' hierarchy of requirements is referenced and used to apply weights to UAS metrics as is discussed in Chapter III.

B. LITERATURE REVIEW

UAS have become an ever-present constant in daily life today. They are frequently used for new and novel purposes outside of amateur photography and entertainment. As a result, the body of work in the academic community is constantly expanding as well. The current body of knowledge associated with UAS and their potential benefits are explored both to determine the potential UAS have to solve the stakeholder's problem and as a source of guidance as well. It is clear that although there is a veritable mountain of work exploring UAS and how they may be used, there are not very many published works that examined the problem this study is addressing.

UAS have enormous potential to solve an ever-expanding problem set and use them to augment ISR capabilities at the front of the list along with Combat Search and Rescue (CSAR) [14]. A common theme of UAS research is while UAS have the potential to revolutionize the way in which ship-shore logistics can be accomplished, a significant barrier to accomplishing that goal is current regulation, and the difficulty inherent in solving the problem of due regard as well as sense and avoid [14] [15]. Simply getting a UAS in the air to accomplish a mission is one part of a complicated concept to fully realize the potential they present. UAS have shown promise for land-based Search and Rescue, but a critical point to ensuring the maximum potential is realized, is to ensure that along with pairing the appropriate UAS for the job, the operator also pairs the appropriate sensor for the job [16]. Picking the right platform and sensor for the mission is the first of many steps and developing a methodology for analyzing the data provided by the UAS is also critical [16]. The potential benefits cannot be realized without ensuring the operators' ability to recognize target inputs in the environment [17]. When using a UAS in tandem with a manned aircraft, the potential benefits are compounded, but there is a delicate balance that must be struck between operating the UAS to increase mission effectiveness and operating the manned aircraft themselves [18].

Concluding our review, while there is a large amount of work exploring the uses of UAS, there is a conspicuously small amount of work analyzing integrating UAS on surface ships to help ships accomplish their missions. There as been research looking at using UAS to solve the problems associated with traditional Search and Rescue missions as well as looking at using UAS to supplement logistics challenges [15]. However, relevant literature analyzing the potential for UAS to fulfill a multi-mission role in general could not be located, much less in the maritime environment while onboard a ship. Regardless of the lack of literature pertaining conducting SAR at sea with UAS, the math behind water-borne search and rescue is vast. This literature discusses different types of man overboard searches a ship can do, how to optimize the search for a man overboard, and also provides a mathematical framework for determining the likelihood of recovering a man overboard given a list inputs [19]. The lack of publicly available literature presents the team with an excellent opportunity to not only analyze potential means of making our country's maritime forces more efficient, but it provides an opportunity to expand the body of work concerned with operationalizing UAS in the maritime domain.

As stated previously, the duties and obligations of all pilots and aircraft under international law and regulations present a difficult problem to solve when conducing UAS operations. The United Nations Convention on the Law of the Sea (UNCLOS) provides a framework for delineating where a nation's territorial seas end, and international waters begin. Much like on the surface of the ocean, the skies have the same type of demarcation. According to UNCLOS: "Every State has the right to establish the breadth of its territorial sea up to a limit not exceeding 12 nautical miles, measured from baselines determined in accordance with this Convention" [20]. The same can be said of a country's national airspace. The Convention on International Civil Aviation Articles 1 and 2 state that the airspace above a nations territory and territorial seas are that nation's territorial airspace [21]. Outside of a nation's territorial airspace is international airspace. The duties and responsibilities of aircraft in international airspace are government by the ICAO procedures. Due to the nature of military and law enforcement operations, the majority of maritime operations are conducted in international waters/airspace which are governed by UNCLOS/ICAO.

Due to the nature of military operations, DOD 4540.01 – *Use of International Airspace by U.S. Military Aircraft and Projectile Firings* discusses flight operations which are not covered by ICAO procedures. DOD 4540.01 states:

> Military aircraft operations in international airspace, through straits used for international navigation, and through the air routes over the archipelagic waters of other States, may not lend themselves to ICAO flight procedures. This may include, but is not limited to, military contingencies, classified missions, politically sensitive missions, routine aircraft carrier operations, and some training activities. [13]

Such operations which are not conducted under ICAO procedures must be conducted with "Due regard for the safety of all other aircraft" [13]. DOD 4540.01 then proceeds to outline a number of conditions, of which, if any one is met, the aircraft can be said to be flying with "due regard for the safety of all other aircraft." These conditions are as follows:

- Aircraft must be operated in visual meteorological conditions. For unmanned aircraft, the aircraft commander, or a visual observer in communication with the aircraft commander must also maintain continuous and direct line-of-sight visual observation of the unmanned aircraft's surrounding airspace.

- Aircraft may temporarily be operated in less than visual meteorological conditions when required by operational needs if the aircraft commander determines that there is acceptable risk to other aircraft.

- Aircraft must be operated under continuous surveillance by, and in communication with, a surface or airborne facility providing the surveillance. Certain aircraft, typically due to small size, shape, or material composition, may not be detected by surveillance. This condition may be satisfied if the facility providing surveillance can ascertain the position of the aircraft and has the capability to maintain continuous surveillance of the surrounding airspace while in communication with the aircraft commander.

- Unmanned aircraft must be equipped with a Military Department-certified system that is sufficient to provide separation between them and other aircraft.

It becomes apparent that operating unmanned aircraft in accordance with the prescribed duties and responsibilities introduces operational limitations outside those which are typically thought of for aircraft. Generally, the range an aircraft can fly is determined by its fuel efficiency and fuel load. However, in the case of unmanned systems, the range a UAS can fly is determined by how far the controlling platform can adequately surveil the UAS and its airspace, or how capable the UAS onboard detect-and-avoid capabilities are. There are numerous tactical and operational constraints that are introduced to UAS operations as a result of these requirements per international law. The analysis of these constraints, the optimization of operating UAS under the regulations, and the risk associated with deviating from accepted procedures are outside the scope of this paper. However, UAS will be able to fully realize their operational potential until the 'Due Regard' question is answered. As such, the tactical and operational implications and how to minimize their impacts, is ground for future work.

C. UAS CAPABILITIES

The pool of available (meaning: DOD-allowed, not discontinued, and commercially available) commercial off-the-shelf (COTS) UAS can be described via their specifications and features. These capabilities and specifications are acquired via the various companies' websites and publicly available documentation. All specifications for these COTS UAS used within this study are cited as references [22] through [35]. With these specifications, a baseline can be derived that indicates lowest performance that can be expected from any of the options. In essence, this baseline defines the least desirable factors from the collected information between all the alternatives—the highest weight, the lowest resolution camera, the least sensitive infrared, etc. For those metrics that are not proprietary such as operating frequency and those that are reported and available via the companies' catalogs, this baseline is defined in Table 4.

Table 4. UAS Baseline Capabilities

Metric	Lowest Expected Value
Max Speed	22.3 mph
Weight	56 lbs
Max Altitude	10,000 ft.
Loiter Time (mission endurance)	27 minutes
Controller Range	2.15 nautical miles
Video Resolution	1080p
Photo Resolution	8 MP
Infrared	Not Equipped

With this baseline, it is possible to gauge and model the performance of any UAS in their projected environments and missions. For the hypothetical UAS with metrics depicted in the table, for instance, given its lack of infrared sighting, it is evident that it is suitable for shorter-range, up-close ISR during daylight hours. However, it is important to note that while this hypothetical UAS indicates a limited mission-space, it is an amalgam of several UAS, and where each individual UAS falls short in one metric, it is often improved upon in another. For example, the UAS whose loiter time is represented as the lowest of the options in the table at 27 minutes, the Skydio X2-D, has a much more capable camera suite capable of 4K video resolution, 16x zoom, and is optionally equipped with infrared sighting. Therefore, it is not sufficient to state that any given UAS is not a suitable solution based on a single metric—each of its metrics must be accounted for and appropriately weighed. Thus, it is evident that a careful balance must be struck between the alternatives and the scope of requirements they are meant to meet. The true values per each individual UAS range with high variability throughout the suite of reported metrics. The data collected on these COTS UAS are documented in the tool described in Chapter III and available to sponsors for reference and utilization going forward.

While the ideal UAS would be the combination of each individual UAS' best features, this is not a useful baseline to draw for this analysis. Given that the sponsor requirements introduced in Section B. of this chapter define minimum accepted values for the metrics, understanding and having a fundamental baseline for the minimum-expected values in each of those metrics is useful in analyzing the solution space.

While not reported in Table 4 as they are not capability-related metrics, the UAS' storage and operational sizes are of concern for the sponsors. For the purposes of storage while the UAS is not in use, the desired outcome is minimal size such that functions aboard the vessels are not disrupted by their presence. Nearly all the sources of COTS UAS report the size of the operational UAS, but not of its storage size, folded shape or size, or the size of its storage case (or if it needs a storage case). In cases when storage size is not reported, it is prudent to estimate that the storage size of each UAS is at least the same as its operational configuration if not larger to account for storage cases. For the vessels of interest in this study such as the Coast Guard's Cutter, storage dimensions are of great concern given that there is little space aboard the vessel not already allocated.

For the Group 1–3 UAS data collected, the typical operational size—that is, the size the system is when ready for flight—ranges greatly from 11.1" to 180." However, some of those found at the higher end of that range are foldable such that they are more compact when not in use, but do not report the effective dimensions when in the folded configuration. In situations such as this, the UAS' storage size is considered to be that of its operational size.

The concept of "loiter time" or "mission endurance" as it is referred to in Table 4 relates directly to the UAS' battery capacity and battery life, or gas storage, and fuel efficiency. These are values reported from the UAS manufacturers which significantly impact the system's ability to operate for relevant lengths of time. Loiter time or mission endurance is of greater value than simply that of each of the constituent values individually in that it directly implies the mission time of the system per operational use to include take off, maneuvering, utilizing sighting capabilities, and static hovering. Though it is out of the scope of this study to acquire and directly test each UAS alternative, it is assumed that this loiter time can be impacted and hindered in extreme use cases. For instance, prolonged maneuvering at maximum speed, using the UAS at sub-100% battery levels, or even in inclement weather where minute attitude corrections may be required. However, for the purposes of modeling these UAS' behavior, the loiter times reported operate as the functional value in any calculation where such a metric is required.

While there is no direct requirement imposed by the sponsors as to the minimum acceptable value for maximum speed of a given UAS, it is an important metric to note given that speed and loiter time culminate in an effective operational range for the UAS. This is not to be confused with the UAS' inherent range as a function of its ability to communicate with the controller; instead, it is a dynamic range that defines the nonlinear distance the UAS may travel before needing to be recovered due to a lack of battery or gas. As an example, for the hypothetical baseline UAS described in Table 2, the value of 22.3 miles-per-hour for maximum speed and a loiter time of 27 minutes imply that a mission requiring no more than 10.04 miles of total travel could be conducted. Ignoring the controller transmission range of only 0.54 nautical miles (0.62 standard miles), this would indicate that a straight-line distance of 5.02 miles could be covered before immediately returning to the vessel for recovery. This calculation is important to conduct for each UAS as their values can range appreciably. As stated above, where one UAS may have a short loiter time, it may have a greater top speed allowing for greater total distance coverage throughout the mission. As an example, the UAS whose loiter time is reported in the baseline as 27 minutes, the Skydio X2-D, also has a far greater maximum speed at 36 miles per hour resulting in a total potential distance coverage of 16.2 miles, again ignoring controller ranges and loiter time inconsistencies.

Related to total nonlinear range coverage discussed above, the range of the various UAS play an important role in the selection of the operational system. For each individual UAS and their reported ranges, a sphere of operation can be drawn around the controlling vessel that more directly imposes limits on missions. The maximum range that is reported in the baseline—as reported from the Vantage Robotics Vesper—2.15 nautical miles (2.47 standard miles) naturally limits the straight-line range of operations whereas the theoretical range is a far exceeding 18.75 miles (37.5 divided by two to account for return) when derived from the loiter time and max speed. This sphere of operations is ceilinged by each UAS' maximum altitude, of course.

The requirements to maintain, operate, and repair the various UAS are likely minimal in comparison to larger crafts from which they may assume some functions. Given the size disparities, maintenance in particular is likely to be much lower. Group 1–3 UAS are small crafts that are generally designed to be modular enough to facilitate simple replacement of parts as well as minimal scheduled maintenance. For instance, as listed by several UAS user manuals, the general requirements for appropriate maintenance are to periodically grease moving parts such as propellers, lightly tighten screws or otherwise ensure the integrity of connectors, and to verify the proper operation of the system's components. For a craft of this size, these maintenance requirements can be conducted regularly and promptly with little impact on other shipboard actions. For fuel considerations, again many of the surveyed UAS are battery-powered, the lifetime of which while in use varies with each UAS alternative as discussed above. However, the cost and operation requirements of these smaller crafts whether battery-powered or gas-powered versus that of a larger craft's gasoline-power are minimal in comparison. This limited maintenance burden compounded with their deployability makes UAS suitable replacements for certain missions. Calculations for cost per use and the benefits of these differences are discussed in Chapter IV of this paper.

The operation requirements of a UAS are inherently different than that of their larger, manned counterparts. Notably, these craft operate without a human presence onboard; this in and of itself is a considerable benefit. For instance, the operation of the craft in unstable, dangerous, or otherwise non-optimal environments entirely removes the risk to human life in these conditions. For those missions where direct human presence is not explicitly required such as simple ISR and environment awareness, the removal of the risk to safety is a massive benefit.

All the above culminates in the need to appropriately balance these metrics in accordance with both the sponsors' requirements and the needs of the vessel to which they will be integrated. To do so, as is discussed further in Chapter III, from the available reported metrics from each manufacturer additional implied metrics have been derived as has been done briefly in this chapter. These extended capabilities and limitations are utilized in the proceeding analyses and the Drone Selector Tool. The Drone Selector Tool serve as a decision-making aid for end-users interested in incorporating UAS onto their ship. Utilizing the Parnell swing weight methodology, it compares each UAS against each other one and mission type/goals to weigh each alternative. This tool is further discussed in Chapter III of this paper.

D. UAS REQUIREMENTS

For a UAS to be integrated with an existing USN or USCG vessel, it must pose as little impact to its normal operations as possible. Stated clearly, the chosen UAS must be capable of performing its mission without hindering the ship or crew's other duties. To accomplish this, basic requirements for these UAS have been defined regarding the operations, missions, and policy adherence that an alternative must meet in order to be selected for operational use. In this section, these requirements are introduced and decomposed into fundamental constraints that each of the COTS UAS are subject to. In general, these requirements are as follows:

- Must be capable of organic (inherent to the system) ISR, SAR, or logistics
- Must be easily launched
- Must be easily recovered post-mission
- Must be capable of extended range of operation
- Must be a Group 1, 2, or 3 UAS
- Must have a suitably small footprint
- Must be commercial-off-the-shelf (COTS)

For each of these requirements, there exists some ambiguity. For example, while the UAS must have inherent ISR capability, no direct requirement has been established on what form that should take. ISR at its core is the ability for a system to perform surveillance on a given target and report the information captured to the controlling entity. Such a capability is already accomplished in several ways aboard ships and in other military environments including radar, live-sighting and radio communication from a pilot in a helicopter, onboard cameras and video-recorders capable of long-range zoom, etc. However, UAS are typically outfitted with cameras and video-recording capability in either the visible spectrum or in infrared. Some UAS in groups 4 or 5 that are outside the scope of the requirements are outfitted with radar capabilities, sonar, or other means of information capture and transmittal. Therefore, for the purposes of this study, the domain of ISR solutions inherent to a given UAS are constrained to visible spectrum or infrared cameras and/or video recording given that the UAS must be a COTS solution and not purpose-made or otherwise contracted and manufactured in accordance with provided requirements.

For the launch requirement, the UAS must be capable of launching from within a constrained environment. The specific ship-based constraints that warrant this requirement are discussed in the following section. However, this requirement implies that the UAS must be launchable in a manner that does not require large equipment or environments such as a runway, and instead can launch from standstill, by being thrown by the operator, or via a launch mechanism. Many of these small (Group 1–3) UAS are rotary wing and can be launched from ground rest with the activation of their propellers; this is known as vertical takeoff and landing (VTOL). A typical method of launch that is employed by similarly grouped but plane-style UAS is the bungee-launch where the craft is affixed to a small and maneuverable mechanism that slings it into flight from a supported ground position. The latter method may still require more allocated space than some vessels are equipped to accommodate but may be suitable for larger ships with more deck-space.

The nature of a UAS solution’s launch is tied to the method by which it is retrieved post-mission. In general, a copter-style UAS that can perform VTOL takeoff is also capable of steady vertical landings within a specified area. This is a preferred solution to the recovery requirement as it does not require specialized equipment or action by operators further than the landing itself at a convenient location. For those UAS whose launches are facilitated by a mechanism, recovery becomes more of a concern as they are generally incapable of VTOL and require a lengthy area in which to land. A UAS example where this can be somewhat easily accommodated is the AeroVironment Puma LE that has skids affixed to the bottom beneath the main body such that water-landings are possible. Given that the primary CONOPS for the UAS will be heavily sea-based, this may be a preferable solution if the UAS is not capable of VTOL as landing can be coordinated in proximity to the ship. Other systems that cannot perform either VTOL or skid-landing in water remain as candidates. However, these systems will be recommended only for ships that can support their method of landing.

The next requirement, extended range capabilities, stems from the stakeholders' desire to perform ISR around the ship's location and to detect and track targets that are not visible from deck-height. The visible horizon for a ship changes dependent upon a few factors including deck height, air quality, fog and/or haze, weather, sea-based turbulence, and waves, and many more [36]. However, the models that have been created to analyze UAS use aboard these vessels assume optimal weather and sea-state conditions. The manufacturers do not list capability degradation due to these conditions—therefore the inclusion of these factors into this study would first require extensive hands-on testing with the UAS alternatives in these conditions. These hands-on live tests are outside of the scope of this study but are recommended endeavors for future studies to undertake.

However, as briefly discussed in the previous chapter, each UAS is subject to both a theoretical maximum range as well as a "hard" maximum range by virtue of their ability to communicate with the controller. This theoretical maximum range is often greater than the controller range, thus why the controller range is deemed the "hard" constraint. For the UAS sampled, the greatest available maximum range is 33 nautical miles (~38 standard miles). This hard constraint that each UAS is subject to is difficult at best to mitigate given that it is inherent to the system; perhaps the only valuable method for "extending" this maximum controller range is to navigate the vessel in the direction of the UAS' flight so that the UAS is technically able to fly further in a given direction than if the ship had remained stationary at the point of the flight's origin. This method does not allow the ship to see farther in front of itself than it would otherwise, and it also forces the ship to travel in the direction of the target area. However, this tactic is useful to note in select scenarios where it is beneficial by the nature of the mission such as when the vessel is in pursuit of a target that is barely visible or not visible to the naked eye in the distance.

The next two requirements are related in that they share common a common goal: the UAS must not interfere with other operations aboard the ship when not in use. The requirement that calls for a "suitably small footprint" stems from the fact that many of the vessels that the UAS will be integrated into do not have a large amount of space to dedicate to the storage or operation of the system. Therefore, the chosen system for these vessels must be able to be stored in a compact location, be launchable without a large runway or large mechanisms, and must be operable with minimal extra equipment and manpower. From these combined needs stems the requirement for the UAS to be within the Group 1, 2, or 3 families of crafts since weight (thus effective size) is a key factor that determine the system's Group designation.

The preceding is not the only reason the UAS must be within the Group 1–3 designation. In 2018, the Secretary of Defense issued a memorandum that defined the guidance for the domestic use of UAS in United States airspace. In this memorandum, authority was given to each military branch's secretary to authorize the use of these smaller UAS systems without further approval or authorizations required at a higher level [37]. Therefore, the approval, procurement, and operation of these small, unmanned crafts are left to the entities that wish to utilize them. Adherence to this policy and the ease of the adjudication of the use of UAS is the main cause for this study to impose this requirement.

The final requirement as listed is the need for the UAS to be a commercial off-the-shelf (COTS) product. This requirement stems from the need to adhere to the limited budget that is currently available for such ventures. The resources required to design and contract the construction of a purpose-built UAS are currently beyond what is deemed appropriate to dedicate to this endeavor. Regardless, the capabilities of these COTS UAS are sufficient to fulfill the current needs of their projected mission-space, which this study intends to demonstrate. However, should further funding be provided in the future so that these resources are available, the ideal UAS could be constructed that improves upon those capabilities to such a degree that additional missions become possible for these UAS to perform. These projected additional missions and the capability requirements and improvements that facilitate them are discussed in Chapter IV of this paper.

E. SHIPS AND SHIP-BASED CONSTRAINTS

This study will look at a broad array of surface ships from the USCG and USN. The data used in the mix-and-match drone selector tool are generic representations of what may be entered if the appropriate data is available to those conducting the analysis. The data that is available for analysis is incomplete in its current form and would greatly benefit from data and measurements sourced from afloat vessels. Due to the classification of this paper as well as data availability limitations, the drone selector tool has been built with a combination of 'best guess' representative data and class-specific standard data. If an office or service wishes to use the excel tool with the relevant data, it would merely be a matter of retrieving the data and adding it the corresponding fields within the tool. The quality of analysis and fidelity of results of the drone selector tool should dramatically improve with a corresponding increase in data quality. The foundation of the data that is used in this paper is open-source ship data sourced mainly from Janes' Fighting Ships online repository [38]. The open-source nature of the data has the potential to lead to approximations and assumptions which may not be true to form depending on the platforms being analyzed. There are specific metrics that will change dramatically from ship class to ship class, and some which may change even within ship classes. Among these metrics are: interior storage space, storage space layout, sensor capabilities, as well as UAS-specific data. A key component of ship compatibility with specific UAS airframes is the ship's ability to appropriately store the UAS, GCS, and additional supporting equipment. A key metric for determining ship-UAS compatibility is the interior storage space capacity and layout. This data, while difficult to acquire remotely, should be trivial to acquire and implement if the tool is used for fleet-use.

The vessels that are listed in Tables 5–15 are chosen to be inputs for the drone selector tool due to their lack of organic aircraft capability, their diversity of configurations, because they represent a broad swath of vessel types, or a combination of all three. Although they will serve as inputs into the tool to demonstrate its capacity for mixing and matching ship inputs and UAS parameters, the representative nature of the data will limit the selector tools fidelity as well as demonstrating its functionality. The quality of analysis will improve with the data used to populate it.

Two representative vessels that meet the criteria listed above for the USN Battle Force Ships are the Flights I and II Arleigh Burke Class Guided missile destroyers. They are multi-mission capable, gas turbine powered, guided missile destroyers with a flight deck for helicopter flight operations as well as a plethora of weapons systems. These vessels' capabilities are discussed in the following sections. The two representative USCG vessels which may be used for the further analysis are fundamentally different from their USN counterparts, not only in their mission sets, authorities, and design parameters but in their physical configurations as well. There are two vessels that both fit the criteria above in addition to being identified for further analysis by USCG stakeholders: the Sentinel-Class Fast Response Cutter and the future, and Heritage-Class Offshore-Patrol Cutter. The former is distinct from the rest of the vessels in the CONOPS baselines due to the lack of a flight deck for helicopter flight operations. The Heritage-Class OPC is a future class of ship for the USCG that is currently under production [39]. They will be the fleet replacement for the Coast Guards' current Medium-Endurance Cutters of the Alex Haley and Famous Classes. The USCG ships are discussed in the following sections.

1. Vessel Inputs for the Drone Selector Tool

The following section will serve as a representative list of the types of vessels that may be analyzed with the drone selector tool, assuming availability of appropriate data. The analysis conducted within this paper is not designed to serve as the 'answer' to which UAS to pair with which ship, but rather demonstrate the tool's ability to ingest the relevant data and provide the user with the optimal matches given the specific input parameters.

a. U.S. Navy Ships

Table 5. Arleigh Burke Class DDG Flt. I and II Characteristics

Arleigh Burke Class Guided Missile Destroyer (Flights I and II)	
Length	504.6 ft.
Width	66.6 ft.
Flight Operations Equipment	Flight Deck Only
Speed	30+ Kts
Endurance	4,400 NM at 20 kts
Sensors	SPY-1D Air Search Radar, SPS-67(V)3 Surface Search Radar, Commercial Navigation Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	Air Traffic Controllers, Anti-Air Warfare Coordinators

Table 6. Independence Class LCS Characteristics

Independence Class Littoral Combat Ship	
Length	421.6 ft.
Width	31.6 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar
Speed	40+ Kts
Endurance	3,500 NM at 14 kts
Sensors	SPS-77 Air Search Radar, Sperry Bridgemaster Surface Search Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers, Anti-Air Warfare Coordinators

Table 7. John Lewis Class T-AO Characteristics

John Lewis Class Replenishment Oiler	
Length	745.7 ft.
Width	105.6 ft.
Flight Operations Equipment	Flight Deck Only
Speed	20 Kts
Endurance	6,147 NM
Sensors	Commercial Navigation Radar[10]
UAS Capable Crew Type	None

Table 8. Lewis and Clark T-AKE Characteristics

Lewis and Clark Dry Cargo Ship	
Length	689 ft.
Width	105.6 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar
Speed	20 Kts
Endurance	14,000 NM at 20 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

Table 9. Lewis B. Puller Class ESB Characteristics

Lewis B. Puller Expeditionary Transfer Dock	
Length	785.1 ft.
Width	164 ft.
Flight Operations Equipment	Flight Deck and Helicopter Hangar (4)
Speed	15 Kts
Endurance	9,500 NM at 15 kts
Sensors	Sea Giraffe Air/Surface Search Radar[13]
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers, Embarked MQ-8C and Maintainers, Operators, and Pilots

Table 10. Spearhead Class EPF Characteristics

Spearhead-Class Expeditionary Fast Transport Dock	
Length	337.9 ft.
Width	93.5 ft.
Flight Operations Equipment	Flight Deck Only
Speed	43 Kts
Endurance	1,200 NM at 35 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	None

b. U.S. Coast Guard Ships

Table 11. Legend Class NSC Characteristics

Legend-Class National Security Cutter	
Length	418 ft.
Width	54.1 ft.
Flight Operations Equipment	Flight Deck and Hangar
Speed	28 Kts
Endurance	12,000 NM at 9 kts
Sensors	Hensoldt TRS-3D/16 Surface Search Radar, Commercial Navigation Radar, SPQ-9B Surface/Air Search Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

Table 12. Heritage Class OPC Characteristics

Heritage-Class Offshore Patrol Cutter	
Length	360 ft.
Width	54 ft.
Flight Operations Equipment	Flight Deck and Hangar
Speed	22.2 Kts
Endurance	9,500 NM at 14 kts
Sensors	Sea Giraffe Air/Surface Search Radar[17]
UAS Capable Crew Type	Embarked Helicopter Squadron: Maintainers, Operators, Pilots, Air Traffic Controllers

Table 13. Sentinel Class FRC Characteristics

Sentinel-Class Fast Response Cutter	
Length	153.2 ft.
Width	25.3 ft.
Flight Operations Equipment	None
Speed	28 Kts
Endurance	2,590 NM at 14 kts[19]
Sensors	Commercial Navigation Radar, EO/IR Sensors (Various)
UAS Capable Crew Type	None

Table 14. Island Class WPB Characteristics

Island-Class Patrol Boat	
Length	110 ft.
Width	21 ft.
Flight Operations Equipment	None
Speed	28-30 kts
Endurance	3,380 NM at 8 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	None

Table 15. Response Board Medium Characteristics

Response Boat-Medium	
Length	44.5 ft.
Width	14.7 ft.
Flight Operations Equipment	None
Speed	45 kts
Endurance	250 NM at 30 kts
Sensors	Commercial Navigation Radar
UAS Capable Crew Type	None

2. Ship Capabilities and Characteristics Context

As illustrated in paragraph section C.1, different vessels have varying capabilities, characteristics, and requirements designed to complete a specific set of missions. Modern

Battle Force surface combatants are multi-mission vessels that are equipped with a litany of sensors and weapons systems that allow them to complete said missions. They are equipped with engineering plants that allow them to get up to speed quickly and have high maneuverability when they get there. Fleet logistics ships like the Lewis and Clark Class dry cargo ship will generally have slower speeds, less maneuverability, and fewer sensors or weapons systems. However, they have incredible endurance and a large carrying capacity to deliver fuel and supplies across the globe. These distinctive characteristics are used as inputs for the drone selector tool. They are used to rank ship-UAS-mission pairs in order to determine the ideal ship-UAS combination to complete whatever mission is desired for fleet planners.

a. Length and Width

An expected limiting factor that will determine which UAS can be supported on a given ship is a function of the storage space that a ship has and a specific UAS' ability to be folded and broken down to maximize the available storage space. No two ship classes will have the same layout and the amount of excess storage space may even vary depending on the mission the ship is configured for. This is apparent in the case of both LCS classes. Each mission module has varying space requirements within the mission module bay, and as such, an LCS configured for ASW may less available storage space than one configured for SUW. Therefore, an ideal data source for determining the space available for UAS storage and operations will be physical in-person measurements. Due to time, availability, and cost constraints, this study uses generic storage space requirements and storage capacity for the UASs and ships, respectively. As mentioned, drone selector tool is formatted such that incorporating real-life measurements is trivial once available.

b. Flight Operations Equipment

The importance of flight operations equipment is discussed in Chapter I as well. The presence of a flight deck will also aid in determining what size UAS can be supported, what type of takeoff and landing method can be supported, and what type of facilities are available for maintaining the UAS. It is common that a ship will have a flight deck to support flight operations but will not have a hangar to support organic flight capabilities.

Therefore, the mere presence of a fight deck alone is not enough to paint a holistic picture of UAS support capabilities. A ship that has a flight deck, as well as the presence of a hangar, will be the optimal scenario with respect to space, maintenance facilities, variety of UAS operations supported. A ship with a flight deck and no hangar will be second, and a ship that has no flight operations equipment or facilities will be the worst-case scenario as it pertains to abilities to support UAS operations. CTF 59 in the Fifth Fleet Area of Operations has shown that a ship without a flight deck is perfectly capable of supporting UAS operations; therefore, the absence of a flight deck will not disqualify a ship for potentially conducting UAS operations [40].

c. Speed and Endurance

The maximum speed of a vessel as well as its endurance are indicators of the type of missions it can accomplish, the size of the vessel, and the areas in which a vessel will operate. The speed of the Response Boat-Medium is significantly higher than that of a DDG, but the endurance of the former pales in comparison to the latter. Response Boats-Medium are fast vessels that are used to patrol inland waters, harbors, bays, and near-shore swatches of the ocean. The DDG is a high-endurance vessel, though not as high-endurance as a fleet oiler or cargo vessel. All three of these vessels can operate anywhere on the world's oceans outside of limitations imposed by sea ice in the Arctic and Antarctic. Therefore, speed and endurance are other characteristics that can be considered when trying to determine the optimal ship-UAS-mission pairing.

d. Sensor Types

As discussed in the introduction to this section, there are many sensors available that ships may employ. They will determine the ship's capability to operate in a wide variety of circumstances, weather conditions, and even time of day. Most modern surface search radars have similar operational ranges, limited less by the power they put out, and more so by the height at which they are mounted. Surface Search and Air Search Radars allow a vessel to be cued to the presence of some type of contact in the air or on the ocean surface, but the type of information they can provide is limited. Using other sensors in concert, for example, an EO/IR sensor onboard the ship can allow the ship to determine vessel type, and perhaps identification. This too is limited by the curvature of the earth and the height-of-eye, much like surface search radars. The more sensors a ship has, both quantity and diversity, will not only determine its likely mission sets but also, its propensity for intelligence gathering as well as search and rescue capabilities. These capabilities will be greatly aided by an organic air asset and will help determine which ship is ideal for mission employment.

e. UAS Capable Crew Type

This characteristic is a way to determine whether a ship has the personnel onboard that have the tools, skills, and experience to operate and maintain UAS. Ships that do not have personnel that are a part of the aviation community either directly or indirectly may still be able to employ an organic UAS asset but will probably require training to do so. Any potential operator or maintainer of the UAS will require some requisite amount of training, but the cost of said training, both in time and money, will vary with the personnel's experience. It is expected that this could be a driving factor when determining both the cost of establishing an UAS-on-Ships program of record and the ease with which these assets may be integrated into existing surface ships and their crews.

F. CONCLUSION

There are a wide variety of characteristics, both for UAS and Surface Ships, that will determine how they may be employed, who will employ them, the best way to employ them, and finally how much it might cost to employ them. This study will use a combination of representative and estimated data for USN/USCG ships, and pair it with corresponding UAS characteristics and data to determine a ranked list of Ship-UAS pairs designed to accomplish a specific mission. This paper is constrained by data availability both for ships and UASs. The data that is used in the drone selector tool is aggregated from a combination of publicly available USN and USCG publications, open-source intelligence sources, and industry fact sheets. If specific data is not available for a specific ship or UAS, an estimated value is implemented. This tactic is used to illustrate the functionality of the selector tool and provide users and stakeholders with an example of the analysis that may be conducted given the proper data inputs. It is critical that the ranked list of Ship-UAS-mission pairings is informed by the stakeholder's requirements both as an example in the case of this paper, or for fleet-use using measured realistic data and specific mission parameters. The purpose of the drone selector tool is to provide the USCG and USN stakeholders with an analytical tool that may be used for mission planning or acquisition purposes, as well as to illustrate the type of analysis than can be done with the appropriate data. Chapter III will discuss the drone selector tool in-depth and provide any potential users with the appropriate context and steps to ensure the tool is implemented appropriately to yield the highest fidelity results possible.

III. TOOLS AND METHODOLOGY

A. INTRODUCTION

As discussed in the previous chapter, there are several factors that go into determining the most capable UAS for each vessel type. The drone selector tool is created in order to down-select those UAS that are likely to provide the most capability to a specific ship type within the constraints (available space, logistics, power, etc.) of the ship. The goal of this tool is to ultimately provide a list of appropriate UAS given a mission-set, the ship of interest, and other factors that impose requirements on the chosen UAS' capabilities. In this chapter, this tool, its purpose, use, as well as the methodology behind it are presented.

B. THE DRONE SELECTOR TOOL

The tool's foundation is the collected data per UAS and USN or USCG vessel type of interest. This early foundation is borne from the necessity to centralize all the collected data into one cohesive structure for easy reference. This initial structure provides all the UAS and ship information that is required to conduct the calculations that are discussed in Section B of this chapter.

Using the collected data, the tool is designed to allow a user to specify which ship type they are investigating giving a UAS asset to, the mission type, as well as certain environment variables and general UAS requirements—each of which is discussed in the following subsections. Additionally, the tool is designed to be modular so that the addition of more UAS and ships is straightforward. It is worth noting that this tool, at present, is not all-encompassing. It does not hold every UAS or USN and USCG ship that exists. Instead, this tool represents a methodology that this study proposes is of use when analyzing the UAS and ship pairings that best suit the stakeholder requirements. However, with the modularity in its design, the end users of this tool are easily able to insert additional UAS and ship specifications and derive from them an analytically sound choice in UAS for their needs.

To assess which UAS specifications are most relevant to the missions, this study began by decomposing the stakeholder requirements. As discussed in Chapter II of this paper, there are no "hard" numerical requirements. Instead, there are general capabilities that a UAS must have in order to perform a mission, such as visual capabilities for ISR/SAR. From these requirements is derived a short-list of UAS capabilities that increase capability for each mission type. From there, the analysis required an understanding of what a ship needed in order to support a UAS of a certain group and type. Each of these processes and resulting specifications/variables are discussed in the following subsections.

1. UAS Information of Interest

The Excel spreadsheet that houses the Drone Selector Tool begins with a sheet that collects and stores pertinent information for each UAS. The parameters and capabilities of each UAS present in this sheet are specifically chosen to represent the UAS' overall fitness to meet the requirements discussed in Section B of Chapter II. These chosen specifications are represented in Table 16.

Table 16. UAS Parameters in the Drone Selector Tool

Spec.	Units	Definition
Supports SAR Missions	Boolean	The UAS has visual or infrared sighting capabilities
Supports Logistics Missions	Boolean	The UAS can have additional payloads attached to it for delivery
Storage Size	$ft.^3$	The UAS' size when in its storage configuration/in its storage case
Takeoff Size	$ft.^2$	The UAS' size when in its flight-ready configuration
Runway Length Required	ft.	The length of runway required for takeoff—0 if VTOL-capable or is launched by hand/some other mechanism

Spec.	Units	Definition
Fuel Type	String	The UAS' power source—gas or battery-powered
Swappable Payload	Boolean	The UAS' cameras or other functionality is swappable to another device/mechanism
Encrypted Datalink	Boolean	The UAS supports encryption for the data it sends
Supports Water Landing	Boolean	The UAS can land in water and await recovery
Supports VTOL	Boolean	The UAS can takeoff from a stationary position and land without a runway
Max Transmission Range	NM	The UAS' maximum range of communication with the controller
Max Loiter Time	Minutes	The UAS' maximum time in flight
Max Altitude	ft.	The UAS' altitude ceiling
Max Payload Weight	lbs	The UAS' maximum safe operating weight
Max Speed	mph	The UAS' top speed in flight
GPS-Denied Flight	Boolean	The UAS can operate without the use of the Global Positioning System (GPS)
Autonomous Flight	Boolean	The UAS is capable of directing itself to a specified location and returning without input from the controller
Obstacle Avoidance	String	The UAS is capable of mitigating collisions
Max Effective Delivery Range	NM	The UAS' theoretical maximum range—a minimum taken of its maximum transmission range and the product of max loiter time and max speed

Spec.	Units	Definition
Sensor Quality	Integer	A value given to its visual or infrared sensors based upon the group number of the UAS[a]

a. This method of assigning sensor quality values is chosen given the typical unavailability of sensor information per UAS. The UAS' reference documentation rarely included values such as video quality, zoom level, and type of zoom. Therefore, an assumption is made based upon the UAS' group level (1-3) in that a higher group level is proportionally related to a higher quality of sensor. Other assumptions are covered inline in proceeding sections and chapters.

These selected values do not represent all the specifications that define a UAS' operational capabilities. However, these are the specifications that have been determined to be most pertinent to enabling and improving capability for the selected missions. The specifications that are not present on this list are either outside of the scope of the requirements or are not representative of the environments in which the chosen UAS will operate.

Though not all of these listed metrics are utilized in the ensuing calculations, they are present in the tool given that they are pertinent to fully understanding a UAS' suitability and capabilities. These other variables serve as a reference point to those that designed the tool and can serve as such to the end-user as well. The specific rationales for each selected metric are as follows:

- Supports SAR Missions (has video capabilities) – In order to satisfy the sponsors' and stakeholders' requirement that the UAS be capable of conducting ISR and SAR missions, the UAS must provide visual information and data that would not be available without an airborne asset.

- Supports logistics Missions (additional payloads) – In order to satisfy the sponsors' and stakeholders' secondary requirement that a UAS should be capable of conducting short-range, lightweight delivery of materials, the UAS should, but is not required to have the ability to support additional weight and payloads for such a delivery.

- Storage Size – The vessels that these UAS will support have little space to store additional materials that were not originally been planned for accommodation.

- Takeoff Size – Some vessels that these UAS will support do not have sufficient space to launch a large UAS.

- Runway Length Required – Similarly, the vessels have limited runway space available to support the launch of a UAS requiring it. The ideal here is either that hand-launch or VTOL is possible, removing the need for a runway to launch the craft.

- Fuel Type – This metric is not weighted in the calculations—the tracking of this metric is to extrapolate what other requirements the vessel will have in order to support a UAS.

- For gas-powered UAS, additional fuel must be carried onboard the ship, or the ship must rendezvous on shore or with another vessel to refuel the UAS frequently depending on the UAS' fuel efficiency.

- For battery powered UAS, additional batteries must be carried onboard, charging components must be carried onboard, or frequent stops to recharge may be required depending on the UAS' battery efficiency.

- Swappable Payload – In order to support missions in varying environments (such as at night), the UAS is favorable if it can support secondary equipment attachments such as exchanging visual cameras for infrared.

- Encrypted Datalink – In order to ensure the security of sensitive collected data in contested environments, the UAS must be capable of encrypting its data.

- Supports Water Landing – A UAS that is capable of landing in water lends to more flexible operation and retrieval, expanding the use-cases and mission sets that the UAS can be considered to undertake.
- Supports VTOL – A UAS that is capable of lifting off directly from a stationary position is greatly valuable to smaller vessels, expanding the variety of vessels the UAS can be considered to support.
- Max Transmission Range – A UAS with greater transmission range is capable of covering more area further ahead and around the vessel controlling it. Additionally, this increases its range of possible logistical deliveries.
- Max Loiter Time – A UAS with greater loiter time is capable of staying in operation longer, thus it is capable of covering more area around the vessel and can spend more time in search of targets. Additionally, this increases its range of possible logistical deliveries.
- Max Altitude – A UAS with greater maximum altitude is capable of bringing more of the environment into view and searching it more efficiently.
- Max Payload Weight – A UAS with greater maximum payload weight is capable of supporting a wider range of additional attachments and logistical delivery items.
- Max Speed – A UAS with greater maximum speed is capable of encroaching on target areas quicker and searching areas faster.
- GPS-Denied Flight – A UAS that is capable of operation without GPS aid is more likely to successfully operate within a contested area, expanding the mission sets that it may support.

- Autonomous Flight – A UAS that is capable of directing itself to a specified location or in a specified pattern greatly benefits the operators by reducing the total time that is required to directly operate the craft.

- Obstacle Avoidance – A UAS that is capable of detecting imminent collisions and mitigating them meets the requirement for due regard without direct observation by the vessel and its operators, expanding the range it may operate from the ship.

- Max Effective Delivery Range – As stated in Chapter II, this the product of max speed and max loiter time, which produces the UAS' maximum theoretical range, i.e., how large a radius around a ship it is capable of traveling or how far a logistical delivery it may undertake.

- Sensor Quality – A UAS with greater visual capabilities provides data and observations that are clearer and easier to glean important details from.

Not every specification listed and considered in the analysis is available for every UAS analyzed at the time of this study. For instance, not every UAS manufacturer publicly lists their UAS' storage volumes. Therefore, as stated in Chapter II, conservative assumptions are made in these regards. The chosen assumptions for each metric wherein there are one or more UAS without information are listed in Table 17.

Table 17. Missing UAS Metric Assumptions

Spec.	Assumption in Absence of Information
Storage Size	At least as large as the largest reported in its group
Takeoff Size	At least as large as the largest reported in its group
Runway Length	At least as long as the longest reported in its group
Fuel Type	No valid assumption can be made
Swappable Payload	No
Encrypted Datalink	No
Supports Water Landing	No
Supports VTOL	No
Max Altitude	At most as low as the lowest in its group
GPS-Denied Flight	No
Autonomous Flight	No
Obstacle Avoidance	No

Note that the chosen assumption in the absence of available metrics is the worst reported value or the inverse of the preferred option. This is in effort to not unfairly weight these options in the proceeding calculations—the chosen UAS should meet the requirements on its own merits. By using conservative assumptions, the tool is less likely to recommend a UAS solution whose values do not *actually* meet the requirements due to inflated values being inserted via other assumption methods such as averaging or taking the best-case metric in its group. This method balances the need to rank UAS relative to each other with the paucity of available data to do so. Additionally, logic is included in the tool that is able to "switch" on or off a UAS' consideration in the absence of reported metrics. This functionality may be preferable for users desiring to compare only UAS with complete data sets.

2. Ship Information of Interest

The USN and USCG ship information is also stored within the Excel workbook in a similar manner to the UAS specifications architecture. Each of the vessels' metrics that are collected and represented within the tool are tied, in some manner, to the metrics of the UAS crafts. These metrics define the parameters that the chosen UAS must fit within in order to be considered a match for the ship. These metrics are represented in Table 18.

Table 18. Ship Parameters in the Drone Selector Tool

Spec.	Units	Definition
Gas Allowed	Boolean	Gasoline is approved to be aboard the vessel
Li-Ion Batteries Allowed	Boolean	Lithium-Ion batteries are approved to aboard the vessel
Equipment Space	ft^3	The space that is available for the storage of the UAS while not in use
Launch Area	ft^2	The area that is available for launching a UAS
Runway Length	ft	The length of runway that is available for UAS that require it
Water Recovery Support	Boolean	The vessel is capable of recovering UAS that have made a water landing/otherwise are in the water
Due Regard Sensors	Boolean	The vessel is equipped with radar or some other means of observing the UAS while in operation to obey due regard policies
Number of Operators	Integer	The number of crew aboard the vessel that is capable and available to operate the UAS when needed
Number of Maintainers	Integer	The number of crew aboard the vessel that is capable and available to maintain the UAS when needed

Like the UAS parameters, the collected ship parameters are not all-encompassing. Here, metrics such as ship speed, operation time, deck height, etc., are not included due to them not being directly related to the UAS being housed aboard them. Metrics such as those play a role in the calculations and models that define how the chosen UAS and its ship interact and perform together while in operation, however. Those additional parameters, calculations, and model results are discussed in Chapter IV of this paper.

The rationale for each metric's inclusion in Table 18 are as follows:

- Gas Allowed: A ship that is approved to have gasoline and gasoline-powered crafts aboard are able to support UAS of that nature, thus expanding the set of potential UAS matches for it..
- Li-Ion Batteries Allowed: Similarly, a ship that is approved to house lithium-ion batteries and battery-powered crafts aboard have an expanded set of UAS that they could potentially support
- Equipment Space: A ship with greater equipment space can support larger UAS and are not relegated to solely small crafts with fewer capabilities. Conversely, a ship with less available storage space can only support UAS with sufficiently small non-operation configurations and/or storage containers.
- Launch Area: A ship with greater free space available for launching UAS can support a wider range of UAS and are not relegated to VTOL or hand/equipment-launched UAS.
- Runway Length: Similarly, a ship with greater runway length (or a runway at all) can support a wider range of UAS to include those that require it.
- Water Recovery Support: A ship that is capable of retrieving UAS from the water can support a wider range of UAS as well as a wider range of operational circumstances when deck-landing is not possible.

- Due Regard Sensors: A ship that houses radar, long-range sighting capabilities, or some other means of monitoring the UAS' activities can support a wider range of UAS to include those that do not have inherent obstacle avoidance.

- Number of Operators: A ship that has a greater number of crewmen available and capable of controlling UAS is able to operate the asset more often with lesser impact to other shipboard duties/capabilities.

- Number of Maintainers: A ship that has a greater number of crewmen available and capable of maintaining UAS increases the ability to perform corrective maintenance when necessary, and preventative maintenance at proper intervals that lessens the impact on other shipboard duties/capabilities.

Naturally, the tool operates in much the same way that this entire study operates—it fits UAS to the ships' ability to house them. It does not attempt to make corrections, edits, or improvements to the ships' capabilities or availabilities in order to suit a specific UAS. However, with the products of this tool, analyses have been conducted to determine concepts that could change and what additional assets could be supported if they were to occur. This analysis does not seek to modify the ships' architectures or add further inbuilt equipment or mechanisms; instead, it examines the impact of altering more feasible variables such as the number of crew, allocated storage space, etc. Considerations for further analysis are discussed in Chapter V of this paper.

3. User Inputs to the Drone Selector Tool

The Drone Selector Tool utilizes user inputs as static independent variables—i.e., they are not edited, improved, or weighted—much in the same way that the ship parameters are. These user inputs are listed in Table 19.

Table 19. User Inputs to the Drone Selector Tool

Input	Units	Definition
Mission Type	String	A dropdown menu with options for ISR/SAR or Logistical delivery mission
Ship Selection	String	A dropdown menu with options for each ship listed in the Sheet containing all of the ship information
Contested	Boolean	A dropdown menu with options for YES (the area is contested) or NO (the area is not contested)
Required Minimum Speed	mph	An input cell that accepts float values for the required minimum speed of the UAS – This option has a toggle switch to activate or deactivate this field's consideration
Required Minimum Loiter Time	Minutes	An input cell that accepts float values for the required minimum loiter time of the UAS – This option has a toggle switch to activate or deactivate this field's consideration
Required Minimum Altitude	ft	An input cell that accepts float values for the required minimum altitude of the UAS – This option has a toggle switch to activate or deactivate this field's consideration

These mission-defining parameters are the final necessary components prior to the tool conducting the weighting and corresponding calculations. The rationale for each parameter's inclusion in the tool are as follows:

- Ship Selection: The user's selection here directly links to that ship's specifications and capabilities as discussed in Section A.2.
- Contested: The environment being contested excludes UAS from consideration if they are not capable of encrypted datalink or GPS-denied flight.
- Required Minimum Speed: The vessel that will make use of the UAS may require a certain minimum speed for that UAS so that it is able to outpace

the ship during ISR/SAR missions, or make logistical deliveries in a certain amount of time.

- Required Minimum Loiter Time: The vessel that will make use of the UAS may require a certain minimum loiter time for that UAS so that it is able to sustain flight or remain on station for the required amount of time.

- Required Minimum Altitude: The vessel that will make use of the UAS may require a certain minimum altitude ceiling for that UAS so that it is able to reach the appropriate height for observation.

C. THE DRONE SELECTOR TOOL'S METHODOLOGY

In this section, the backend logic behind the tool's weighting, calculations, and ultimate suggestions are described in detail. In the most basic terms, this is accomplished by utilizing the Parnell method of weighing alternative solutions based upon their importance [41]. The hierarchy of weighted metrics discussed in the previous section along with each of those metrics' variability between alternatives defines our swing weight matrix. The resulting values, as also shown in the previous section, are then combined with each UAS' specification values. This results in a concise list of UAS that both meet the mission requirements, and how well they meet them compared to other suitable alternatives.

However, prior to the definitive calculations accounting for user input and mission conditions, the Drone Selector Tool conducts preliminary exclusions based on more fundamental considerations. These require nothing more than simply the ships specifications and the UAS specifications. The first of these is the ship-to-UAS supportability—the comparison of ship specifications against UAS requirements as they allow or disallow UAS regardless of mission type. As an example, a ship that is not approved to carry gasoline onboard can automatically disqualify gas-powered UAS. Second is that of the UAS-to-mission supportability—the comparison of UAS specifications and the most basic mission types as they allow or disallow each UAS to perform them. As an example, a UAS that is not capable of GPS-denied flight can automatically be disqualified from contested environments, regardless of the mission type.

From there, the tool then takes the shortened list of UAS that are supported by the vessel of choice and that can perform the chosen mission and applies the weights to each to determine the best fit. A simple diagram of this process is shown below at Figure 1. Each of these steps are detailed at length in the following subsections.

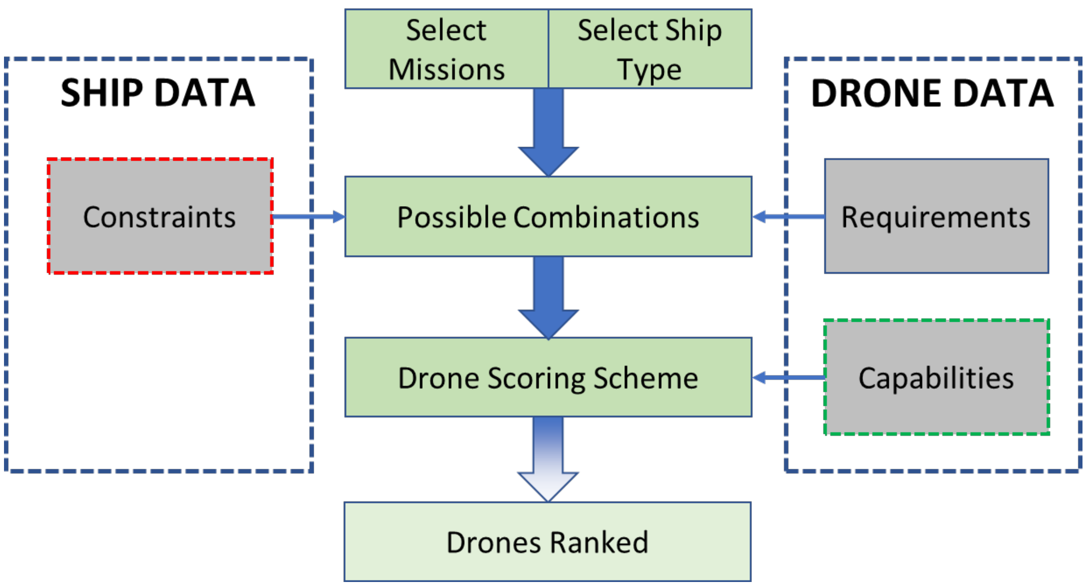


Figure 1. The Drone Selector Tool

1. Ship-To-Drone Supportability

In order to preemptively disqualify UAS, there are several criteria that must be met. As it is designed in the tool, a matrix has been created with each ship as the leftmost column, and each UAS as the uppermost row. The intersecting cell of each ship and UAS holds logic that compares the UAS' support requirements and the ship's corresponding specifications from their respective sheets within the document. This logic, as required by Excel, exists as a series of nested IF statements with each possible answer corresponding to a specific response and color for the cell. Each step in the logic's flow and possible results are detailed in Table 20. However, note that the logic has been generalized—the specific cells that are being referenced are not represented here. Instead, this is a representation of the logic as it exists for each ship/UAS pair regardless of the specific identity and location within the Excel document of either. Note as well that the cell color is presented for each result—these colors do not represent severity levels of the returns. Instead, they are simply for visual cues when scanning the returns in their sheet within the Excel document.

Table 20. Ship-To-Drone Supportability Logic Within the Drone Selector Tool

Criteria	Definition	Cell Response	Cell Color
Missing Information	If the UAS or ship in the pair being checked does not have any of the following: • storage size • fuel type • runway length required • launch space required the check is failed	"Information Unavailable – UNK"	
Fuel Type	If the ship does not support the UAS' fuel type whether gasoline or battery, the check is failed	"Fuel Not Supported"	
Runway Length	If the ship's runway length is less than that required by the UAS, the check is failed	"Insufficient Runway"	
Launch Space	If the ship's launch space is less than that required by the UAS, the check is failed	"Insufficient Launch Space"	
Storage Space	If the ship's storage space is less than that required by the UAS, the check is failed	"Insufficient Storage"	
Final	If none of the above checks have been failed, the corresponding UAS and ship are considered to be a preliminary match, the check is passed	"SUPPORTED"	

The results of this preliminary exclusion or inclusion of UAS from the solution space are later referenced in the "backend" sheet of the Excel document. In that later logic, the response from this section determines whether the UAS will have the weights applied, be added to the list of possible solutions, and ultimately be reported to the user for consideration. This is only conducted if the UAS and user-chosen ship's intersecting cell is "SUPPORTED." Note here that the selection of the ship is not required for the above logic to run. This process is conducted for all possible ship and UAS pairs and exists within the document without the need for user prompting; thus, this information is always present. This design choice is so that the results can be quickly referenced by the user to determine a ship's ability to house any of the UAS so long as their required specifications are present in their respective sheets.

2. Drone-Mission Supportability

The next step in the logic's flow is to determine whether a UAS is capable of performing the most basic operational cases. For this portion of the logic, the "most basic" operational cases are that of both ISR/SAR and logistics in both contested and uncontested environments. Therefore, at this stage, there is no consideration to flight time, distance, payload weight, or any of the more specific specifications of the mission to be performed. Similar to the preemptive exclusions discussed in the previous subsection, in this way UAS can be removed from the solution space based solely on their capabilities fundamental to these missions. This is accomplished in much the same way as the Ship-Drone Supportability section wherein the various UAS are listed on the uppermost row, and the four basic mission types are along the leftmost column. This logic also consists of nested IF statements in standard Excel syntax. Each step in the logic's flow and possible results are detailed in Table 21. Again, note that the logic has been generalized—the specific cells that are being referenced are not represented here. Instead, this is a representation of the logic as it exists for each UAS/mission pair regardless of the specific identity and location within the Excel document of the UAS.

Table 21. Drone-Mission Supportability Logic Within the Drone Selector Tool

Criteria	Definition	Cell Response	Cell Color
ISR/SAR – Uncontested			
Missing Information	If the UAS being checked is missing a value for Payload Weight, the check is failed	"Information Unavailable – UNK"	
Final	If none of the above checks have been failed, the corresponding UAS and mission are considered to be a preliminary match, the check is passed	"SUPPORTED"	
ISR/SAR – Contested			
Missing Information	If the UAS being checked does not have any of the following: • GPS-denied flight • encrypted datalink the check is failed	"Information Unavailable – UNK"	
Encrypted Datalink	If the UAS being checked does not support encrypted datalink, the check is failed	"Encryption Not Supported"	
GPS-Denied Flight	If the UAS being checked does not support GPS-denied flight, the check is failed	"GPS-Denied Not Supported"	
Final	If none of the above checks have been failed, the corresponding UAS is considered to be a preliminary match, the check is passed	"SUPPORTED"	

Logistics – Uncontested			
Missing Information	If the UAS being checked is missing a value for Payload Weight, the check is failed	"Information Unavailable – UNK"	
Final	If none of the above checks have been failed, the corresponding UAS and mission are considered to be a preliminary match, the check is passed	"SUPPORTED"	
Logistics – Contested			
Missing Information	If the UAS being checked does not have any of the following: • payload weight • GPS-denied flight • encrypted datalink the check is failed	"Information Unavailable – UNK"	
Payload Weight	If the UAS being checked does not support an additional payload, the check is failed	"Does Not Support a Payload"	
Encrypted Datalink	If the UAS being checked does not support encrypted datalink, the check is failed	"Encryption Not Supported"	
GPS-Denied Flight	If the UAS being checked does not support GPS-denied flight, the check is failed	"GPS-Denied Not Supported"	
Final	If none of the above checks have been failed, the corresponding UAS is considered to be a preliminary match, the check is passed	"SUPPORTED"	

Note in Table 21 that the logic asks virtually the same questions of the UAS being checked whether in the ISR/SAR case or the logistics case. The defining characteristic of ISR/SAR missions versus that of logistics missions is the fundamental need for a visual sensor or suite of sensors to identify targets of interest. However, given that this functionality is required by the stakeholders regardless of the mission that is being conducted, UAS without this functionality have been excluded from the study. Therefore, the logic between the two mission types in this section differs only in that the support of an external additional payload is not required for ISR/SAR missions. This leaves the potential for a UAS to be chosen for ISR/SAR missions if it does not support a payload given that its other parameters may be suitable for that operational case.

The result of this logic is a down-selected list of UAS that are suitable for the mission parameters chosen by the user. Again, similar to the Ship-Drone Supportability logic, these results are referenced in the "backend" sheet to determine which UAS will have their weights applied and ultimately reported to the user as a viable option or not. This is only conducted if the UAS and user-chosen mission type and contention's intersecting cell is "SUPPORTED." Note here that the selection of the ship is not required for the above logic to run. This process is conducted for all possible UAS and mission pairs and exists within the document without the need for user prompting; thus, this information is always present. This design choice is so that the results can be quickly referenced by the user to determine a UAS' ability to conduct a specific mission type and contention so long as its required specifications are present in the "Drone Specs" sheet.

3. UAS User Specifications Supportability

As discussed previously, the user can input values corresponding to their unique requirements for certain UAS specifications: speed, loiter time, and altitude. Unlike Ship-to-drone supportability and drone-mission supportability, the results of these pre-exclusions do not exist in a sheet of their own. Instead, they are calculated and stored in the "Backend-Mix&Match" sheet wherein all the results of the previous pre-exclusions and forthcoming swing weight calculations are stored.

In this sheet, each UAS' column contains four rows at the bottom of their information corresponding to the three user-input fields with a fourth to indicate each of those three have been satisfied. Each of the specification cells contains logic that compares the user-input minimum required value against the UAS' maximum value found in the "Drone Specs" sheet of the containing Excel document. If the maximum corresponding value is greater than the user's provided minimum value, or this field's consideration has been disabled with its toggle switch, the cell reports "YES" indicating a match. If the toggle is enabled and the UAS does not meet the minimum threshold, the cell reports "NO." If each of the three specification fields report "YES," the "Meets All Conditions" field then also reports "YES." If one or more of the specification fields are "NO," the "Meets All Conditions" field also reports "NO." The combination of these values being condensed to the "Meets All Conditions" field is simply for logical ease in determining if the UAS has not been pre-excluded.

The result of this comparison is a down-selected list of suitable UAS. Similar to the ship-to-drone supportability and drone-mission supportability results, the results of this user-specification check are also preemptively created and permanently stored in the "backend" sheet. This allows the user to input their known specific requirements and quickly reference UAS that meet them. Those UAS that are not pre-excluded due to any of the criteria discussed here or prior are considered preliminary matches for the ship and mission conditions as input by the user. These preliminary matches will proceed to have their swing weights applied to them and they are ranked against each of the other remaining options.

4. Ranking the UAS With Swing Weights

Once the preliminary exclusions have been made, the remaining shortened list of UAS is ranked according to their primary specifications and the chosen mission. This is the first step in the tool process that requires input from the user. Once a new variable is input into the "Mix & Match" sheet of the Excel document, the tool automatically begins calculating each UAS' suitability scores. Once the calculations are completed, a graph titled "Output Scores" in the same "Mix & Match" sheet is updated to reflect the list of suitable UAS alternatives. The user may continue to input new variables as they pertain to the mission being investigated and the graph will continue to update with the additional information provided.

As previously discussed, the underlying methodology in the UAS ranking system is that of the Parnell swing weight method. The goal of this methodology is to better define values applied to alternatives' metrics and specifications. The alternative approach to this goal is known as Importance Weighting—a comparatively simplistic approach that relies solely on the priority (or importance) the analyst applies to each metric being studied. In their paper titled "Using the Swing Weight Matrix to Weight Multiple Objectives" [41], Parnell and Trainor argue that the Importance Weighting system is weakened by its lack of a mathematical definition for these weights. Therefore, the inclusion of a consideration for the spectrum of variability that the analyst's chosen specifications fall within results in more mathematically and analytically sound weights to be applied to those metrics.

The basis of the Swing Weight methodology relies on the analyst first concluding the degree of variability that a metric is subject to between the available alternatives. The possible results of this analysis are "High," "Medium," and "Low," which respectively reflect a decreasing variability. Note here that these variance labels are relative to the set of all variables being considered—i.e., there are no universal ranges that equate to "High," "Medium," or "Low" labels. In order to determine the degree of variation, the analyst simply subtracts the smallest value of a specification from the greatest and then divides the average of the entire range of values. For the UAS included in this study, Table 22 provides these ranges and variance scores for the weighted specifications.

Table 22. Variance in Weighted Drone Specifications

Spec.	Value Range	Variance Score
ISR/SAR		
Maximum Transmission Range	0.54-300 NM	635% – High
Max Loiter Time	25-960 minutes	318% – Medium
Max Speed	22-100 mph	154% – Low
Sensor Quality (Integer Score)	1-3	82% – Low
Logistics		
Max Effective Delivery Range	0.54-300 NM	635% – High
Max Speed	22-100 mph	154% – Low
Max Payload Weight	2.6-84 lbs	348% – Medium

Once the variance of each metric of evaluation (MOE) is calculated, the analyst must then determine the importance of each metric to the goals of the mission. For the purposes of this study, the different mission types (ISR/SAR, logistics) warrant unique MOEs and importance weightings. Tables 23 and 24 depict the matrices of variability and importance per MOE for each mission type.

Table 23. ISR/SAR MOE Matrix

		Importance		
		Very Important	Important	Less Important
Variance	High	Max Transmission Range		
	Medium	Max Loiter Time		Max Speed
	Low		Sensor Quality	

Table 24. Logistics MOE Matrix

		Importance		
		Very Important	Important	Less Important
Variance	High	Max Effective Delivery Range		
	Medium			Max Payload Weight
	Low		Max Speed	

These MOEs are chosen based on the inherent differences in the demands of each mission type. Naturally, for either mission type, the maximum range of the UAS is important given that a longer range is indicative of more area coverage for ISR/SAR, or a further delivery range for logistical deliveries. However, maximum transmission range is chosen as the prime specification for ISR/SAR due to the fact that this metric defines how far away a UAS may be and still be in direct contact with the controller. For those UAS that are capable of autonomous flight in these situations, they are able to maintain their location and/or return to the vessel outside of this range. However, their video feeds will not be delivered live—i.e., the UAS must be reacquired, and their data must be manually extracted. The lack of a live feed reduces the tactical effectiveness of the UAS in these scenarios, therefore maximum transmission range is the true bottleneck for these mission types.

For ISR/SAR missions, the second most important UAS specification is maximum loiter time. A UAS with a greater loiter time is capable of staying at or near the point of interest longer and is therefore able to obtain more data for the operators aboard the vessel. The third ranked metric is the UAS' sensor quality. A higher quality sensor is capable of more refined imagery, thus clearer visual data, as well as more effective and greater zoom levels for obtaining data from a distance. The final metric for ISR/SAR is the maximum speed of the UAS. This metric is important due to it determining how long the UAS will take to travel to the area of interest, thus how quickly crucial information can be captured. However, it is not weighted stronger due to the fact that roughly equivalent ground can be covered with a complementarily greater loiter time, and crucial information can be gathered from further away with higher quality sensors.

For logistics missions, the maximum effective delivery range—the lesser of the theoretical maximum range and maximum transmission range—is chosen as the prime specification for the contrary reasoning to that of ISR/SAR. One of the primary goals of UAS performing these types of missions is to mitigate the impact of diverting ships off course or off station. Therefore, the UAS' ability to travel further without need to refuel is of greater importance in these scenarios. The second most important metric is the UAS' maximum speed. This metric determines how quickly the UAS can arrive at the recipient entity, thus how little an impact there is to either entity's other duties with shorter waiting times for delivery. The final specification chosen is the maximum payload weight. While seemingly an unsurpassed important consideration for logistical deliveries, its placement as third and last for these missions is due to the stakeholder's assurance that the payloads will be of minimal weight. Naturally, with greater payload capabilities, the set of payloads that *can* be delivered in this manner expands, thus it is present as a weighting metric. However, the stakeholders in this study are confident that the use cases for this capability do not include exceedingly heavy payloads.

With the variance calculated and importance determined, the swing weights must then be given to each MOE. The method to do so involves appropriately assigning values to each MOE depending on its placement in the importance/variance matrix. Metrics that are higher in the matrix (higher variance) must be of a higher value than those below it. Metrics further to the left (higher importance) must be of a higher value than those to the right of it. The reference [41] utilized for this methodology does not supply guidance on what these values should be exactly. Instead, it only notes that a common choice for cell A (highest and furthest left) is 100, and each subsequently less impactful MOE is then assigned a value appropriately lower depending on its placement in the matrix. Following this guidance for each of the matrices yields the swing weights depicted in Table 25. Note in Table 25 that the swing weight values are unitless and are simply a definition of the importance of a given metric in relation to the others.

Table 25. MOE Swing Weights

Spec.	Swing Weight
ISR/SAR	
Max Transmission Range	100
Max Loiter Time	80
Max Speed	40
Sensor Quality	60
Logistics	
Max Effective Delivery Range	100
Max Speed	80
Max Payload Weight	30

Swing weights are unitless values representing the relative importance or "weight" of each metric against the others.

These weights are only applied to a UAS in the event that it meets the rigid requirements for the chosen ship. As is discussed in the following section, a UAS is first subject to exclusion due to not meeting mission-specific requirements, the ship being unable to support it, or not meeting the user-input specification requirements. Each UAS that is not pre-excluded for any of the listed reasons will then have its weights applied and it is ranked against each of the other remaining UAS. Note here that the end-user is easily able to adjust these values in the Drone Selector Tool itself to reassign the importance of each MOE.

Following the selection of swing weights, the individual swing weights must be normalized as a portion of the total of the swing weights given. Stated explicitly, each swing weight is divided by the sum of all the swing weights in its category (ISR/SAR or logistics)—thus the resulting measure weights are fractional multipliers that together sum to one. Each metric's swing weight, calculation, and resulting measure weights are depicted in Table 26. Note that the calculated measure weights reported in Table 26 are unitless in the same manner as the swing weights—they are a representative value for the relative importance of each metric.

Table 26. Measure Weight Calculations by Specification

Spec.	Swing Weight	Calculation	Measure Weight
ISR/SAR			
Max Transmission Range	100	100/280	0.36
Max Loiter Time	80	80/280	0.29
Max Speed	40	40/280	0.14
Sensor Quality	60	60/280	0.21
Logistics			
Max Effective Delivery Range	100	100/210	0.48
Max Speed	80	80/210	0.38
Max Payload Weight	30	30/210	0.14

The final step in calculating each UAS' suitability score is to conduct a sum-product of its values for these chosen specifications and the calculated measure weights. Stated explicitly as an example for a logistics-mission calculation, a UAS' max delivery range value is multiplied by the measure weight of that specification (0.48), its max speed is multiplied by that measure weight (0.38), and its max payload weight is multiplied by that measure weight (0.14). These products are then summed together, and the resulting value is this UAS' suitability score. Once this has been conducted for each UAS, the process has been completed and the UAS are ready to be fully evaluated. The suitability scores for each UAS identified are provided at Appendix A.

As discussed in the earlier subsections, each UAS has, at this point, already been prescreened based upon their inherent ability to support each base mission type, and each ship's ability to support the UAS itself. Therefore, the results of this screening and the suitability scoring processes are both referenced and reported in the "Backend" sheet of the containing Excel document. This sheet exists as a matrix with each UAS alternative as the uppermost row, and each ship as the leftmost column. Each ship is subdivided into ISR/SAR and logistics rows, and the intersection of these rows with an individual UAS is either the pre-exclusion reasoning (i.e., contested not supported, not enough storage space, etc.), or the suitability score of the UAS. This sheet is the reference point for the graph reported to the user in the "Mix&Match" sheet previously discussed. If the UAS' value in the "Backend" sheet is anything other than a numerical value (its suitability score), it is not ranked in the user's final graph—it is still present, but it is not given a bar depicting its suitability level. If the UAS' value *is* that numerical score, this score is represented in this bar graph. This results in potentially several UAS having scores depicted in this graph at a time, and the UAS with the highest score, thus the longest bar in the graph, is taken to be the most advisable UAS for the supplied mission and inputs.

D. TOOL OUTPUTS AND SUGGESTED UAS

In order to generate a down-selected list of UAS for ongoing analysis, and to test the methodology and logic of the Drone Selector Tool, hypothetical data is generated to represent a ship in the USN/USCG fleet. The hypothetical ship metrics for this run have been designed to be both within the realm of possibility for a real-world ship as well as representative of a range of capabilities and limitations. The metrics chosen for this run are reported in Table 25.

The major drawback of this approach is that it does not necessarily represent any particular ship's metrics and/or capabilities—meaning, the suggested UAS resulting from the run cannot be taken to be meaningful suggestions for any one ship. However, the alternatives to this approach each have their own difficulties as well. For instance, a number of the metrics such as storage space, number of operators, and number of maintainers are fluctuating values between ships. This means that while one USCG Cutter may have 50 cubic feet of storage space to allocate to a UAS, another may have much less or much more depending on their current status and mission.

Therefore, it is important to note that this body of work is not intended to make recommendations to these particular ships outright. Instead, the goal of this study is to provide the underlying methodology in the decision-making process regarding fitting certain UAS with a ship of interest. The Drone Selector tool and its results reported here serve as proofs of concept for this methodology. In addition, it is worthwhile to again note that the tool has been designed in such a way as to allow easy manipulation of the input data as described earlier in this chapter. Any of the hypothetical data that is currently present in the "Ship Specs" sheet of the tool's Excel document can simply be changed to represent a real-world ship without impact to the underlying logic.

With that, the hypothetical ship metrics for this run have been designed to be both within the realm of possibility for a real-world ship as well as representative of a range of capabilities and limitations. The metrics chosen for this run are reported in Table 27.

Table 27. Drone Selector Tool Test-Run Hypothetical Ship Data Inputs

Specification	Value	Reasoning
Gas Allowed	NO	This represents the possibility that a ship either cannot or does not want to carry extra Gasoline onboard due to storage limitations, policy, or otherwise
Li-Ion Batteries Allowed	YES	This represents the possibility that the vessel is either capable of carrying extra batteries for the UAS, or that they have a means of recharging it reliably
Equipment Space	5000 cubic feet	This is representative of a 500 square foot (25'x20') storage area with 10 feet of overhead clearance
Launch Area	500 square feet	This is representative of a launch area that is 50 feet long by ten feet wide
Runway Length	50 feet	This is a realistic available runway for ships that were not designed to support the launch of aircraft requiring a runway

Specification	Value	Reasoning
Supports Water Recovery	NO	This is representative of a ship that either cannot or does not want to support water landings
Due Regard Sensors	YES	This is representative of a ship that is equipped with at least a rudimentary radar system for tracking the UAS while in flight
Number of Operators	2	This is representative of a ship that either cannot or does not want to divert more than two shipmen from their typical duties to operate the UAS
Number of Maintainers	2	This is representative of a ship that either cannot or does not want to divert more than two shipmen from their typical duties to maintain the UAS

Note in Table 27 that the equipment space and launch area space inputs are defied as 5,000 cubic feet and 500 square feet respectively. Their corresponding individual measures (length, width, and height) are reported as well. While, for example, a 5,000 cubic foot space could also be achieved with a height of 5,000 feet, a width of one foot, and a length of one foot, reasonable values are utilized in the creation of these spaces. In essence, realistic assumptions for these spaces are utilized here to model the measures of the ship. Additionally, it is worthwhile to note that some UAS alternatives are capable of vertical takeoff and landing (VTOL), thus their required runway length is set to zero within the tool. In simple terms, this means that any UAS with zero runway length required will pass the runway length check for any vessel.

These ship specifications are used in a variety of runs of the Drone Selector tool that encompass the four base mission sets—ISR/SAR contested & uncontested, and logistics contested and uncontested. Each of these runs are then carefully checked via manually performing the logic and comparing the results to what the tool itself reported. Note here that the user-input specifications are forgone for these runs for the purpose of maximizing the number of reported UAS to manually verify. However, each user-input specification (speed, loiter time, and altitude) are variably toggled on and off with a range of input values and their UAS exclusions/inclusions are manually checked and found true.

The first step in retracing the tool's logic is to verify that the pre-exclusions are successfully performed and each UAS was either included or excluded for the correct reasons. For the ship inputs reported in Table 25, many of the UAS are excluded due to insufficient storage space aboard the vessel; in fact, nine of the currently available sixteen UAS are excluded from consideration for this reason. Two additional UAS are excluded due to insufficient launch space and incorrect fuel type respectively. Therefore, five UAS remained for consideration as the logic proceeded. Upon manually confirming these results, the tool is found to be correct. However, it is worth noting that while a select few of the UAS are incompatible for more than one reason, the tool reports only one of these reasons—whichever check was failed first.

Next, the second round of pre-exclusions are checked—the UAS' ability to support each base mission at all. This logic, as described earlier in this chapter, accounts for each UAS' ability to support a payload and operate within a contested environment. Unsurprisingly, every listed UAS is considered able to support ISR/SAR missions in uncontested environments since they each are able to sustain flight and provide visual information. However, thirteen of the sixteen are excluded from ISR/SAR in contested environments with an even distribution of two reasons: either a lack of support for data encryption or GPS-denied flight. Similar results are found for the logistics base mission wherein most UAS are suitable for operation in uncontested environments since the only reason for exclusion is a UAS' inability to support an additional payload. In this case, six of the sixteen are excluded from further consideration. Finally, the logistics case in contested environment yields the fewest UAS for consideration since the UAS must be able to operate in those environments *and* support an additional payload. From this set of logic, only three UAS remain for consideration. Six are excluded for a lack of payload support, five for not having GPS-denied flight capabilities, and three for not supporting data encryption. Similar to the above, each of these are manually confirmed and found true.

Finally, the application of the swing weights and resultant calculations for each remaining UAS are conducted and manually confirmed. Unsurprisingly again, the

ISR/SAR uncontested case results in the most UAS recommendations given its relatively light requirements so long as a UAS is supported by the ship. Indeed, each UAS that is not pre-excluded due to lack of ship-based support is carried forward and scored. These UAS and their scores for this run with the hypothetical ship data are depicted in Figure 2 as an example output of the tool.

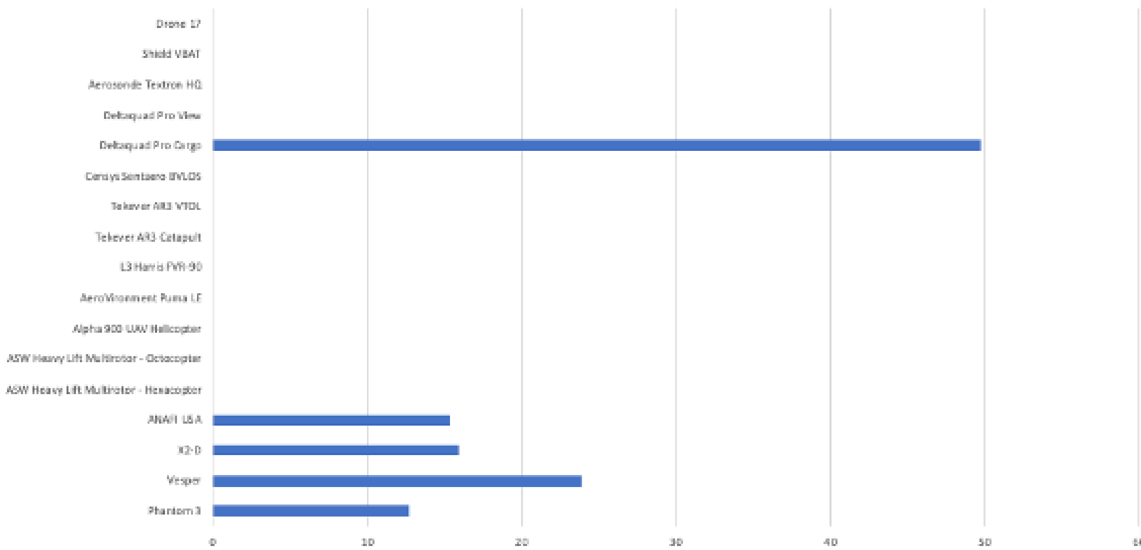


Figure 2. Example Output from the Drone Selector Tool

With the change from uncontested to contested comes a sharp drop in the number of UAS recommendations. In fact, for the ISR/SAR contested case, only one UAS is scored at all. The Vesper was the only UAS not pre-excluded due to lack of ship and/or mission support, and thus its score in this case maintains as 23.89.

Next, the logistics uncontested case results in, again, one UAS recommendation. The Deltaquad Pro Cargo is the only UAS to not be pre-excluded, and its resulting score is 34.56. Lastly, there are no UAS recommendations for the logistics contested case given that each UAS is either pre-excluded due to lack of ship support, lack of mission support, or both. The difficulty in this case is due to not every UAS supporting a payload or contested environments, and those that do are not suitable for the hypothetical ship's metrics for storage or launching reasons. Each of these results are again manually calculated and confirmed. Thus, the logic within the tool as it exists is sound and operates as designed.

With the results provided, it is important to note that generating the results and interpreting them are two completely different matters. The Drone Selector Tool itself exists to logically parse the inputs and mathematically determine each UAS' suitability in an objective manner. The subjectiveness in the decision-making process is theoretically accounted for in the swing weight calculations where the highest-priority characteristics are favored. However, an individual decisionmaker may be unique in that they prioritize an unaccounted-for metric over others. For example, in the case of uncontested ISR/SAR, the Deltaquad Pro View is mathematically the correct choice, but is of a slightly larger takeoff size than the second place UAS, the Vesper. Should a stakeholder want to minimize the space allocated to takeoff in certain situations, perhaps the Vesper is a better choice for their needs if they predict they can sacrifice other metrics such as maximum effective range. For those metrics that are accounted for within the tool—the MOEs—the user is able to adjust the swing weights to better align with their unique needs or goals.

Ideally, more of a UAS' characteristics and specifications are accounted for in the swing weight calculations. However, there is a level of convolution that is bound to occur if too many metrics are prioritized against each other in a hierarchy. There is a careful balance to be struck between mandating weights and priority to these metrics and leaving some of them to an individual's unique and subjective needs. For this study, the hierarchy of necessary metrics are provided by the stakeholder and sponsors. However, further research can be conducted regarding widening the spectrum of metrics that are accounted for in the swing weight calculations so that this appropriate balance is determined. This example and other opportunities for future work are covered in Chapter V of this paper.

E. CONCLUSION

The drone selector tool serves as a proof of concept for the decision-making process regarding outfitting USN/USCG ships with UAS. By ingesting and comparing ship, UAS, and user-input data, the tool mathematically indicates which UASs appear most capable for a vessel type via the Parnell swing-weight methodology. In certain unique cases, it is better suited for guiding the decision makers toward suitable options in the event that a subjectively prioritized metric is not accounted for. In these cases, the user is able to easily adjust the ship data and UAS requirements inputs to reflect their real-world circumstances to produce results most closely aligned with their needs.

IV. ANALYSIS, MODELS, AND RESULTS

A. INTRODUCTION

This chapter utilizes the findings from the previous chapters concerning ship parameters and UAS capabilities, limitations, and use cases to define the impacts to be derived from UAS inclusion aboard USN and USCG vessels. Introduced here are the series of operational cases that define a ship's base functions when conducting ISR/SAR or logistics missions. Next, the models that are created to encompass these missions both with and without UAS assistance are defined. Finally, the results of these models and calculations are presented.

B. CONCEPT OF ANALYSIS

Prior to any of the calculations taking place or models being built, the concept of analysis is defined in order to structure the methods and goals for these analyses. In broad terms, the primary objective of the analysis is to determine what effect the inclusion of UAS has on well-defined operational base cases.

The first step in conducting these analyses is to determine which metrics defining these scenarios are pertinent to the goals of each mission type—whether ISR, SAR, or logistics. These metrics are described in the Scenario Development section of this chapter.

Each of the mission types (ISR, SAR, logistics) have had "base cases" defined for them—that is, basic scenarios that the vessel must complete these missions within. These base cases are further defined in the following subsections. Each base case is first analyzed without the inclusion of UAS. Key result values are then extracted from the results of these runs and stored.

The results of these runs serve as the baseline that is then compared to a case with an integrated UAS. Each base case is conducted again with the inclusion of UAS with identical varied input variables. Each of the key values are then extracted again to be compared against the previously defined baseline. The changes in these key metrics between the distinct runs represent the effect of UAS inclusion in these operational base cases. Finally, an experimental design is conducted to demonstrate how changes to input factors affect scenario performance. These effects are then analyzed to define the benefits to the vessel and mission with the employment of UAS. The results of which are reported with reduced accuracy—i.e., numbers and calculated metrics are rounded to some degree. This is in effort of respecting the fact that live tests were not conducted, and all results are borne from models that cannot perfectly recreate real world scenarios. These results may be enhanced in the future with additional variables added to the models, or with live tests.

C. SCENARIO DEVELOPMENT

The modeling software, ExtendSim, is utilized for ISR & SAR scenario modeling, and Microsoft Excel for back of the envelope (BOE) ISR & SAR calculations as well as basic calculations in a generic afloat logistics scenario. The following sections discuss the models designed to quantify potential UAS benefits for surface platforms, the concept of operations that models are structured after, as well as the quantitative results of the models and their implications for their respective scenarios. The first section below discusses the operational concept around which the ExtendSim ISR and SAR models are built, the operational concept for the logistics scenario immediately follows. Once the operational context for the models has been established, the quantitative results for the back-of-the-envelope calculations and higher fidelity ExtendSim models then follows along with the implications of those results.

Simple and generic operational base case for the ISR, SAR, and logistics mission cases are designed. These base cases are designed to be scenarios wherein the afloat platform is not augmented by UAS to complete the specific mission being modeled. These generic operational contexts are modeling tool-agnostic. The same basic framework of analyzing a scenario base case without the benefit of UASs, and then building on those scenarios to quantify the impact of UASs, holds true regardless of the modeling tool being used. This section discusses the base cases and UAS cases for each mission set being analyzed: ISR, SAR, and logistics.

1. ISR/SAR Scenarios

The base case for ISR and SAR are similar in their modeling construct, regardless of their real-world differences—Section IV below expands on these real-world and modeling case differences. A simple operational scenario is constructed to serve as means by which to demonstrate and discuss the implications of UAS integration.

The ISR and SAR cases are centered on a search sector in the form a square in the middle of the ocean. The size of the square may change between the ISR and SAR scenarios to reflect their real-world differences, but the scenarios themselves are built around the same operational context. The search sector an afloat platform is tasked to conduct ISR operations in is substantially smaller than the search sector assigned to a platform conducting a search in support of SAR operations. The subjects of the search are referred to as Targets of Interest (TOIs) which are distributed throughout the search sector. The term 'targets of interest' is used throughout this section as a term meaning object to be identified within a given search area. A target of interest can be anything from an afloat adversarial surface combatant to a missing person adrift at sea. The term target does not connote the status of an object, as it pertains to national affiliation or adversarial status. The term target does not connote the status of an object, as it pertains to national affiliation or adversarial status.

Figure 3 illustrates the generic operational context for the project's ISR and SAR scenarios. Figure 3 contains the various elements that make up the ExtendSim modelling portion: a search sector of 160 NM by 160 NM, tracks within the search sector that represent the path the surface vessel takes to conduct their search of the box, TOIs to be detected by the searching platform, and shaded green and blue circles which represent the visual search range and radar range, respectively of the searching platform. This generic context is consistent across the various base case and UAS case scenarios. The variables that change are the radar and search range and how the ship reacts to targets that have been detected.

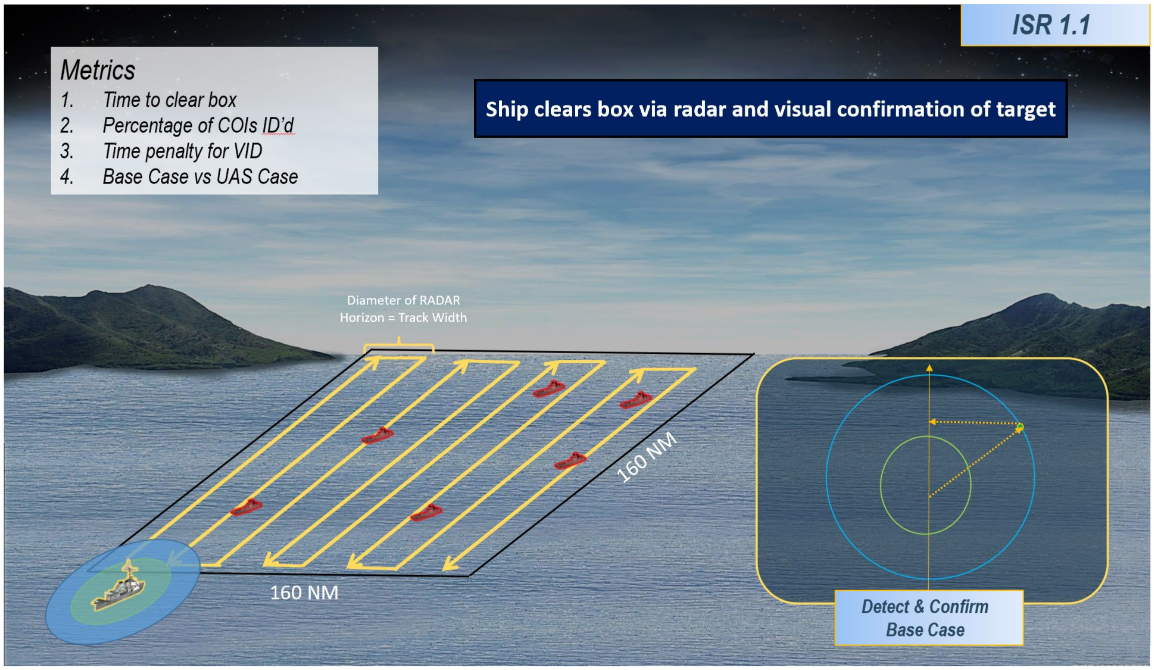


Figure 3. ISR Scenario 1.1

a. *ISR Scenario 1.1*

The ISR base case represented by Figure 3 depicts a scenario where a ship is tasked to clear a search sector and positively identify all TOIs within the sector. As the search platform progresses through the search sector on their base course, represented by the yellow lines within the sector, they have two ways of detecting and classifying vessels: either by radar or visually. The distance between these tracks that the ship is driving is referred to as track width (TW). The track width in the ISR scenarios is represented by the radar horizon of the search platform's surface search radar. radar allows the search platform to be alerted that a TOI is present, but in general, simple radar contact has been made insufficient for classification or identification. The search platform must close the TOI to within the visual range in order to classify and identify the TOI. When a radar detection occurs and the base course of the searching platform does not bring it within visual range, the searching platform must alter its course so that the new course brings the ship within visual range of the TOI. Once the TOI is identified, the searching platform returns to the base course and continue its course. This course deviation for identification comes with a cost. The time spent off-course for identification is time that the vessel is not on its base course completing its search path. As such, the longer the amount of time that a vessel is off-course for target identification is associated with a longer time for the search platform to complete its mission of clearing the search sector. The ISR case utilizing UAS to augment the search is designed to demonstrate how that off-course time may be mitigated by utilizing a UAS for target identification.

b. ISR Scenario 1.2

This scenario is displayed in Figure 4. It is identical to the one discussed in the previous section with one important exception: rather than the search platform having to divert from its base case for TOI identification, the vessel has a UAS onboard to aid in TOI ID. The UAS in this case is used to conduct a cued search based on a radar contact from the ship. The search platform had to divert from its base course when the radar came in contact with a TOI, but in this case, rather than diverting, the ship launches a UAS, fly the UAS to the TOI radar contact, and identify the target of interest with the UAS' onboard sensors. As a result, the search platform is able to continue on its base course to search its sector vice having to divert for TOI ID. Once the UAS IDs the TOI, the UAS returns to the search platform, waiting to be cued to the next radar contact.

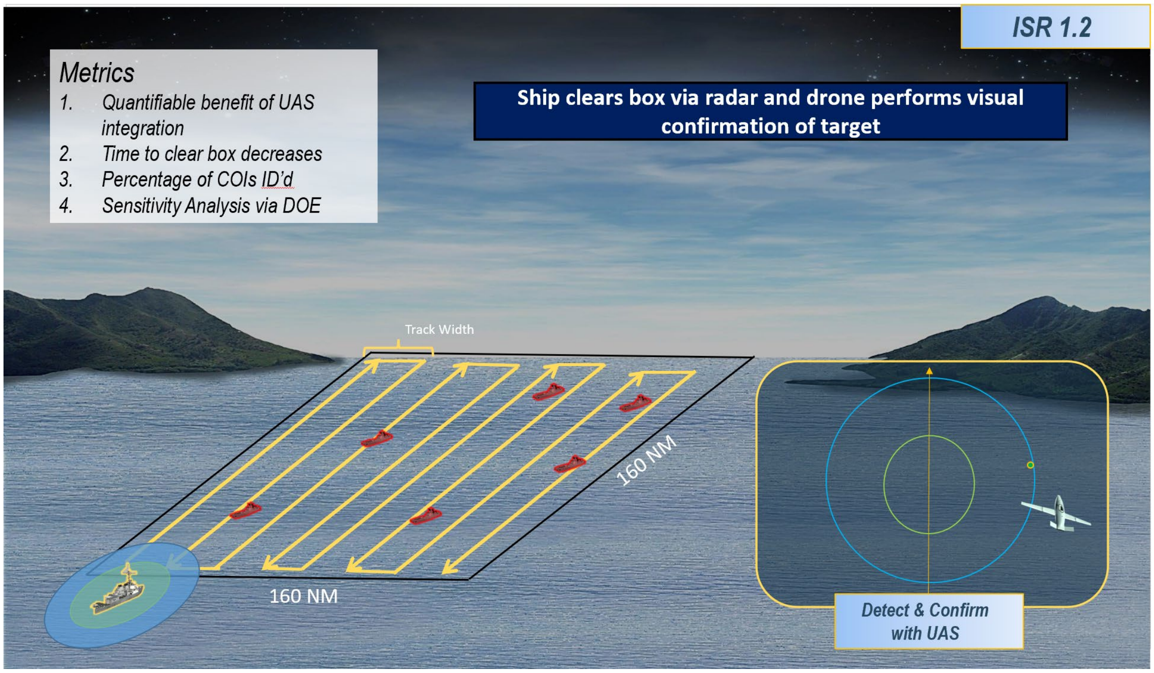


Figure 4. ISR Scenario 1.2

c. *SAR Scenario 1.1*

The SAR scenario's generic operational context is identical to the ISR scenario with the exception of the size of the box, the method by which the UAS are utilized, and the visual and sensor ranges. The decrease in visual and sensor range represents the dramatic difference in radar returns, and visual representation of a person in the water when compared with a vessel afloat. The search platform is able to detect and identify large vessels at much longer ranges than it would be able to for small, human-size contacts. As a result, the TW for the SAR scenarios has been made much smaller than in the ISR scenarios. The TW varies throughout the SAR scenarios to represent different UAS utilization methods. The TW may be the ship's visual range at which it can expect to see a human-sized object in the water, or it may be the range at which a human-sized object could be detected by a UAS-based sensor.

The SAR 1.1 scenario is one in which the TW is the search platform's visual range for human detection. This scenario is displayed in Figure 5. Due to the smaller TW, relative to the ISR scenarios, the search platform must drive to an increased number of tracks within the search sector to complete the search of the area. Radar or sensor range is not a factor in the SAR 1.1 scenario as all detections are made visually. SAR 1.1 serves as the base case upon which the rest of the SAR scenarios are built. As such, the metrics for 'search time' and 'TOIs detected' are used to ascertain the potential benefit of incorporating UAS into the SAR mission.

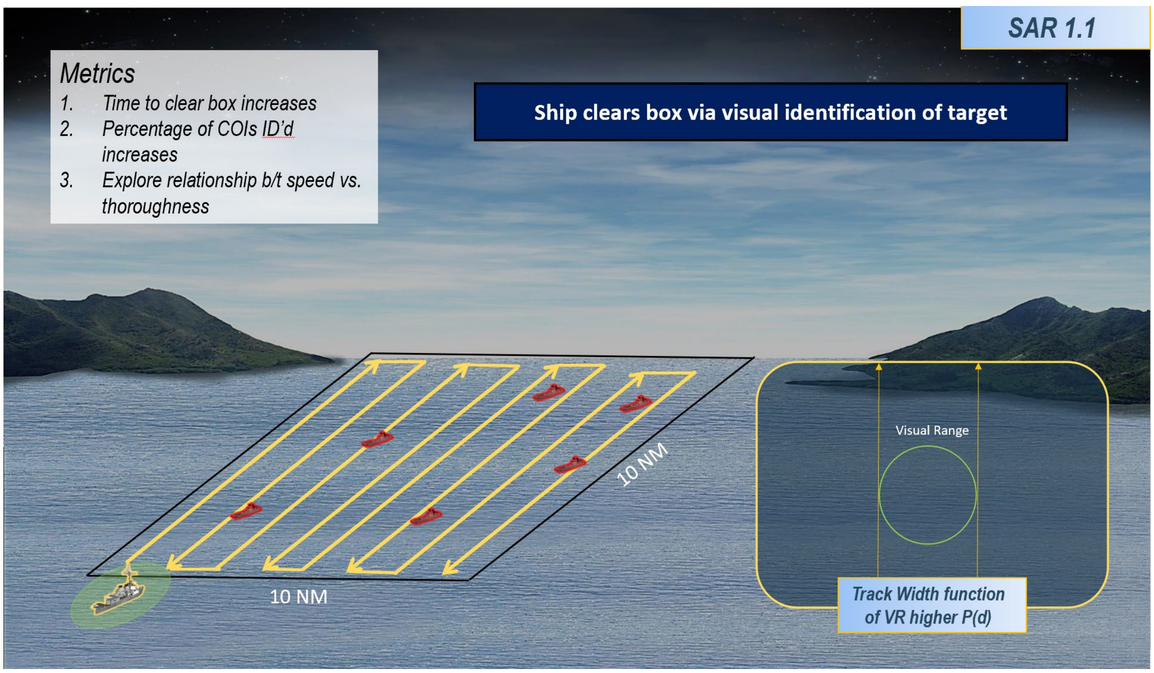


Figure 5. SAR Scenario 1.1

d. *SAR Scenario 1.2*

The critical difference between SAR 1.1 and SAR 1.2 is the track width of the search platform. SAR 1.2 is the first SAR scenario that utilized a UAS, and it is represented by Figure 6. The UAS in this scenario is centered on the search platform, at an increased altitude. This has the effect of increasing the range at which the search platform is able to detect TOIs. This has the effect of decreasing the time it takes a vessel to clear its search sector due to having to run fewer tracks within the sector as a result of its increased track width. However, due to the difficulty of detecting human-sized objects in the vastness of the ocean, increasing the range at which a sensor can detect them, may have a corresponding decrease in the number of TOIs detected. Therefore, while the time it takes to search the sector may decrease, the accuracy with which the sector is searched may have a corresponding decrease as well. This has the effect of not detecting objects when they are present. SAR 1.2 may be thought of as a scenario where the speed at which a search may be conducted may outweigh the focus on the accuracy of the search. This may be representative of a scenario where the time to complete a search is the more important factor during real-world scenarios; for instance, the scenario where a person is in the water in extremely cold water. This scenario is one where the person in the water has a small amount of time before they succumb to the elements and, as such, covering a large amount of water quickly is vitally important.

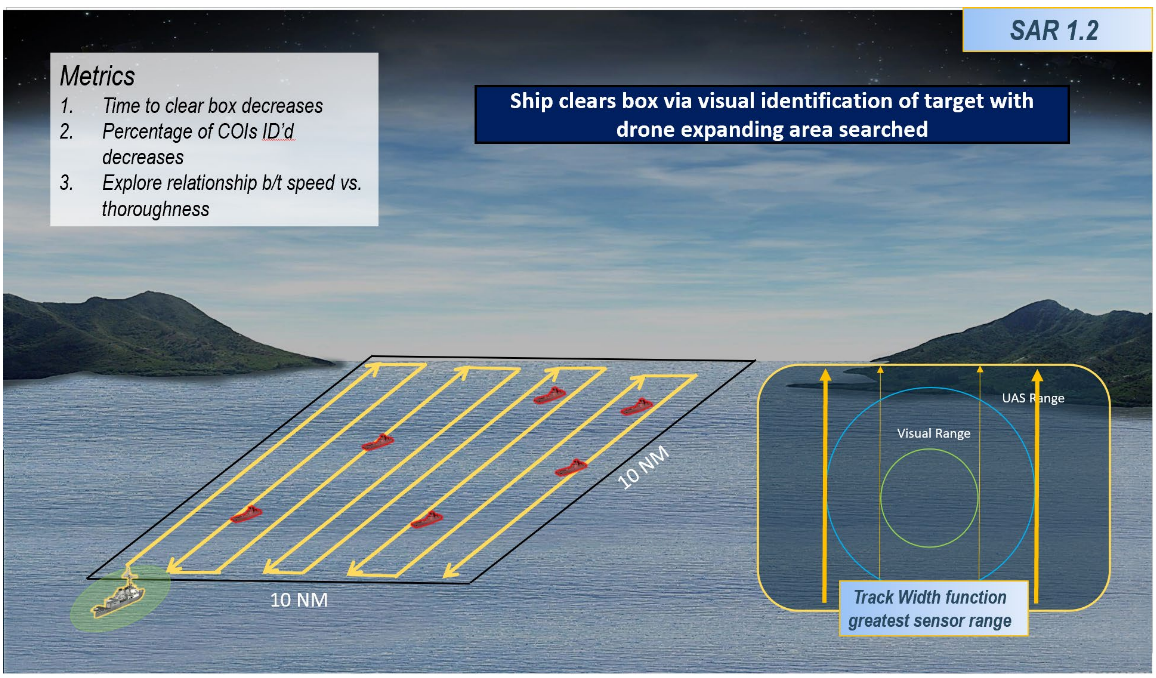


Figure 6. SAR Scenario 1.2

e. SAR Scenario 1.3

SAR 1.3 is another scenario where the UAS is integrated into the scenario. The UAS is once again centered on the ship at an increased altitude. However, unlike in SAR 1.2, the track width is not increased to the UAS sensor range. Rather, the TW remains the visual detection range from the ship, as is the case in SAR 1.1. In this usage pattern, the UAS is being used to increase probability of detection as opposed to expanding the search range. SAR 1.3 is displayed in Figure 7. This scenario is designed to test the assumption that using the UAS centered on the ship and keeping a small TW leads to an increased probability of detection of human-sized objects at sea. Unlike SAR 1.2, the time it takes the search platform to clear its search sector is similar to SAR 1.1 but it does so with increased accuracy, and with a higher probability of detecting the object in the water.

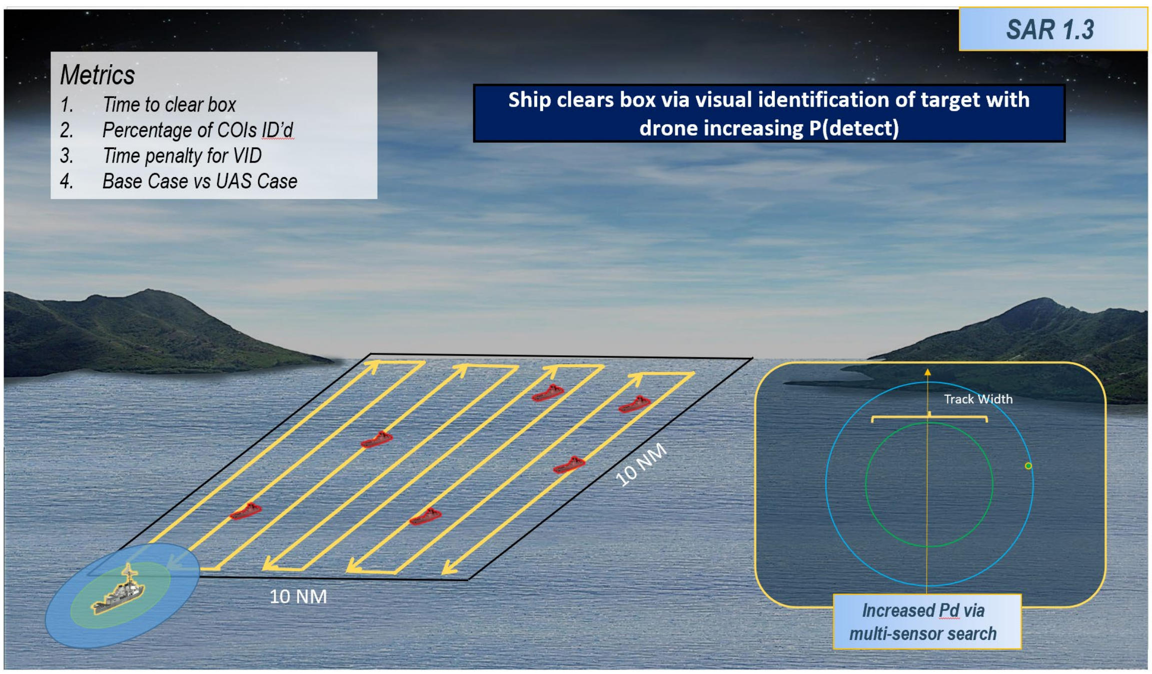


Figure 7. SAR Scenario 1.3

2. ISR/SAR Impacts to be Derived

Each of the modeling instantiations looks at a number of metrics that are used to quantify the benefit of implementing UAS scenarios. Although the operational context and ultimate goal, or 'mission success' criteria are vastly different between the ISR and SAR mission sets in real-world operations, the elements of these two missions are extremely similar when analyzing them from a modeling perspective. Generally speaking, ISR missions are meant to conduct a search and collect intelligence on an operational area and disseminate this information to relevant concerned units. The ultimate goal of a SAR mission is to conduct a search for a missing person, people, or vessel, and once identified, transport them to safety. While these two goals are vastly different, the elements which compose them are extremely similar: both scenarios are conducting a search in a given area, attempting to identify targets of interest, and in both scenarios, the area to be searched and the time it takes to search them are determinants of mission success.

The relevant metrics for the modeling effort emerge from the scenario descriptions in the preceding sections. Each scenario regardless of the modeling tool has specific metrics that are used to quantify the potential benefit that may be derived from UAS integration.

Another large driver of the potential benefit is the time that it takes the search platform to complete its search of the sector. As stated earlier, the search sector size is constant across each iteration of a given scenario (within its mission subset), and as such, a change in the time it takes to complete the search of a given area is a tool that may be used to determine the efficiency with which search platforms are conducting their search; whether that is for an adversarial surface combatant, a drug smuggler, or a man overboard that needs saving. Using ISR 1.1 as an example, every minute that the search platform is off its base course to close a radar contact for identification is a minute that is not spent progressing through its search. It is expected that this time penalty will manifest itself in the total time it takes to complete the search of the sector.

These two metrics in concert—the number of targets identified and the time it takes to complete the search—facilitate the determination of whether UAS integration into different mission scenarios have an appreciable impact or not. A decrease in search time to clear the search sector would be an indication that by incorporating UAS to augment a vessel conducting SAR or ISR operations, the total amount of time that it takes for the search to be conducted goes down. Ideally, this decrease in search time would also be associated with an increase in the number of TOIs identified or a stable number of TOIs identified rather than a decrease in the number of TOIs identified. A result of decreased search time to complete and an increase in TOIs identified would indicate that UASs are allowing surface platforms to complete the search of their sectors faster coupled with a higher probability that they identify targets within the search sector given they are present.

ISR 1.1 and SAR 1.1 are the base cases that are used to quantify the benefits of integrating UASs for ISR and SAR missions. The relative change in the time to complete a search, and the number of TOIs detected and classified is a tool that can be used to attempt to answer the question: *Do UAS provide significant aid in completing this mission?*

3. Logistics Scenarios

This study sought to analyze the at-sea logistics mission in addition to ISR and SAR missions. The modeling completed for the logistics mission is much lower fidelity than the modeling done to quantify the potential benefit of UAS in ISR and SAR. Rather than using ExtendSim, a simple Excel calculator is used instead. The benefits of incorporating UAS in the logistics mission may be adequately modeled at an introductory level by simple time, speed, and distance calculations due to the variables identified to quantify the benefit. The potential benefits are discussed later in this section.

Figure 8 shows the operational context of the logistics scenario. There is a plethora of potential logistics scenarios that can be modeled to represent the benefit of incorporating UAS into the mission, but the modeling required dramatically increases with a marginal increase in scenario complexity. This scenario is simple enough to 1) illustrate the potential benefits of UAS for this mission and 2) be a manageable modeling effort for a project with limited time constraints.

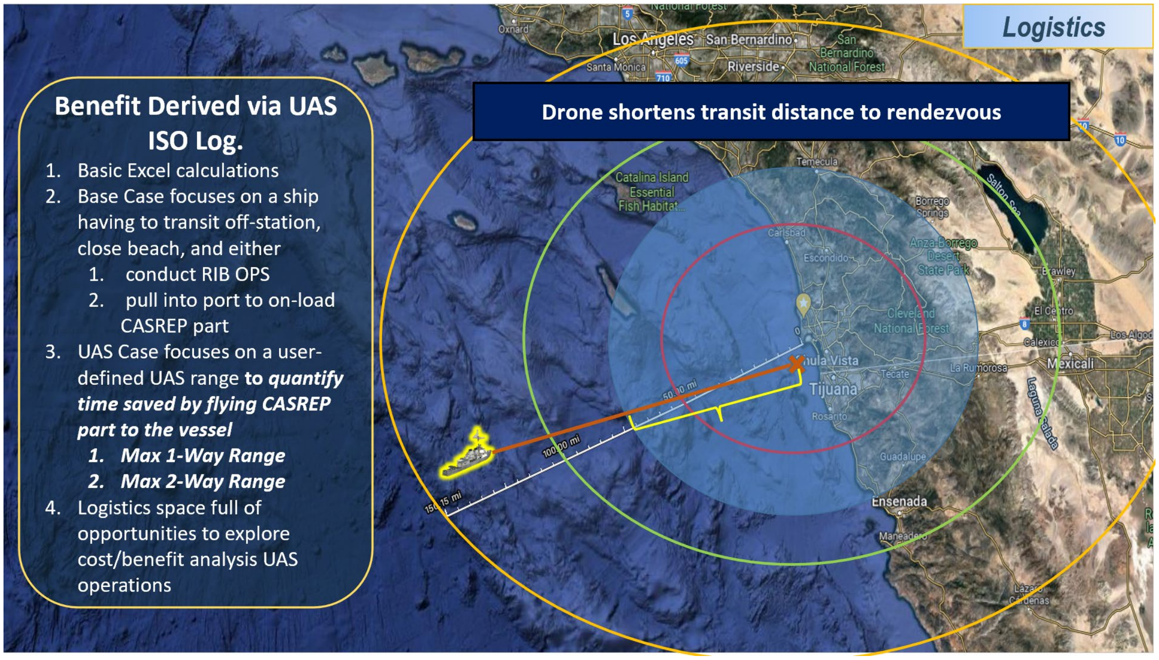


Figure 8. Logistics Operational Context

This scenario is built around a surface ship at sea. This scenario is a ship that suffers a critical casualty while conducting training operations. The ship does not have the required parts onboard to fix the equipment that has suffered from the casualty. As a result, the ship must onload a replacement part from the logistics hub on shore. The ship has several options to accomplish this. The suitability of the option is determined by the length of time it takes the ship to onload the part and return to its operational area and resume its operations. Any amount of time spent onloading the replacement part costs the ship as well as the USN/USCG in a number of ways: the dollars spent on gas and personnel while the ship is off-station picking up its part, in addition to the opportunity cost associated with having an operational asset off-station.

The first option for getting the part onboard is also the costliest. This option has the ship returning to port, mooring up pier-side, onloading the part, and returning to sea. This option is the costliest in time off-station, gas, and the opportunity cost of missed training or operational time spent conducting the mission. This option requires the ship to depart its operational area (OPBOX) and drive towards the beach. The amount of time that it takes the ship to get to shore is a function of its distance from shore as well as its speed. Once the ship is in the vicinity of shore, the ship commences the process of pulling into port, also known as the Sea and Anchor detail. Sea and anchor details are notoriously difficult evolutions where the risk of accidents is dramatically increased when compared with open ocean steaming in peacetime. The amount of time it takes to complete the Sea and Anchor detail and moor up pier-side varies with the port the ship is pulling into, but it does so regardless of how long it takes, every minute pulling in is a minute spent not training or operating as tasked.

The second option is the scenario where the ship once again has to leave its OPBOX and close the beach. However, rather than pulling in to shore and mooring pier-side, the ship pulls to within a mile of shore, deploys the rigid inflatable boat (RIB), and drives the RIB to the shore to pick up and return with the part needed to return the ship to full operational capability. This option requires a shorter amount of time to complete than option number one, but the ship is still required to close the beach to a distance where RIB operations are possible. The ship saves time by not pulling in, but it is still spending a large amount of time off-station to complete a part transfer.

The final option for getting the required parts onboard the ship is to use the available UAS onshore as a parts-delivery platform. The specific tactic that this study uses for incorporating a UAS in a logistics mission is to have the receiving ship traverse to a rendezvous point that is half the maximum distance of the UAS. In this context, the maximum distance is determined by the fuel state on the UAS vice communications range limitations. As the ship nears the rendezvous point, the UAS will depart the base on shore to rendezvous with the ship in such a manner that minimizes the time the ship is loitering at the rendezvous location. Using this tactic allows the UAS to save time that would otherwise be spent on refueling aboard the ship after the part delivery. There likely exists an operational scenario that favors using the UAS at its maximum operational range, but that tactic is not explored within this report. There are methods to minimize the time the UAS would spend refueling on the ship such as using a gas-powered UAS, or having spare, fully charged batteries in the scenario the UAS is battery powered.

4. Logistics Impacts to be Derived

The previous section referenced the various costs that are associated with a surface ship having to leave its OPBOX to onload a part that is required to maintain operational status. Using a UAS to augment the logistics mission for ships may save time, money, and operational asset loss in addition to mitigating the risks that are inherent with ships operating close to shore or within busy harbors.

Each of the part onload options discussed above requires the ship to leave its OPBOX to onload a replacement part. The only way the ship is able to remain on station constantly is if the ship's OPBOX is close enough to shore, or a sea-based logistics hub, such that it is within the UAS range without having to close to a rendezvous location. The key metric to determining the potential benefit ff using UAS in this specific logistics context is 'time off-station.' Except for the circumstance mentioned previously, each of the logistics scenarios requires the ship to leave its OPBOX. The longer the ship is away from its OPBOX, the greater the cost. Whether that cost comes in the form of excess gas expenditure transiting to shore, or to a rendezvous location, every minute the ship spends away from its mission is time and money wasted. Therefore, the logistics model is used to see if incorporating a UAS is able to minimize the amount of time that a ship is spending away from its OPBOX.

One way to quantify this at a basic level is to determine how much money it costs for a USN surface vessel to be at sea. This is not intended to be a representation of in-depth cost analysis, but as a way to demonstrate a way to quantify the potential benefits of UAS at a 10,000-foot level. The Government Accountability Office (GAO) released a report in February of 2023 which quantified the total annual cost of operating a ship in 2021 by ship class. This report states that in 2021, it costs $80.5MM dollars to operate and sustain an Arleigh-Burke Class Destroyer [42]. This cost includes maintenance, sustainment, and operations, and as such is a holistic representation of how much it cost to operate an Arleigh-Burke class DDG in 2021. Additionally, each year the Department of the Navy budgets for a specific number of underway days for afloat platforms per quarter. The DON budgets for a specific number of underway days per quarter for deployed ships as well as for non-deployed ships. The 'non-deployed ship' underway days per quarter is used for the purposes of this section. The FY21 budget included 24 days/quarter for non-deployed ships. Converting 24 days/quarter to hours/year yields a number of 2,304 underway hours budgeted for non-deployed ships in FY2021 [43]. Therefore, using the annual cost of an Arleigh-Burke DDG in FY21 mentioned above, it is possible to crudely quantify the cost of each non-deployed underway hour in FY21 for an Arleigh-Burke DDG as $34,939.24. Therefore, each hour that a UAS can save a non-deployed Arleigh-Burke from being off-mission, saves taxpayer money to the tune of $35,000. As mentioned, there are many assumptions that are baked into this calculation, but the purpose of this exercise is to demonstrate how expensive it is to operate ships at sea, and the importance of saying as much time as possible in as many ways as possible.

The proceeding sections discuss how the generic operational contexts and mission scenarios are converted to models used to quantify the potential benefits that are discussed in the previous sections. Once the models have been appropriately defined, the results of the models as well as the implications of those results are discussed.

D. PRELIMINARY MODEL CALCULATIONS

Prior to designing the models that the previously defined base cases simulate, there is need to formulate them mathematically. In the case of ISR/SAR, there is a non-trivial formulation that defines the area searched by the ship and/or drone as they traverse the operational area. In the case of logistics, there is the somewhat simpler formulation that kinematically defines the optimum use of the UAS in receipt/delivery of a package. Both are presented at length in the following subsections.

1. Area Searched

The primary mode of search for the ISR/SAR case in this study is known as "exhaustive search." This mode of search relies on maintaining a search pattern within an operational area in effort to cover the area entirely. The alternative mode of search presented by our source is that of random search which relies on unsystematically covering an operational area. This is a "memoryless" approach wherein the time taken on previous searches thus far does not affect the likelihood of a successful subsequent search. With that being the case, the time to search is based entirely on the number of targets available to be detected and how "lucky" a searcher is in locating them. The prior in this case, exhaustive search, is the focus for this study's models given that its systematic approach lends to the inverse notion—any unsuccessful search increases the likelihood of subsequent searches. Stated simply, the exhaustive search mode allows for more accurate prediction of the time needed to search an operational area entirely. The increased certainty in the search time necessary allows for largely unambiguous extraction of the effect UASs have on search success [44].

The source for the methodology for this portion of the study, "An Analytical Comparison of Random and Exhaustive Search of an Expanding Area with Binary Sensors" [44], provides equations for the percentage of an operational area swept per unit time.

For a single searcher (ship without a UAS):

$$Search\ Ratio = \begin{cases} \dfrac{wvt}{A} & ,C \leq 1 \\ 1 & ,C > 1 \end{cases}$$

where:

- w is the radius of the searcher's visual range
- v is the velocity of the searcher
- t is the time of search
- A is the square area of the operational area
- C is the product of w, v, and t divided by A

For multiple searchers (ship with a UAS):

$$Search\ Ratio = \begin{cases} \dfrac{(w_D v_D t) + (w_S v_S t)}{A} & , C \leq 1 \\ 1 & , C > 1 \end{cases}$$

where:

- w_D is the radius of the UAS's visual range
- v_D is the velocity of the UAS
- w_S is the radius of the ship's visual range
- v_S is the velocity of the ship
- t is the time of search
- A is the square area of the operational area
- C is the sum of the products of w_D, v_D, t, and w_S, v_S, and t divided by A

Note here that the caveat for C's relation to 1 is present in both cases. This is a simple "catch" to prevent answers larger than 100%. Given that the products of v, w, and t can result in an area larger than A, it is possible to consider area outside of the operational area if this caveat is not in place.

These equations may be rearranged to solve for time. Doing so for the single searcher case yields:

$$t = \frac{SR \cdot A}{wv}$$

For multiple searchers:

$$t = \frac{SR \cdot A}{w_D v_D + w_S v_S}$$

With these four equations, preliminary calculations may be conducted that represent a UAS' effect on the search capabilities of a ship. Utilizing the equations solving for search ratio, the average increase in the percentage of the operational area searched can be determined. To accomplish this, an Excel sheet has been set up to hold the following variables constant:

For SAR:

- Ship velocity: 15 nautical miles
- Ship sensor radius: 0.25 nautical miles
- UAS velocity: 40 nautical miles
- UAS sensor radius: 0.0625 nautical miles

For ISR:

- Ship velocity: 15 nautical miles
- Ship sensor radius: 70 nautical miles
- UAS velocity: 40 nautical miles
- UAS sensor radius: 10 nautical miles

ISR and SAR are both conducted in two sets—one with the time being the varied input, and another with operational area being the varied input. For the cases where operational area is the varied input, the time allotted is held constant at two hours for SAR, and four hours for ISR. For the cases where time is the varied input, the operational area is the resulting value—i.e., it is a raw return of how much space can be covered for the allotted time. The results of these runs are depicted in Figures 9 through 12.

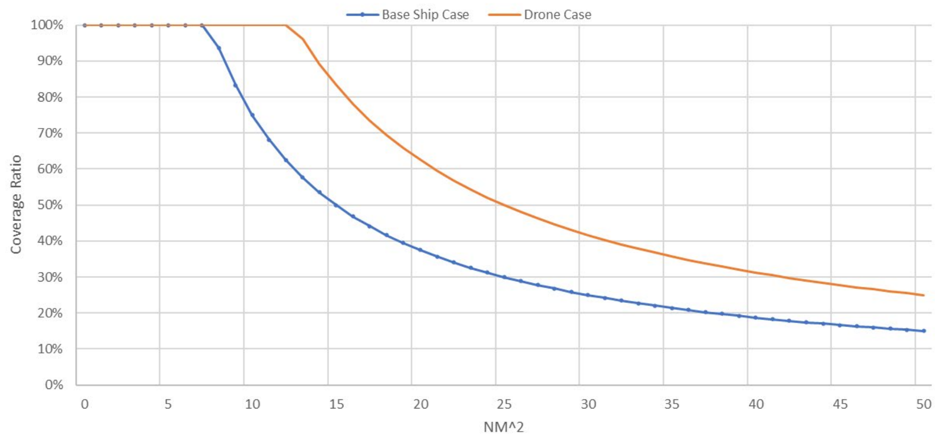


Figure 9. SAR Coverage Ratio with Two-Hour Search Time

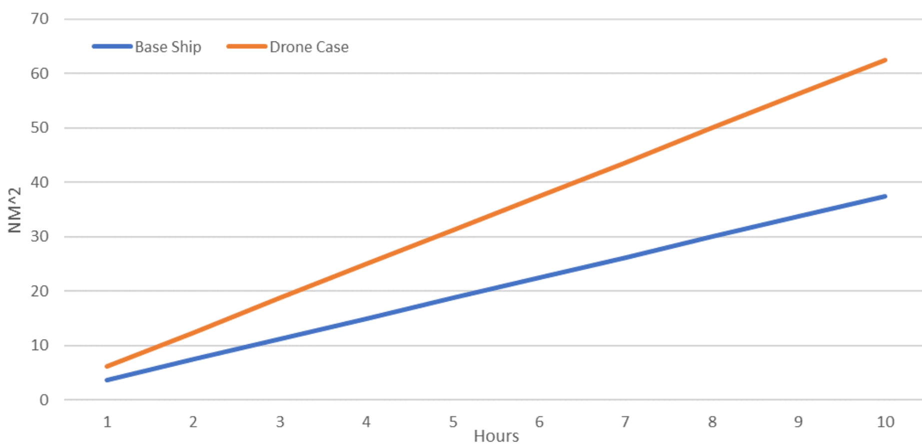


Figure 10. SAR Area Covered per Unit Time

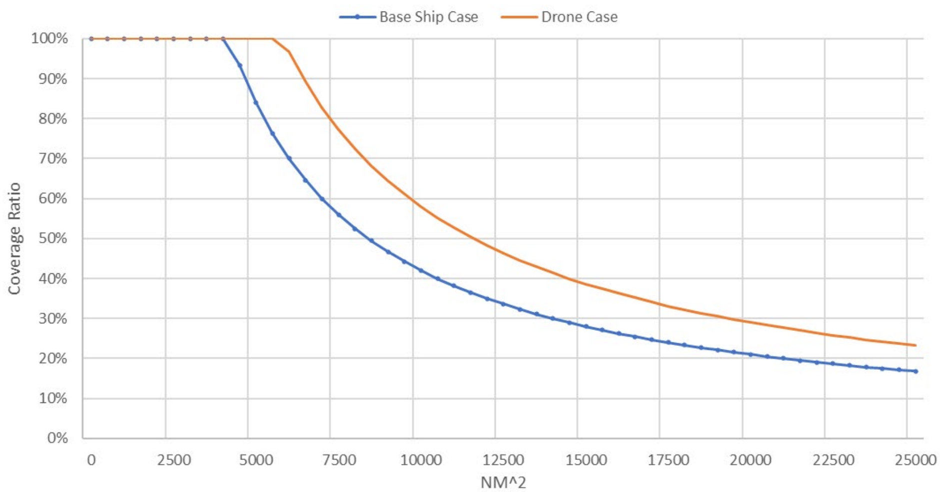


Figure 11. ISR Coverage Ratio with Four-Hour Search Time

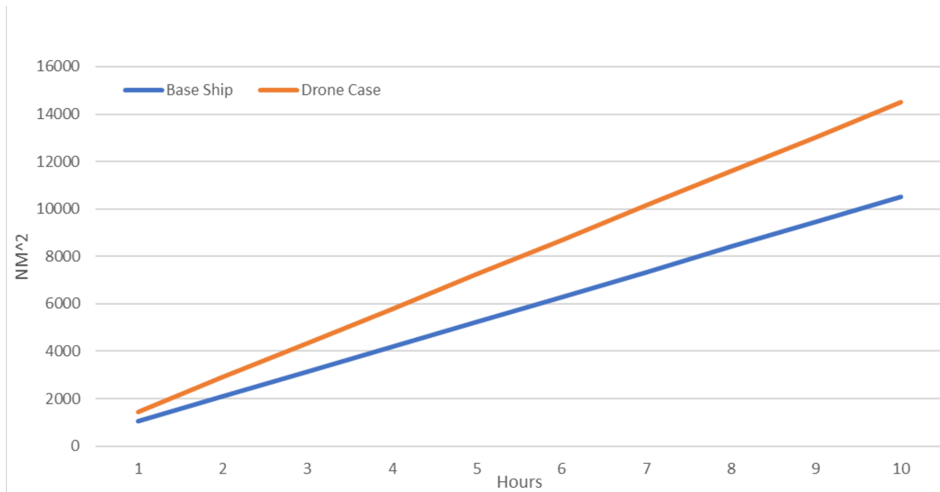


Figure 12. ISR Area Covered per Unit Time

In each case, it is clear that the addition of a UAS to the search pattern is beneficial. In the case of both the ISR and SAR area covered per unit time examples, the addition of UAS increased the searched area by 1.38x and 1.66x respectively. For the SAR coverage ratio with a two-hour search, the addition of UAS saw an average increase of 16% to the area covered. For the ISR coverage ratio with a four-hour search, the addition of UAS saw an average increase of 10% to the area covered.

2. Logistics

For logistics missions, this study focuses on elucidating but one of the many potential benefits UAS may bring—save time for the ship by reducing how far it must divert from its station in order to receive a delivery. The calculations for this are quite simple, requiring only the fundamental connection between velocity, distance, and time:

$$t = \frac{d}{v}$$

Utilizing this simple equation, the time required for the ship alone to complete delivery may be calculated and compared to the time required for a ship aided by a UAS. To exemplify the effect UAS have on this mission, two base cases have been defined and are represented in Tables 28 and 29.

Table 28. Logistics Case 1

Parameter	Units	Value
Distance From Shore	NM	150
Ship Speed	NM/hr	20
Two-Way Range of UAS	NM	30
UAS Speed	NM/hr	40
Distance to Rendezvous Location	NM	120
In-Port Transit Time	Hr	1
Part Onload Time	Hr	.25
Part Offload Time	Hr	.25

Table 29. Logistics Case 2

Parameter	Units	Value
Distance From Shore	NM	150
Ship Speed	NM/hr	20
Two-Way Range of UAS	NM	15
UAS Speed	NM/hr	30
Distance to Rendezvous Location	NM	135
In-Port Transit Time	Hr	1
Part Onload Time	Hr	.25
Part Offload Time	Hr	.25

In both cases, the distance from the shore, ship speed, in-port transit time, and part onload/offload time are held constant between them. The only differences between the two cases are the speed of the UAS and its two-way range (i.e., its maximum range divided by two to account for the return trip). The distance to the rendezvous location changes necessarily because of the change in the UAS' two-way maximum range—that is, the distance the ship must travel in order to guarantee that the UAS makes it to shore and back increases when the two-way range decreases.

For each of these cases, there are a series of calculations that must take place in order to garner a full picture of the events:

- Time to Shore (ship without UAS)
- Time to Rendezvous Location (ship with UAS)
- Total Time (ship without UAS)
- Total Time (ship with UAS)

The key results from these calculations are those of the total times in each case (with or without UAS aid). The difference between these values is representative of the effect the UAS has on the total off-station time the ship needs to undergo in order to receive the delivery. To accomplish this, each respective case is run explicitly and distinctly via the following calculations:

$$Total\ Time_{no\ UAS} = 2\left[\frac{d_{shore}}{v_{ship}}\right] + t_{onload} + t_{offload}$$

$$Total\ Time_{with\ UAS} = 2\left[\frac{d_{rendezvous}}{v_{ship}} + \frac{\left(d_{shore} - d_{UAS\ range}\right)}{v_{UAS}}\right] + t_{onload} + t_{offload}$$

Performing these calculations for each of the logistics base cases yields the results provided in Tables 30 and 31.

Table 30. Logistics Case 1 Results

Parameter	Value
Time to Shore – Ship without UAS	7.5 Hrs.
Total Time – Ship without UAS	17.5 Hrs.
Time to Rendezvous – Ship with UAS	6 Hrs.
Total Time – Ship with UAS	14 Hrs.
Time Saved	3.5 Hrs.

Table 31. Logistics Case 2 Results

Parameter	Value
Time to Shore – Ship without UAS	7.5 Hrs.
Total Time – Ship without UAS	17.5 Hrs.
Time to Rendezvous – Ship with UAS	6.75 Hrs.
Total Time – Ship with UAS	15 Hrs.
Time Saved	2.5 Hrs.

As evidenced by these results, even with a sharp decrease in UAS capability (range and speed), the time saved to conduct these deliveries is not inconsequential. The impacts to be derived from their use are especially stark when considering the cost per hour incurred by maneuvering these vessels including fuel and manpower requirements. These cost benefits are calculated and further discussed in a following subsection.

E. MODELING

1. ExtendSim Introduction

ExtendSim, a simulation software created by Imagine That Incorporated, is used for the modeling in the following sections. ExtendSim is a suite of simulation software that allows for continuous, discrete event, and other forms of simulation modeling. The software contains libraries of "blocks" and "connectors" and a simple graphical user interface that allow for the development of complex models of scenarios, processes, and flows. ExtendSim allows for stochasticity in models using various distributions as well as rapid updating and addition of inputs into models. Using the libraries, ExtendSim models are rapidly updateable such that they can be refined over time to approximate the real-world system under consideration more closely. Importantly, ExtendSim allows the tracking of statistics, metrics, and outputs of models which allows for detailed analysis of real-world process being approximated [45]. In the following sections, the several continuous ExtendSim models built as well as the analysis of the resulting outputs are described.

2. ISR Modeling

a. Detect and Confirm

This model replicates the ISR queued search scenario described earlier in this chapter and calculates the impact on mean time to search when one or multiple UAS' are introduced into the scenario. In this model, the UAS is used only to confirm targets that have been detected via the ships radar or lookout. A high-level diagram of the model is shown in Figure 13.

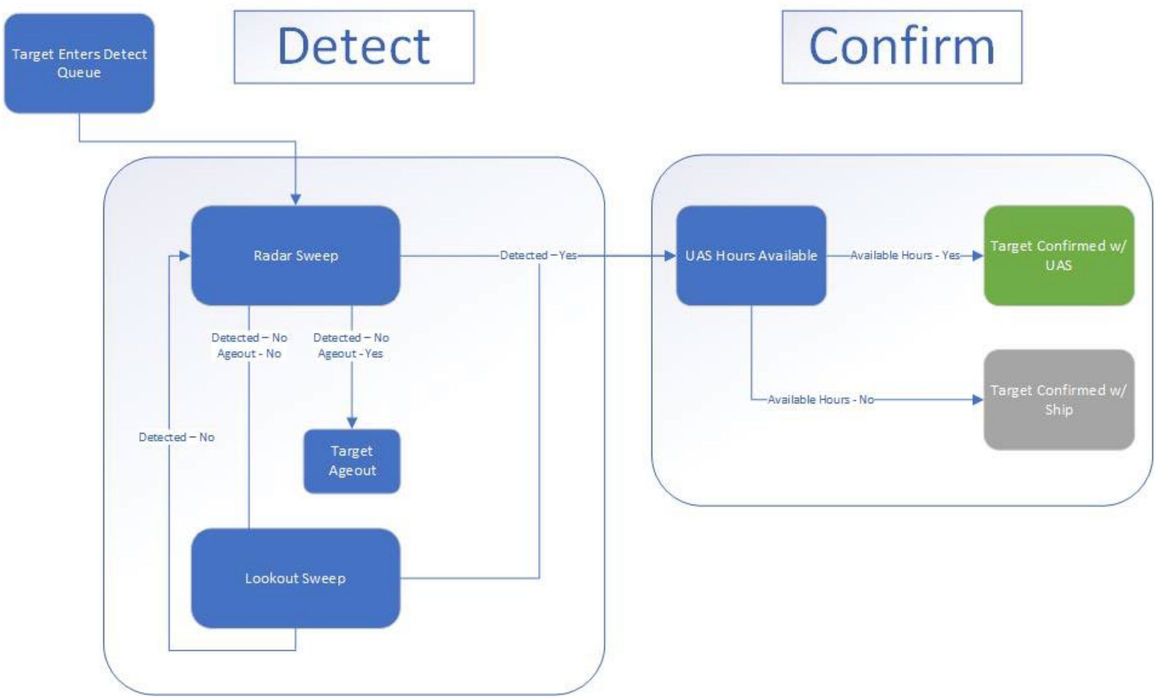


Figure 13. ISR Detect and Confirm Diagram

This model begins by generating a number of items equal to the number of targets. These items then are initialized with attributes relating to the input values shown in Table 32. Next, the model calculates global variables that determine total search time. These variables feed random number generators to determine a position in time for each target. Each item then waits in a queue until the ship is in radar range of the target.

Once the ship is in radar range (i.e., the appropriate time has been reached), the item is released from the queue and, if the ship has already diverted course to confirm another target, time is added to its location. The item is then fed to the radar queue. If the radar detects the item, the item moves on to the confirm portion of the model. If the radar has not detected the target, the model checks to see if the lookout is within range. If the item is within visual range, the lookout has the chance to detect the target. If either the radar or the lookout is successful in detecting the target, the item moves onto the confirm portion. If neither the radar nor the lookout detects the target, the item is recycled back into the radar queue. This loop continues until the item has been detected or passed by the ship and outside of the ships visual and radar range. If this happens, the target is marked as not detected.

The first portion of the confirm model checks for available UAS hours via the equation below:

$$H = n_{UAS} \cdot t_{Loiter}$$

where:

- H is the number of flight hours possible
- n_{UAS} is the number of UAS in operation
- t_{Loiter} is the loiter time for the UAS

If the number of hours remaining is greater than then number of hours it would take to send the UAS out to confirm the target, then a UAS is dispatched. If not, the ship diverts course to confirm. If the ship confirms a target time is added to subsequent items and thus the length of the mission increases. The amount of time it takes for a UAS to confirm a target is decremented from the current total of UAS hours.

The model slices the search box into lanes that the ship must search given its sensor range. For the D&C model the sensor range used is the radar. The models discussed in the SAR section of this chapter use a similar calculation but use either an min or max of visual and UAS range. Below, the equations used for the D&C model are presented. These equations provide the total search time required to cover the box.

$$n_S = \frac{L_{SB}}{2r_R}$$

$$t_{ST} = \frac{W_{SB} - 2r_R}{s_S}$$

$$t_T = \frac{2r_R}{s_S}$$

$$T_{seg} = n_S - 1$$

$$t_{total} = n_S \cdot t_{ST} + T_{seg} \cdot t_T$$

where:

- n_s is the number of segments
- L_{SB} is the length of the search box
- r_R is the radar range
- t_{ST} is the segment transit time
- W_{SB} is the width of the search box
- s_S is the ship speed
- t_T is the transition time
- T_{seg} is the segment transitions

- t_{total} is the total time

Knowing the total time needed to scan the box, the model then randomizes the target locations. Target 2-dimentional locations are generated and stored as times for when the ship is perpendicular to the target. First and last allowable detection times are created using the initial target time for each sensor. The model uses ship speed, UAS speed, and current time to calculate a relation to target position. As time moves forward, so does the ship, until the targets first allowable detection times are reached. A target then has a chance to be detected by the onboard sensors. If no detection by any sensor is made by the last allowable detection time, the target is marked as a non-detection. The stochasticity of the model comes from the randomized location generation and probabilities of detection.

This model takes the inputs shown at Table 32 and returns the time it took to complete a run, the number of confirmations made with UAS, the number of confirmations made with the ship, and the number of non-detections.

Table 32. ISR Detect and Confirm Model Parameters

Input	Description
Search Box Length	Length of the box where the target(s) can be found
Search Box Width	Width of the box where the target(s) can be found
Number of Rescue Targets	The number of targets in the search box
Create Time	Variable required to initialize the creation of targets. This value is always 0
Ship Speed	The speed at which the ship travels
Visual Range	The distance that the target(s) can be detected by a lookout from the ship
Ship Visual Detect Probability	The likelihood of a target being detected by a ship's lookout
Ship Radar Range	The distance that the target(s) can be detected by the ship's radar
Ship Radar Detect Probability	The likelihood of a target being detected by a ship's radar
AddTime	Used to increment the location of other targets if the ship is diverted to confirm a target because a UAS is not available
UAS Speed	The speed at which UAS travels
UAS Loiter	The length of time that a UAS can spend in the air on a sortie
Number of UAS	The number of UAS available during the scenario

b. ISR Detect and Confirm Model Results

The base case exercises the model without the integrated UAS (i.e., NumUAS = 0). It provides a baseline to compare against the integrated drone case and consider the validity of the results the model provides. The following inputs shown in Table 33 are used to establish the base case. The model is run with the same inputs for 100 runs.

Table 33. ISR Detect and Confirm Base Case Inputs

Parameter	Value
Visual Range	5 NM
Search Box Length	160 NM
Search Box Width	160 NM
Ship Speed	15 knots
Number of Rescue Targets	4
Ship Radar Range	25 NM
Ship Visual Detect Probability	0.2
Ship Radar Detect Probability	0.99
Number of UAS	0
UAS Loiter	N/A
UAS Speed	N/A

The results of the base case are shown in Table 34.

Table 34. ISR Detect and Confirm Base Case Results

Parameter	Value
Average Time to Complete Mission	25.2 Hours
Number of UAS Confirmations	N/A
Number of Ship Confirmations	4
Number of Non-detections	0

The drone case exercises the model with a single integrated UAS. It provides a baseline to compare against the base case and is used to verify the functionality of the model before running a design of experiments. The model is run with the same inputs for 100 runs. Table 35 depicts the inputs used to establish the drone case.

Table 35. ISR Detect and Confirm Drone Case Inputs

Parameter	Value
Visual Range	5 NM
Search Box Length	160 NM
Search Box Width	160 NM
Ship Speed	15 knots
Number of Rescue Targets	4
Ship Radar Range	25 NM
Ship Visual Detect Probability	0.2
Ship Radar Detect Probability	0.99
Number of UAS	1
UAS Loiter	5 Hours
UAS Speed	30 knots

The results of the integrated drone case are shown in Table 36.

Table 36. ISR Detect and Confirm Drone Case Results

Parameter	Value
Average Time to Complete Mission	25.2 Hours
Number of UAS Confirmations	N/A
Number of Ship Confirmations	4
Number of Non-detections	0

For a drone with the parameters in Table 35, comparing the base case to the drone case shows that the mean time to complete the scenario is unchanged, while in the drone case the UAS now makes most of the confirmations.

Using Minitab statistical software, a more detailed look at the statistics for the 100 runs of the base and integrated drone cases is considered. A histogram was created to view the distribution of the scenario times for both cases. The histogram is presented in Figure 14.

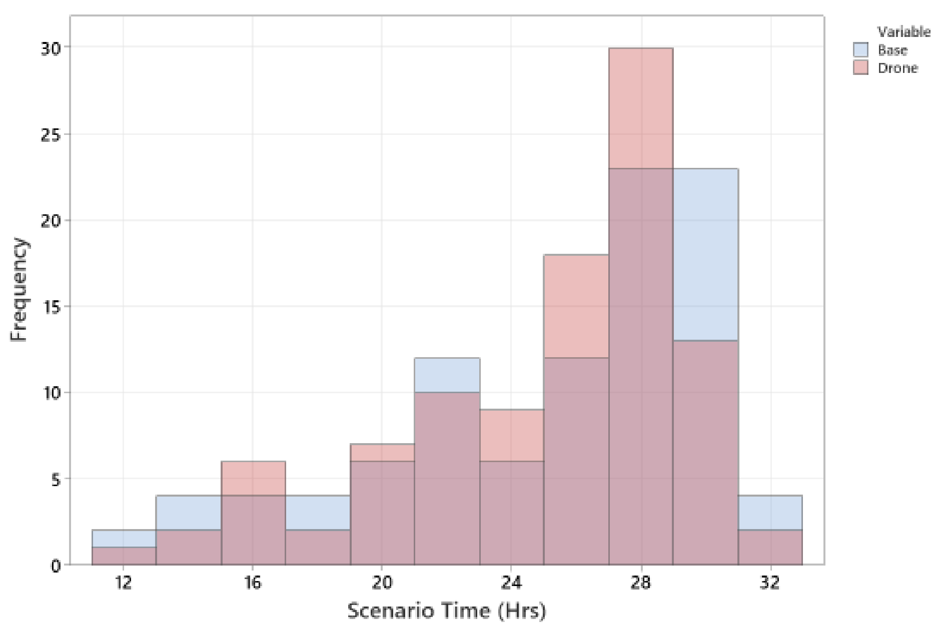


Figure 14. ISR Detect and Confirm Scenario Time Data Distribution

Based on the histogram and the results of an Anderson-Darling test for normality, it is evident that the data is not normally distributed. A Mann-Whitney u-test is then conducted to compare the medians of the two cases. . Use of the Mann-Whitney u-test when comparing the differences in two sample medians is appropriate when two conditions are satisfied [46]:

- The data are independent.
- The data are continuous or ordinal.

The replicates are simple random samples, and each replicate is run independently of the others, satisfying the first condition. The data is continuous, satisfying the second [46]. The summary statistics for the two cases, the result of the Mann-Whitney u-test, and a plot of the individual results are shown in Tables 37 and 38, and Figure 15 respectively.

Table 37. ISR Detect and Confirm Base Case vs. Drone Case Statistics

Case	N	Mean	Standard Deviation	SE Mean
Base Case	100 scenario runs	25.21 Hrs	5.02 Hrs	0.50 Hrs
Drone Case	100 scenario runs	25.23 Hrs	4.41 Hrs	0.44 Hrs

Table 38. ISR Detect and Confirm Mann-Whitney U-Test Results

Method
η_1: median of Base
η_2: median of Drone
Difference: $\eta_1 - \eta_2$

Descriptive Statistics		
Sample	N	Median
Base	100	26.9168
Drone	100	26.6726

Estimation for Difference		
Difference	CI for Difference	Achieved Confidence
0.335724	(-0.774304, 1.32414)	95.01%

Test	
Null hypothesis	$H_0: \eta_1 - \eta_2 = 0$
Alternative hypothesis	$H_1: \eta_1 - \eta_2 \neq 0$
W-Value	P-Value
10311	0.524

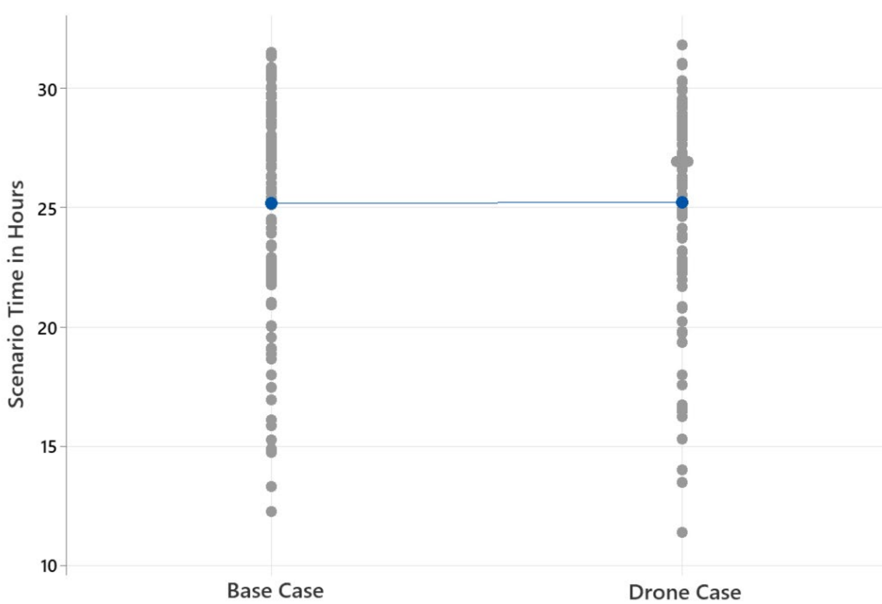


Figure 15. ISR Detect and Confirm Base Case vs. Drone Case Mean Scenario Time

The null hypothesis of the Mann-Whitney u-test is that the median time of the two scenarios is the same. Based on the p-value of the t-test, the null hypothesis cannot be rejected. Using the drone parameters (i.e., NumUAS, UAS Loiter, and UAS Speed) in the integrated drone case, there appears to be no change to the median time to complete the scenario.

c. ISR Detect and Confirm Design of Experiments and Analysis

To further explore the ISR D&C scenario model and verify if changes to drone parameters would have an impact on either the mean time to complete the scenario or the total number of detections. Next a Design of Experiments is performed on inputs into the model using Minitab. The DOE allows us to consider a broad range of inputs and the interactions between those inputs. The DOE is a general full factorial design with 20 replicates for each run. This DOE resulted in 3420 unique design points and 64800 total scenario runs. The input values used in the DOE are shown in Table 39.

Table 39. ISR Detect and Confirm Design of Experiments Inputs

Parameter	Units	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
Search Box Size	NM^2	5000	10000	15000	n/a	n/a	n/a
Number of Rescue Targets	Integer	2	4	6	8	10	12
Ship Speed	Kts/hr	15	25	n/a	n/a	n/a	n/a
Number of UAS	Integer	0	2	4	6	8	10
UAS Speed	Kts/hr	20	40	60	n/a	n/a	n/a
UAS Loiter Time	Hours	1	2	3	4	5	n/a
Ship Visual Range	NM	5	n/a	n/a	n/a	n/a	n/a
Ship Radar Range	NM	5	n/a	n/a	n/a	n/a	n/a

There are several changes to the inputs relative to the base and integrated drone cases. Note that the DOE combines search box width and search box length into "search box size." This is done to limit the number of factors (and thus scenario runs) used in the DOE. To manage this in the model, the square root of "search box size" shown in Table 38 is calculated and populated the inputs "search box width" and "search box length" with that value. Also note that while the base and integrated drone cases used a UAS speed of 30 Kts/hr. For the DOE, a linear coverage is used for the space of reasonable values for UAS in the groups that this paper considers. Next, the DOE results are populated into our ExtendSim model and each of the 3,420 design points is run 20 times. Using the outputs of this model run, mean time, mean number of UAS confirms, mean number of ship confirmations, and the mean number of non-detections are able to be generated for each design point.

The main effects plot at Figure 16 averages the scenario time results for each of the input values in our DOE. Note that the Y-Axis is mean time to complete the scenario while the X-axis shows, for each factor (described across the top of the figure), the input values summarized in Table 39.

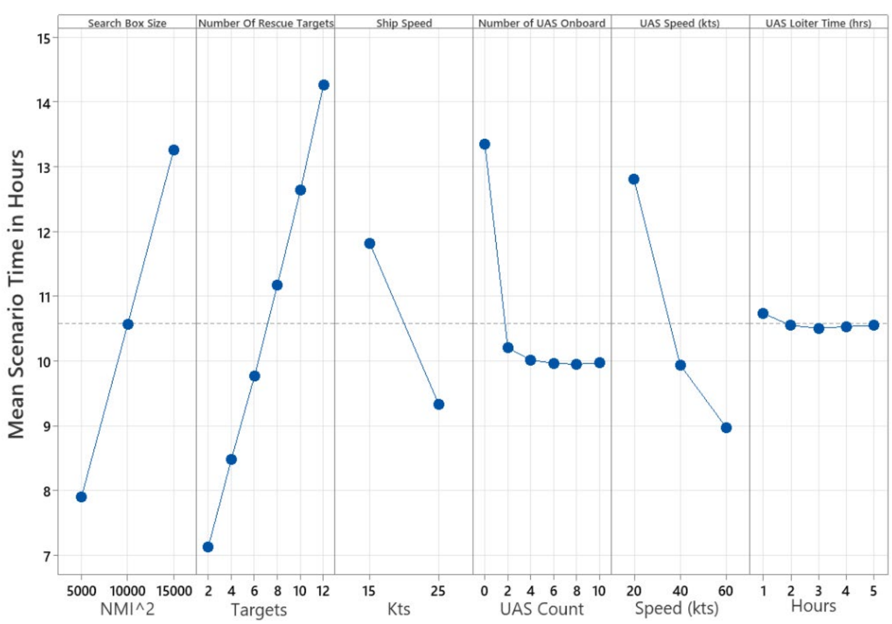


Figure 16. ISR Detect and Confirm Main Effects Plot for Time

To verify that the model is appropriately capturing the defined scenario, the results of changes to search box size, number of rescue targets, and ship speed are all considered. Intuition suggests, and this plot confirms, that mean scenario time should increase with the size of the search box and the number of targets. Similarly, mean scenario time should decrease as ship speed increases, and that trend is evident in Figure 16.

Next, the factors defining parameters of the UAS are considered. The chart shows that increasing the number of UAS sorties from 0 to 2 reduces mean time from 13.4 hours to 10.2 hours, or roughly 20%. Similarly, increasing the speed of the drone from 20 knots to 40 knots reduced mean scenario time from 12.8 hours to 9.9 hours, or roughly 20%. Further increasing drone speed to 60 knots further reduced mean time to 9.0 hours, or an additional 10% reduction. Finally, the UAS loiter time factor has limited impact on scenario time in our model. This analysis suggests that adding one drone capable of two sorties (or two UAS each capable of a sortie) and traveling at 40 knots to a single ship ISR D&C scenario significantly reduces the time to complete the scenario. However, this effect significantly reduces as additional drone sorties are added to the scenario. Comparing the DOE to the base and integrated drone cases, the integrated drone cases do not show improvements to search time. When evaluating a much broader range of inputs and smaller (but reasonable) box sizes, adding UAS to the scenario can reduce search time.

To further understand how changes in the input factors affect the mean scenario time, a two-way interaction plot for the input factors is created, shown in Figure 17. Note that UAS loiter time has been excluded from the plot as it has a limited effect on scenario time. On this plot, the X-axis (shown at the top) again shows the values for each of the input factors. Similarly, the Y-axis (shown on the right), is scenario time. The legend for each line is also shown on the right-hand side. This view shows how mean scenario time changes as two of the factors are varied. As an example, considering the intersection of Ship Speed and Number of UAS onboard, there are differences in the effect Number of UAS has for the different ship speeds. The plot shows that the impact on mean time of adding two UASs onboard is much less if the ship is searching at a faster rate, a logically sound result. This result is also meaningful for consideration in determining whether to integrate UAS onto ships to execute queued searches—if, during an ISR mission, a ship can be expected to be travelling at higher speeds, the effect of incorporating UAS on scenario time is reduced.

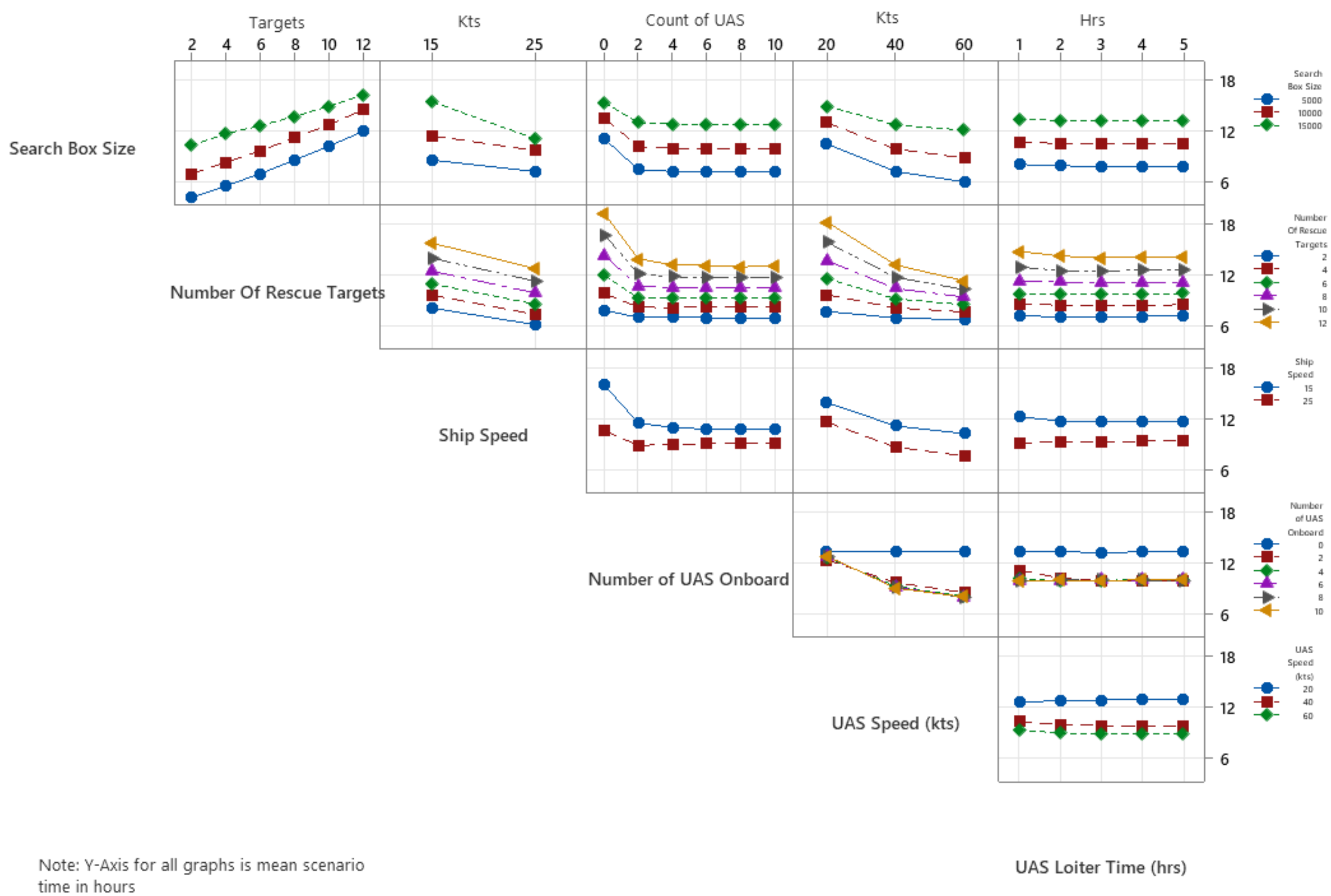


Figure 17. ISR Detect and Confirm Interaction Plot for Time

Several additional interesting results can be drawn from Figure 16 and Figure 17:

- Increasing drone speed has a considerable effect on the mean scenario time. The reduction in mean scenario time is much larger for improving from 20 to 40 knots than it is from 40 to 60 knots.

- Number of UAS and UAS speed have heightened impact when there are more targets to be confirmed. Increasing drone speed is more impactful for smaller search box sizes and scenarios that have many targets.

- UAS have lower impact as the size of the box increases. This may seem counterintuitive but is logical based on the scenario modeled and the randomness of target dispersion. Holding the number of targets constant, larger box size means that the ship, on average, searches longer with its radar before it identifies the target to be confirmed. Stated another way, less of the total scenario time is spent "confirming" for a larger box size, which means the drone has less opportunity to make an impact.

Several other plots, including for changes to number of detections, are at Appendix B.

3. SAR Modeling

a. Decrease Search Time

This model replicates the scenario described earlier in this chapter where the UAS is available to support SAR missions and is used to increase the radius of the search. For simplicity, the UAS in this model is centered on the ship. Using the UAS in this way effectively decreases the time it takes to search the box at the expense of the larger search radius only being covered by the drone sensor. A high-level diagram of this model is shown at Figure 18.

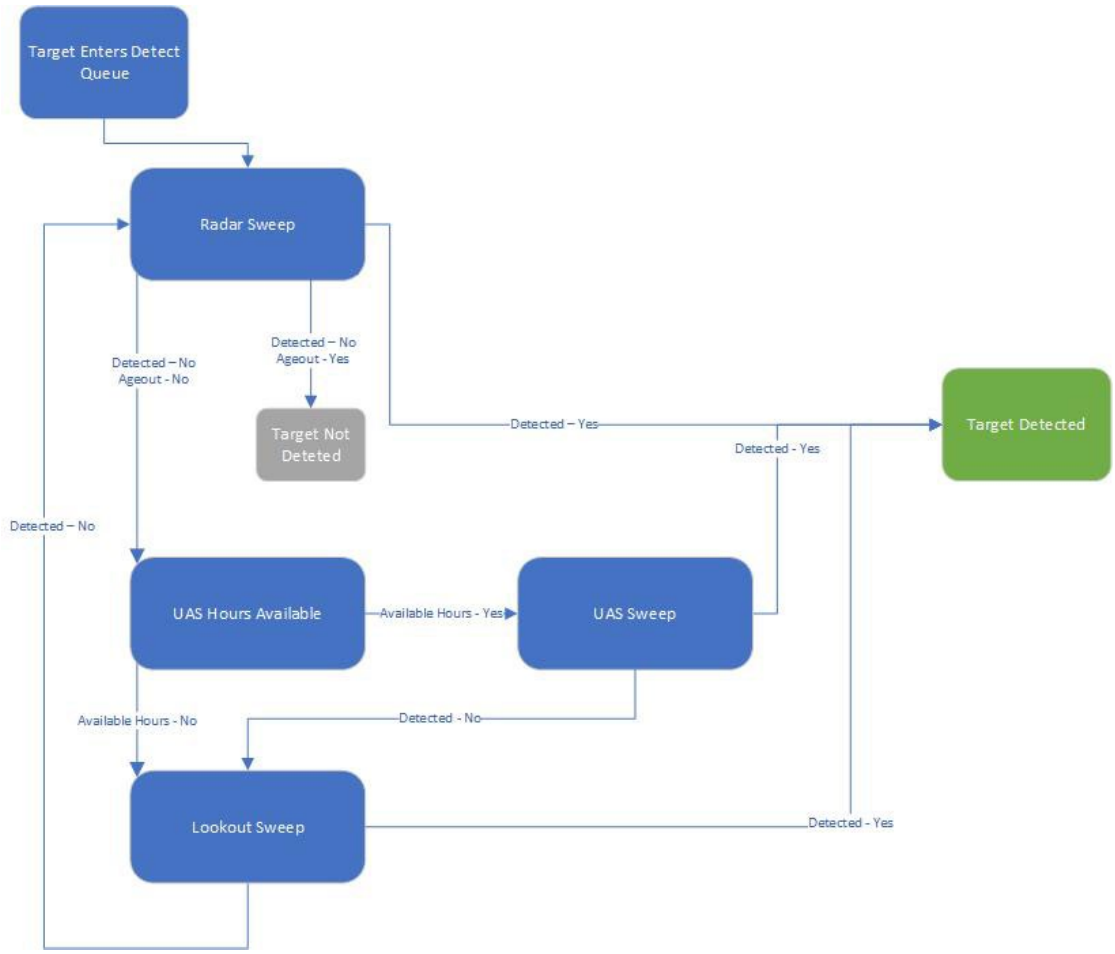


Figure 18. SAR Decrease Search Time Diagram

Like the D&C model, the UAS with Ship Decrease Search Time model first creates a number of items equal to the number of targets. These items are then initialized with attributes relating to the input values. Next, the model calculates global variables that determine total search time. These variables then feed random number generators to determine the position of each target. Each item then waits in a queue until the UAS or lookout can detect the target.

Once the time at which the UAS or lookout can detect the target has been reached, the item is released from the queue. In this model, because the UAS is in the air aiding the search, UAS hours are continuously decremented and are not replenished. If there are available UAS hours then the drone has a chance to detect the target. If there are no UAS hours, then the item is sent to the lookout queue for a chance of detection. This loop continues until the item has been detected or passed by the ship and outside of the ships visual and radar range. If this happens, the target is marked as not detected.

This model takes the inputs depicted in Table 40 and returns the time it took to complete a run and the number of detections and non-detections.

Table 40. SAR Decrease Search Time Model Parameters

Input	Description
Search Box Length	Length of the box where the target(s) can be found
Search Box Width	Width of the box where the target(s) can be found
Number of Rescue Targets	The number of targets in the search box
Ship Speed	The speed at which the ship travels
Visual Range	The distance that the target(s) can be detected by a lookout from the ship
Ship Visual Detect Probability	The likelihood of a target being detected by a ship's lookout
UAS Visual Range	The distance that the target(s) can be detected by a UAS
UAS Detect Probability	The likelihood of a target being detected by a UAS
UAS Speed	The speed at which UAS travels
UAS Loiter	The length of time that a UAS can spend in the air on a sortie
Number of UAS	The number of UAS available during the scenario

b. SAR Decrease Search Time Model Results

The base case exercises the model without the integrated UAS (i.e., NumUAS = 0). It provides a baseline to compare against the integrated drone case and consider the validity of the results the model provides. The following inputs shown in Table 41 are used to establish the base case. The model is run with the same inputs for 100 runs.

Table 41. SAR Decrease Search Time Model Inputs

Parameter	Value
Visual Range	0.25 NM
Search Box Length	10 NM
Search Box Width	10 NM
Ship Speed	15 knots
Number of Rescue Targets	4
Ship Visual Detect Probability	0.2
Number of UAS	0
UAS Loiter	N/A
UAS Detect Probability	N/A
UAS Visual Range	N/A

The results of the base case are shown in Table 42.

Table 42. SAR Decrease Search Time Base Case Results

Parameter	Value
Average Non-detections	0.06
Average Detections	3.94
Average Time to Complete Mission	10.5 Hours

The drone case exercises the model with a single integrated UAS. It provides a baseline to compare against the base case and is used to verify the functionality of the model before running a design of experiments. The model is run with the same inputs for 100 runs. The inputs depicted in Table 43 are used to establish the drone case.

Table 43. SAR Decrease Search Time Drone Case Inputs

Parameter	Value
Visual Range	0.25 NM
Search Box Length	10 NM
Search Box Width	10 NM
Ship Speed	15 knots
Number of Rescue Targets	4
Ship Visual Detect Probability	0.2
Number of UAS	1
UAS Loiter	5 Hours
UAS Detect Probability	0.2
UAS Visual Range	0.5 NM

The results of the integrated drone case are shown in Table 44.

Table 44. SAR Decrease Search Time Drone Case Results

Parameter	Value
Average Non-detections	0.03
Average Detections	3.97
Average Time to Complete Mission	3.0 Hours

For a drone with the parameters in Table 43, comparing the base case to the drone case shows that the mean time to complete the scenario is significantly reduced, while the impact to the average number of detections is negligible. This negligible impact on the average number of detections is expected given the probability of detect used for both the ship and drone is the same.

Using Minitab statistical software, a more detailed look at the statistics for the 100 runs of the base and integrated drone cases is considered. A histogram was created to view the distribution of the scenario times for both cases. The histogram is presented in Figure 19.

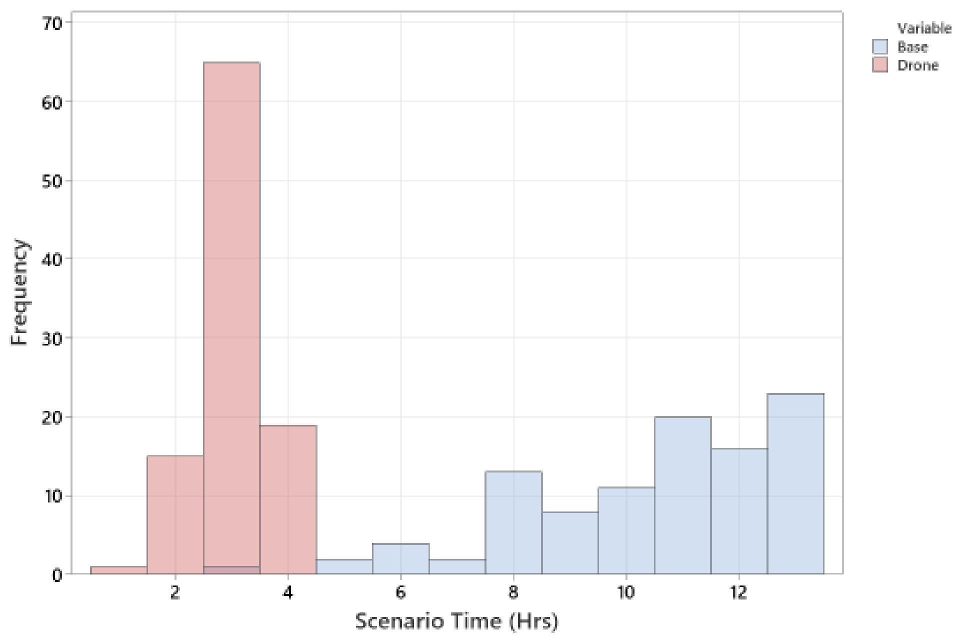


Figure 19. SAR Decrease Search Time Scenario Time Data Histogram

Based on the histogram and the results of an Anderson-Darling test for normality, it is evident that the data is not normally distributed. A Mann-Whitney u-test is then conducted to compare the medians of the two cases A Mann-Whitney u-test is then conducted to compare the medians of the two cases. Use of the Mann-Whitney u-test when comparing the differences in two sample medians is appropriate when two conditions are satisfied [46]:

- The data are independent.
- The data are continuous or ordinal.

The replicates are simple random samples, and each replicate is run independently of the others, satisfying the first condition. The data is continuous, satisfying the second [46]. The summary statistics for the two cases, the result of the Mann-Whitney u-test, and a plot of the individual results are shown in Tables 45 and 46, and Figure 20 respectively.

Table 45. SAR Decrease Search Time Base Case vs. Drone Case Statistics

Case	N	Mean	Standard Deviation	SE Mean
Base Case	100 scenario runs	10.46 Hrs	2.29 Hrs	0.23 Hrs
Drone Case	100 scenario runs	2.954 Hrs	0.541 hrs	0.054 Hrs

Table 46. SAR Decrease Search Time Mann-Whitney U-Test Results

Method
η_1: median of Base
η_2: median of Drone
Difference: $\eta_1 - \eta_2$

Descriptive Statistics		
Sample	N	Median
Base	100	11.0113
Drone	100	3.0025

Estimation for Difference		
Difference	CI for Difference	Achieved Confidence
7.99065	(7.49426, 8.44423)	0.9501

Test	
Null hypothesis	$H_0: \eta_1 - \eta_2 = 0$
Alternative hypothesis	$H_1: \eta_1 - \eta_2 \neq 0$
W-Value	P-Value
14791	0.0000

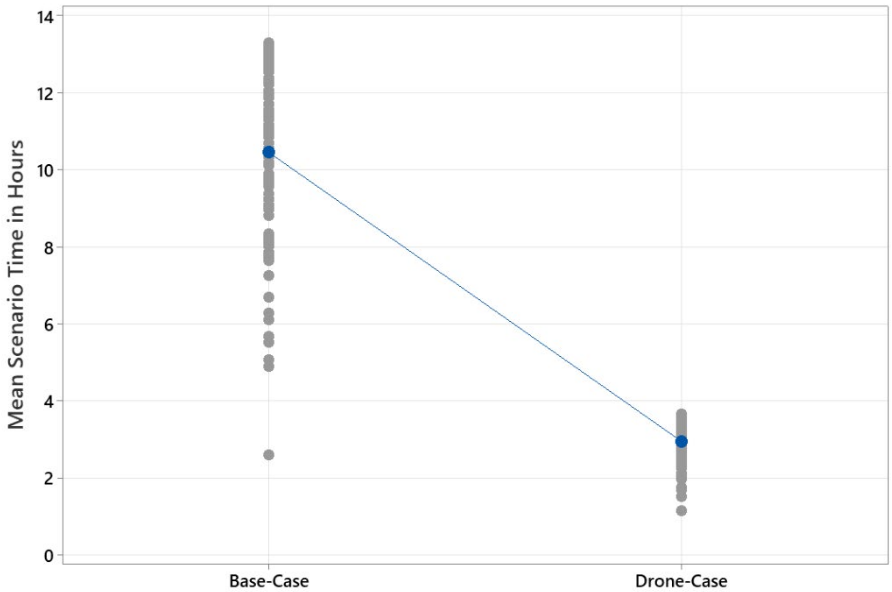


Figure 20. SAR Decrease Search Time Base Case vs. Drone Case Mean Scenario Time

The null hypothesis of the Mann-Whitney u-test is that the median time of the two scenarios is the same. Based on the p-value of the Mann-Whitney u-test, the null hypothesis is rejected. Using the drone parameters (i.e., NumUAS and UAS Loiter) in the integrated drone case, there appears to be dramatic decrease in the median amount of time required to complete the SAR mission.

c. SAR Decrease Search Time Design of Experiments and Analysis

To further explore the SAR Decrease Search Time scenario model and verify if changes to drone parameters would have an impact on either the mean time to complete the scenario or the total number of detections, a Design of Experiments on inputs into the model is then conducted using Minitab. The DOE allows us to consider a broad range of inputs and the interactions between those inputs. The DOE is a general full factorial design with 20 replicates for each run. This DOE resulted in 3420 unique design points and 64800 total scenario runs. The input values used in the DOE are shown at Table 47.

Table 47. SAR Decrease Search Time Design of Experiments Inputs

Parameter	Units	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
Search Box Size	NM^2	100	250	400	n/a	n/a	n/a
Number of Rescue Targets	Integer	2	4	6	8	10	12
Number of UAS	Integer	0	2	4	6	8	10
UAS Loiter Time	Hours	1	2	3	4	5	n/a
UAS Visual Range	NM	0.125	0.25	n/a	n/a	n/a	n/a
UAS Detect Probability	Prob.	0.01	0.1	0.2	n/a	n/a	n/a
Ship Visual Range	NM	0.15	n/a	n/a	n/a	n/a	n/a
Ship Visual Detect Probability	Prob.	0.1	n/a	n/a	n/a	n/a	n/a

Note here that, relative to the base and integrated drone cases, there are changes to both the ship visual range, drone visual range, ship probability of detect, and drone probability of detect. The DOE considers more conservative assumptions for each of those inputs. Given those more conservative assumptions, the time to search for the DOE cases is lower, as the rate at which area is searched is determined by the visual ranges. The lower bound for UAS visual range, 0.125 NM, is specifically chosen to be lower than the assumed visual range for the ship. Also, given the lower probabilities to detect, there are more non-detections in the DOE cases than in either the base or integrated drone cases.

The main effects plot at Figure 21 averages the scenario time results for each of the input values in our DOE. Note that the Y-Axis is mean time to complete the scenario while the X-axis shows, for each factor (described across the top of the figure), the input values summarized in Table 47.

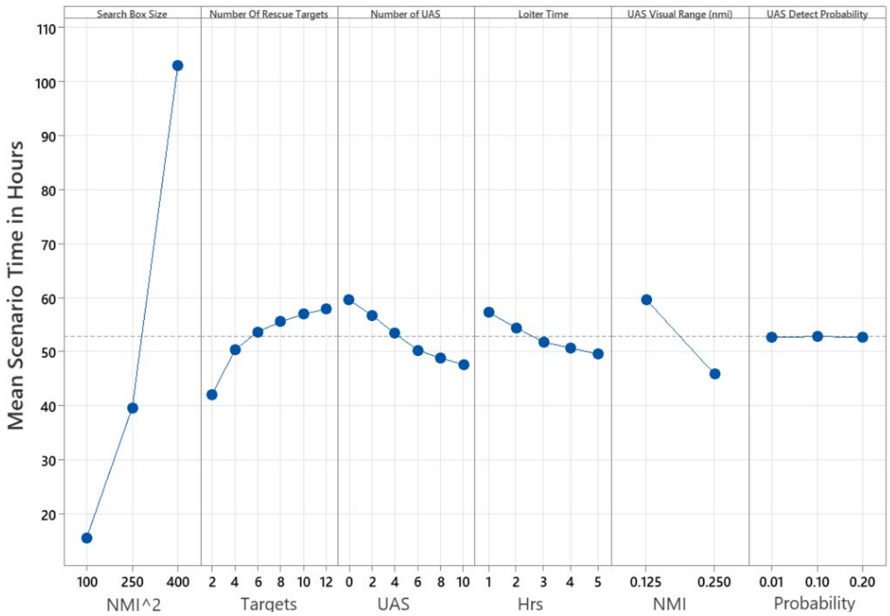


Figure 21. SAR Decrease Search Time Main Effects Plot for Time

The results depicted in Figure 21 align with intuition regarding how the model should function. Time to search is increased by increasing the box size and the number of targets. Adding UAS sorties and additional UAS time decreases mean time to perform the search. For the scenarios with UAS visual range of 0.125 (i.e., less than the ships), the mean time is equal to the scenarios in which there are no drone (i.e., Number of UAS = 0). Given the overall scenario considered has the UAS centered on the ship, if the UAS has a smaller search radius than the ship, then there is no time saved.

Given that the assumed tradeoff in this scenario is increasing the search radius but decreasing the number of sensors searching, a main effects plot for the number of detections missed in the scenario is then generated, shown at Figure 22. The plot shows that the UAS probability of detection has a significant impact on the number of non-detections in the scenarios. For scenarios with .01 UAS probability of detection, the mean number of non-detections is 3.04. Increasing the UAS probability of detection to 0.2 reduces the mean number of non-detections to 1.84, roughly a 40% reduction. The main effects plot for non-detection shows unintuitive results for the effects of search box size, number of UAS, and loiter time on the mean number of non-detections. However, given that the average UAS probability of detection across the scenarios is lower than the ship probability of detection, this result makes sense. More of the total scenario time spent searching (i.e., increased number of UAS and drone loiter time) with a lower probability of detection leads to more non-detections. The opposite effect is evident in the Search Box Size trend. Because the UAS have a finite amount of time in the air, the larger the Search Box Size the lower the percent of total time searched with the lower average probability of detection.

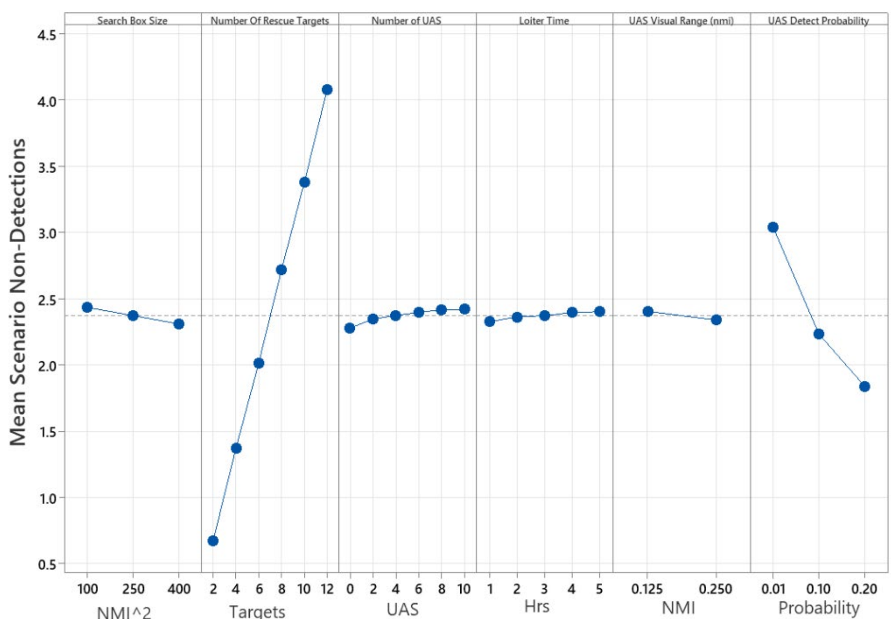
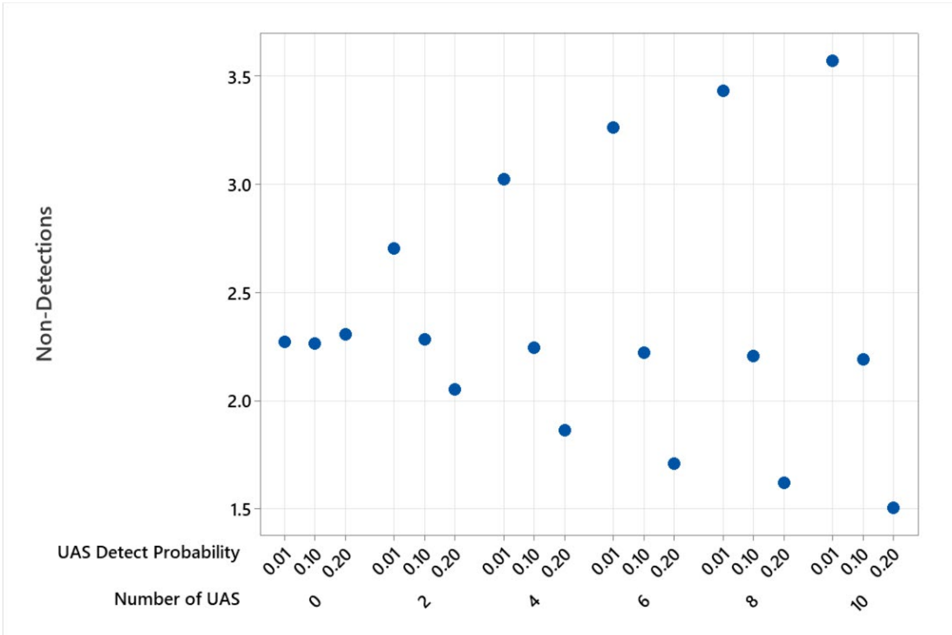


Figure 22. SAR Decrease Search Time Main Effects Plot for Non-detections

To validate this, a plot of the mean non-detections for each UAS Detect Probability and Number of UAS input factor is generated. That plot is shown in Figure 23. The Y-axis for the plot is mean non-detections. The X-axis shows two variables; UAS Detect Probability in the top row and Number of UAS in the lower row. As an example, the point in the top right of the plot is the mean number of non-detections for all the scenarios in which Number of UAS is equal to 10 and UAS Detect Probability is equal to 0.01.



Individual standard deviations are used to calculate the intervals.

Figure 23. SAR Decrease Search Time Interval Plot of Non-detections

Note that for the Number of UAS equal to 0 cases (the left-most grouping), the means are bunched together. That is, UAS Detect Probability has limited impact on the mean-non detections because there is no UAS. Because the amount of time that the UAS spend in the air is a function of Number of UAS, as you move left to right through the plot the amount of scenario time the UAS are spending in the air is increasing. As evidenced in the drone cases, three trend lines become evident as Number of UAS (and thus drone aerial time) increases, each representing one of the UAS Detect Probability inputs. The top trend line is the UAS Detect Probability = .01 case, the middle trend line is the UAS Detect Probability = .1 case, and the lower trend line is the UAS Detect Probability = .20 case. This plot indicates that, unsurprisingly, more searching with higher probability of detect is good, and more searching with lower probability of detect is bad. Several other plots are generated during our analysis the SAR Decrease Search Time Model results. Those additional plots are located at Appendix C.

d. Increase Detections

This model replicates the scenario described earlier in this chapter where the UAS is available to support SAR missions and is used to increase the probability of detect of the search. For simplicity, the UAS in this model is centered on the ship. This model and its inputs are identical to the SAR – Decrease Search Time described in the previous subsection, with one exception. In the UAS with Ship Increase Detection model the smallest sensor radius is used to calculate the number of segments needed to cover the box. This takes the ship more time to complete the search but increases the likelihood of detection.

This model takes the inputs depicted in Table 48 and returns the time it took to complete a run and the number of detections and non-detections.

Table 48. SAR Increase Detections Model Parameters

Input	Description
Search Box Length	Length of the box where the target(s) can be found
Search Box Width	Width of the box where the target(s) can be found
Number of Rescue Targets	The number of targets in the search box
Ship Speed	The speed at which the ship travels
Visual Range	The distance that the target(s) can be detected by a lookout from the ship
Ship Visual Detect Probability	The likelihood of a target being detected by a ship's lookout
UAS Visual Range	The distance that the target(s) can be detected by a UAS
UAS Detect Probability	The likelihood of a target being detected by a UAS
UAS Speed	The speed at which UAS travels
UAS Loiter	The length of time that a UAS can spend in the air on a sortie
Number of UAS	The number of UAS available during the scenario

e. SAR Increase Detections Model Results

The base case exercises the model without the integrated UAS (i.e., NumUAS = 0). It provides a baseline to compare against the integrated drone case and consider the validity of the results the model provides. The following inputs shown at Table 49 are used to establish the base case. The model is run with the same inputs for 100 runs.

Table 49. SAR Increase Detections Model Inputs

Parameter	Value
Visual Range	0.25 NM
Search Box Length	10 NM
Search Box Width	10 NM
Ship Speed	15 knots
Number of Rescue Targets	4
Ship Visual Detect Probability	0.2
Number of UAS	0
UAS Loiter	N/A
UAS Detect Probability	N/A
UAS Visual Range	N/A

The results of the base case are depicted in Table 50.

Table 50. SAR Increase Detections Base Case Results

Parameter	Value
Time	41.2 Hours
Average Non-detections	0.08
Average Detections	3.92

The drone case exercises the model with a single integrated UAS. It provides a baseline to compare against the base case and is used to verify the functionality of the model before running a design of experiments. The model is run with the same inputs for 100 runs. The inputs depicted in Table 51 are used to establish the drone case.

Table 51. SAR Increase Detections Drone Case Inputs

Parameter	Value
Visual Range	0.25 NM
Search Box Length	10 NM
Search Box Width	10 NM
Ship Speed	15 knots
Number of Rescue Targets	4
Ship Visual Detect Probability	0.2
Number of UAS	1
UAS Loiter	5 Hours
UAS Detect Probability	0.2
UAS Visual Range	0.5 NM

The results of the integrated drone case are shown in Table 52.

Table 52. SAR Decrease Search Time Drone Case Results

Parameter	Value
Time	43.6 Hours
Average Non-detections	0.03
Average Detections	3.97

For a drone with the parameters in Table 51, comparing the base case to the drone case shows that the mean time to complete the scenario is slightly higher, while the average number of detections is now marginally higher.

Using Minitab statistical software, considered a more detailed look at the statistics for the 100 runs of the base and integrated drone cases is considered. The summary statistics for the two cases are shown in Tables 53 and 54.

Table 53. SAR Increase Detections Base Case vs. Drone Case Scenario Time Statistics

Case	N	Mean	SE Mean	Standard Deviation	Min	Q1	Median	Q3	Max
Base Case	100 scenario runs	41.194 Hrs	0.943 Hrs	9.429 Hrs	6.310 Hrs	35.341 Hrs	42.192 Hrs	48.789 Hrs	53.238 Hrs
Drone Case	100 scenario runs	43.582 Hrs	0.809 Hrs	8.090 Hrs	17.596 Hrs	38.208 Hrs	46.598 Hrs	50.013 Hrs	53.197 Hrs

Table 54. SAR Increase Detections Base Case vs. Drone Case Non-detections Statistics

Case	N	Mean	SE Mean	Standard Deviation	Min	Q1	Median	Q3	Max
Base Case	100 scenario runs	0.08 Non-detections	0.0273 Non-detections	0.2727 Non-detections	0 Non-detections	0 Non-detections	0 Non-detections	0 Non-detections	1 Non-detections
Drone Case	100scenario runs	0.03 Non-detections	0.0171 Non-detections	0.1714 Non-detections	0 Non-detections	0 Non-detections	0 Non-detections	0 Non-detections	1 Non-detections

A histogram was created to view the distribution of the scenario times for both cases. The histogram is presented in Figure 24.

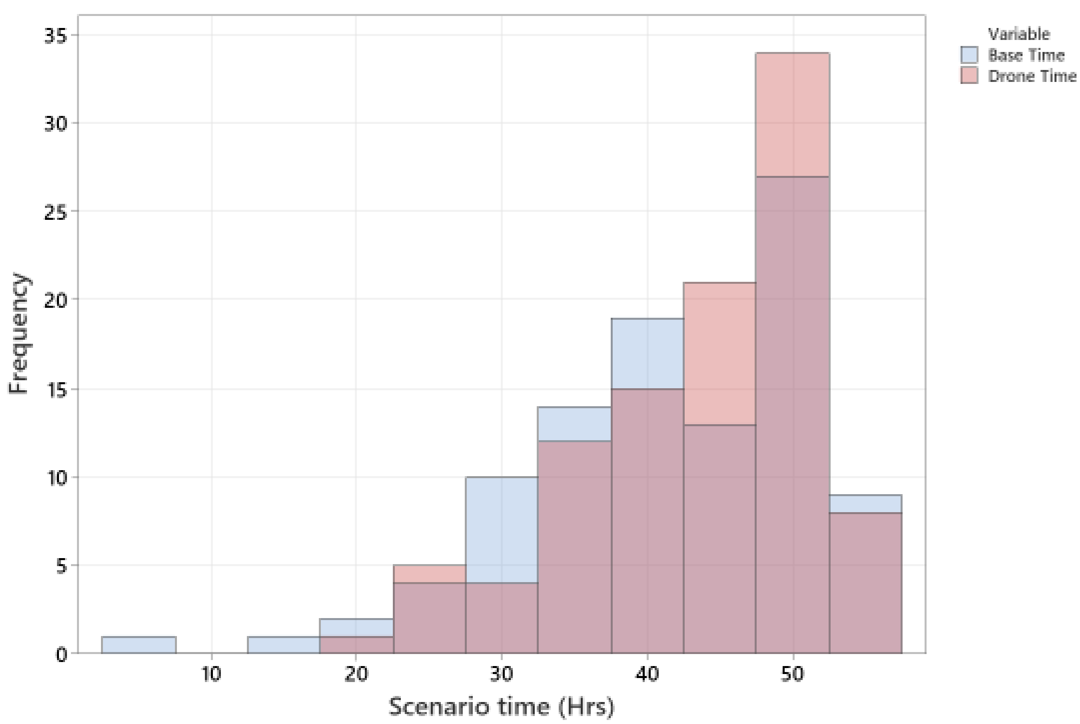


Figure 24. SAR Increase Detections Scenario Time Data Histogram

Based on the histogram and the results of an Anderson-Darling test for normality, it is evident that the data is not normally distributed. A Mann-Whitney u-test is then conducted to compare the medians of the two cases. Use of the Mann-Whitney u-test when comparing the differences in two sample medians is appropriate when two conditions are satisfied [46]:

- The data are independent.
- The data are continuous or ordinal.

The replicates are simple random samples, and each replicate is run independently of the others, satisfying the first condition. The data is continuous, satisfying the second [46]. The summary statistics for the two cases, the result of the Mann-Whitney u-test, and a plot of the individual results are shown in Table 44, and Figures 19 and 20 respectively.

The test and the plot of individual values are shown in Table 55 and Figure 25.

Table 55. SAR Increase Detections Scenario Time Mann-Whitney U-Test Results

Method
η_1: median of Base
η_2: median of Drone
Difference: $\eta_1 - \eta_2$

Descriptive Statistics		
Sample	N	Median
Base	100	42.192
Drone	100	46.5984

Estimation for Difference		
Difference	CI for Difference	Achieved Confidence
-1.9126	(-4.19158, 0.238228)	0.9501

Test	
Null hypothesis	H_0: $\eta_1 - \eta_2 = 0$
Alternative hypothesis	H_1: $\eta_1 - \eta_2 \neq 0$
W-Value	P-Value
9339	0.0830

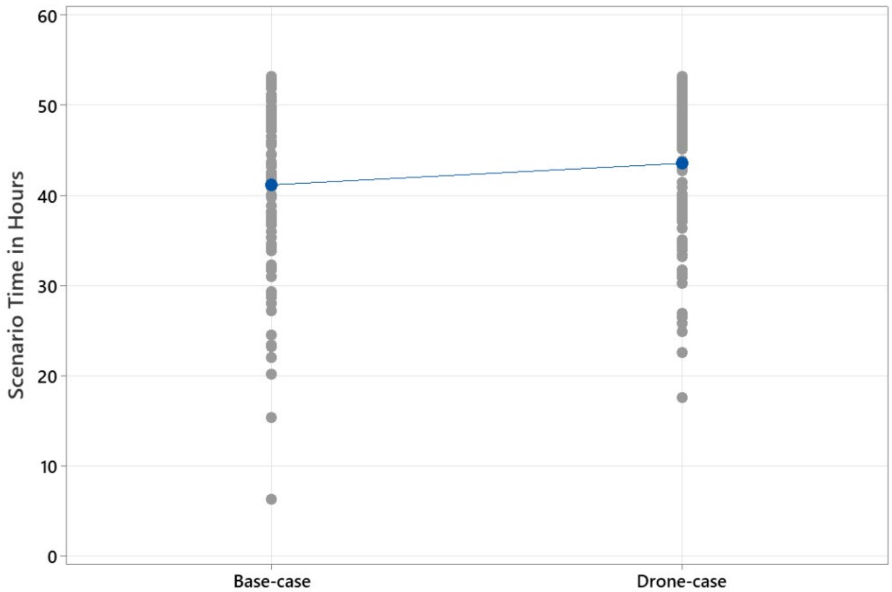


Figure 25. SAR Increase Detections Base Case vs. Drone Case Mean Scenario Time

The null hypothesis of the Mann-Whitney u-test is that the median time of the two scenarios is the same. Based on the p-value of the Mann-Whitney u-test at 95% confidence level, the null hypothesis cannot be rejected.

f. SAR Increase Detections Design of Experiments and Analysis

To further explore the SAR Increase Detection scenario model and verify if changes to drone parameters would have an impact on either the mean time to complete the scenario or the total number of detections, a Design of Experiments is then performed on inputs into the model using Minitab. The DOE allows us to consider a broad range of inputs and the interactions between those inputs. As this model takes the same inputs as the SAR Decrease Time model, the experimental design is appropriate to reuse for that model. The input values used in this DOE are described in the previous subsection and are shown in Table 49.

The first step is to generate a main effects plot for scenario time. The main effects plot at Figure 26 averages the scenario time results for each of the input values in our DOE. Note that the Y-Axis is mean time to complete the scenario while the X-axis shows, for each factor (described across the top of the figure), the input values are summarized in Table 49 in the previous subsection.

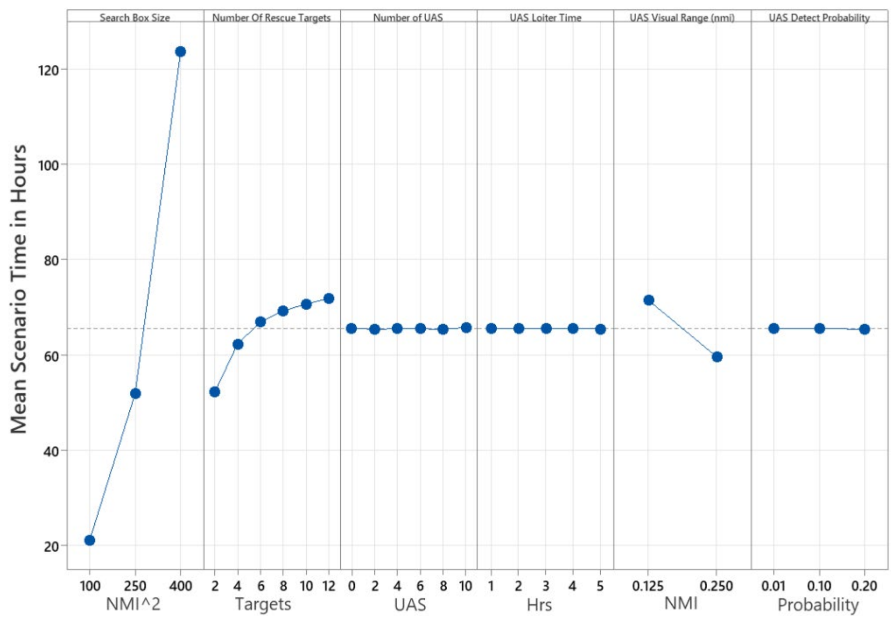


Figure 26. SAR Increase Detections Main Effects Plot for Time

The plot shown in Figure 27 shows that, in the SAR Increase Detection model, the only drone factor that affects scenario time is UAS Visual Range. This follows from the scenario logic where the drone is being used to increase the probability of detect and thus the smallest sensor range within the scenario is used to determine how quickly the target area is searched. In the 0.125 NM input scenarios, the drone's visual range is the lowest ranged sensor and becomes the limiting factor for scenario time. For the 0.250 NM UAS Visual Range scenarios, the ship's visual detection range (0.15 NM) becomes the limiting factor and there is a resulting decrease in time to search the box.

A similar plot for mean non-detections in the scenario is then generated, shown in Figure 27. Note here that the Y-Axis is now mean non-detections.

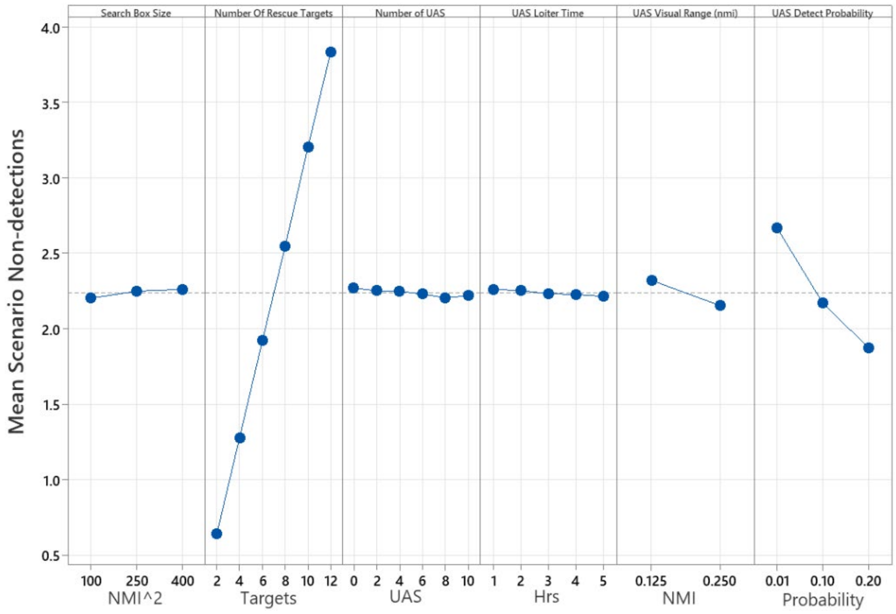


Figure 27. SAR Increase Detections Main Effects Plot for Non-detections

The plot in Figure 28 shows a decrease to mean non-detections associated with increasing UAS Visual Range and a large decrease in mean non-detections associated with increasing UAS Detect Probability. For UAS Detect Probability, this decrease is from 2.67 non-detections for the .01 case, to 2.17 non-detections for the .10 case, to 1.87 for the .25 case. The reduction from the worst case to the best case is roughly a 30% decrease in non-detections.

Next, a two-way interaction plot for the input factors is generated, shown at Figure 30. Note that Number of UAS and UAS Loiter Time have been excluded from the plot as they had a limited effect on scenario non-detections. On this plot, the X-axis (shown at the top) again shows the values for each of the input factors. Similarly, the Y-axis (shown on the right), is mean non-detections. The legend for each line is also shown on the right-hand side. This view shows how mean non-detections changes as two of the factors are varied.

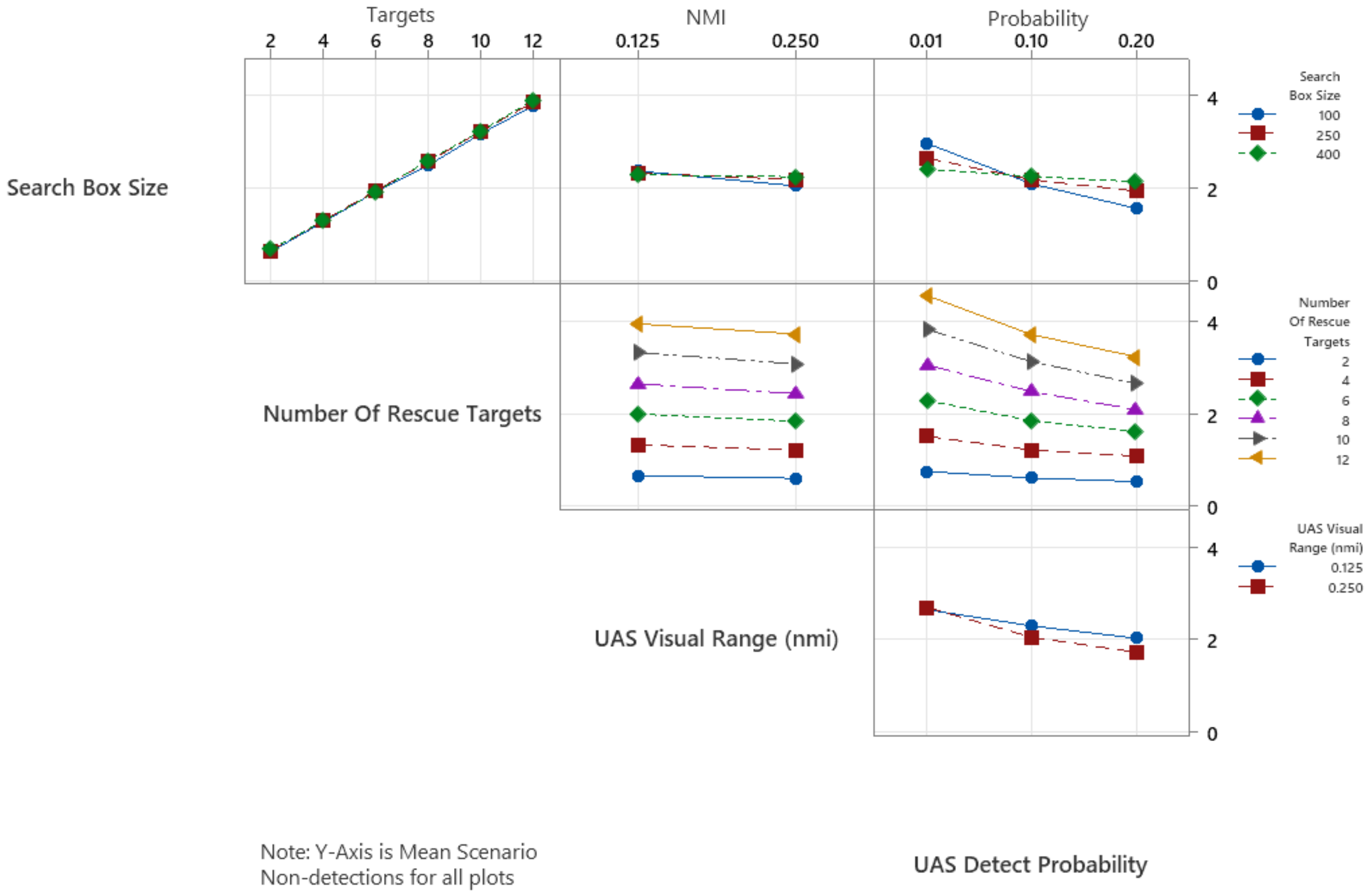


Figure 28. SAR Increase Detections Two-Way Interactions Plot for Non-detections

Two interesting facts are highlighted in the interaction plot shown in Figure 28. First, the impact of improving drone capability is greater when the search box size is smaller. This can be seen most clearly at the intersection of UAS Detect Probability and Search Box size. Second, the value of adding UAS in terms of reductions to non-detections increases as more targets are added into the scenario. For the lowest number of targets, 2, improving UAS Detection Probability from 0.01 to 0.2 reduces mean non-detections from 0.76 to 0.54. This represents a rough 30% reduction. For the highest number of targets, 12, the same improvement reduces non-detections from 4.56 to 3.24. While at 30% this is a similar percent reduction, the real value of the reduction is much higher because the baseline number of non-detections is so much higher.

F. COST ANALYSIS AND COLLECTED DATA

Adding (or duplicating) capabilities to the fleet is desirable, but all capabilities come at a cost. While the analysis earlier in this section suggests that there is significant capability to be gained by adding UAS' to surface ships, decisions about whether to take this step must be informed by an understanding of the cost to be paid. This section provides a preliminary "rough order of magnitude" analysis of the possible costs and savings associated with integrating UAS into the fleet.

Traditionally, system procurement in the Department of Defense includes the following phases (which oftentimes overlap) and sources of funding:

- Development – Includes the costs associated with deriving system requirements, creating a system architecture, creating detailed designs for system components, manufacturing test units, integration, verification, and validation. This activity is generally funded with the Research, Development, Test, and Evaluation (RDT&E) appropriation.
- Procurement – Following on from system development, operational units and their associated support equipment, test equipment, initial spares, data, and training systems are purchased. This activity is generally funded with the Procurement (PROC) appropriation.

- Operations and Sustainment (O&S) – Once operational units are procured, the units are operated and maintained. This activity is generally funded via a combination of the Operations and Maintenance (O&M), Military Pay (MILPERS), Civilian Pay (CIVPAY), and Fuel appropriations.

This study is primarily focused on COTS UAS solutions and as such assumes that no or minimal system development is required for a selected UAS system. System Procurement and O&M costs are considered and placed in context of the systems they may be substituted for.

This analysis is based on available unclassified data sources. Note that there is a paucity of available unclassified data for both Procurement and O&S costs for small UAS. Contact was attempted with several drone manufacturers to acquire additional information, but no responses were received. Readers in acquisition organizations within the DOD may have better access to data sources which could be used to populate a more informed version of this analysis. Data for larger DOD UAS programs is relatively more accessible, although still sparse. Additionally, as points of comparison, data for certain manned programs is collected as well.

The collected data is summarized at Table 56. This data is collected from a variety of sources, including GSA Advantage, Office of the Secretary of Defense (OSD) Comptroller Reimbursable Rates, contractor UAS drone catalogs, DOD budget documents, and Selected Acquisitions Reports (SARs). The sources for this information are citations [47] through [57] and are denoted in the table in line with its information. Note that weights are provided as collected with the weight measure specified when provided. Weights are not directly comparable unless they contain the same content. For example, empty weight does not contain the weight of any fuel or lubricants, whereas all-up weight generally does. Weights in this context are included to give a general sense of the size of the various systems.

Table 56. Cost Analysis Collected Data

System	Approximate Weight	Unit Procurement Cost (Year Dollars)	Unit Cost Per Hour (Year Dollars)	Data Sources
Wingtra One	~60 lbs	$26.9K (2023)	Unavailable	GSA Advantage [47]
Spirit Blue UAV	~1.2 lbs	$61.0K (2023)	Unavailable	GSA Advantage [48]
Skydio X2D	~3 lbs	$10.4K (2023)	Unavailable	GSA Advantage [50]
Aviator UAV 200	~3 lbs	$45.5K (2023)	Unavailable	GSA Advantage [49]
Martin UAS	~120 lbs (All-up)	$120-320K (2012)	Unavailable	Martin UAV Catalog [51]
RQ-21 Blackjack	~80 lbs (Empty)	$837.5K (2023) (Air Vehicle only)	$4.4K (2022)	President's Budget 2024 Documentation [57], OSD Comptroller Reimbursable Rates 2022 [56]
MQ-8B/C	~2000 lbs (MQ-8B) (Empty)	$28.9M (Combined) (Base Year 2017)	$6.5K/$8.2K (2022)	December 2018 SAR [54], OSD Comptroller Reimbursable Rates 2022 [56]
MQ-9	~12000 lbs (Max Take-off)	$20.8M (Base Year 2008)	$.8K (2022)	December 2019 SAR [55], OSD Comptroller Reimbursable Rates 2022 [56]
MH-139A	~14000 lbs (All-up)	$30.7M (Base Year 2018)	$4.5K (2022)	December 2022 SAR [52], OSD Comptroller Reimbursable Rates 2022 [56]
TH-73	~3300 lbs (Empty)	Unavailable	$2.2K (2022)	OSD Comptroller Reimbursable Rates 2022 [56]
MH-60S	~14400 lbs (Empty)	$21.6 (Base Year 1998)	$7.4 (2022)	December 2011 SAR [53], OSD Comptroller Reimbursable Rates 2022 [56]

The cost data collected spans a broad range of dollar types and base years. To appropriately compare program costs, all costs to 2023 dollars are normalized using standard DOD escalation and inflation guidance and 2023 indices [58]. The normalized costs are presented in Table 54. Note that the reimbursable rates provided include costs for O&M, manning, and fuel.

1. Total Ownership Cost Per Hour

After collecting data, Total Ownership Cost (TOC) Per Hour (PH) values are generated for notional COTS UAS. TOC PH is calculated by combining unit procurement cost with the sum of hourly costs and dividing the resulting value by the number of hours operated. This TOC PH can then be compared to the O&S cost PH (i.e., not including procurement costs which are assumed to be sunk) for helicopter assets and surface ships which are already in existence. Stated another way, this analysis compares a blended cost of purchasing and operating a UAS with the cost of operating the system it is standing in for. Using these numbers, we can calculate whether procuring and operating a UAS alternative would be less expensive or more expensive than using current assets.

To develop TOC PH for a notional UAS, several assumptions must be made. First, it is assumed that the unit procurement costs identified for UAS do not capture ancillary equipment that may be required to operate the UAS. For a typical DOD acquisition program this would include support equipment, initial spares, technical data, and various other content. Using procurement data from the MQ-8 and MH-60S programs, this additional cost as a factor of recurring flyaway cost 39.5% and 17.7%, respectively, is calculated. That is, for every $100 spent on procuring MQ-8 units, an additional $39.5 (of procurement dollars) was spent procuring ancillary materiel to enable operations of the MQ-8. To be conservative, the MQ-8 factor will be utilized for the TOC CPH analysis.

Second, as there is limited cost data for operating COTS UAS, we must generate assumed O&S cost PH values. To do this, the ratio of procurement unit cost to cost per hour is calculated where possible. These values are shown in Table 57. For the larger systems with much higher unit procurement costs, this ratio is much lower. For the only small drone with O&S costs available, the ratio is much higher. To maintain conservatism, the higher RQ-21 ratio is utilized.

Third, as a stand-in for the notional UAS, the Martin UAS procurement costs are used. The Martin UAS values included a low and high number for different configurations. They represent a mid-point between the much smaller and less capable UAS systems and the RQ-21.

Table 57. Procurement Cost to Cost per Hour Ratio

System	Unit Procurement Cost	Unit O&S Cost Per Operating Hour	Ancillary Procurement Factor	Unit Procurement Cost/Unit O&S Cost Per Hour
Unit of Measure	Constant Year 2023 dollars, in thousands	Constant Year 2023 dollars, in thousands	Percentage	Percentage
Wingtra One	26.9	unavailable	unavailable	unavailable
Spirit Blue UAV	61.0	unavailable	unavailable	unavailable
Skydio X2D	10.4	unavailable	unavailable	unavailable
Aviator UAV 200	45.5	unavailable	unavailable	unavailable
Martin UAS	**156.7/418.0**	unavailable	unavailable	unavailable
RQ-21 Blackjack	837.5	4.6	unavailable	**0.00551**
MQ-8B/C	35,215.2	6.8/8.6	**0.395**	0.00022
MQ-9	28,863.9	0.8	unavailable	0.00003
MH-139A	36,603.3	4.7	unavailable	0.00013
TH-73	unavailable	2.3	unavailable	unavailable
MH-60S	36,099.0	7.8	0.177	0.00021

Based on the assumptions and the normalized values in Table 57, notional high and low TOC PH values are calculated assuming the UAS is flown for 100, 500, and 1000 hours. These calculations are shown at Table 58.

Table 58. TOC PH Values

	COTS UAS Low ($K)	COTS UAS High ($K)
Unit Cost	$156.7	$418.0
Ancillary Factor	0.395	0.395
Total Procurement Unit Cost	$218.6	$583.1
O&S Cost Per Hour Factor	0.00551	0.00551
O&S Cost Per Hour	$1.2	$3.2
TOC Per Hour (100 Hours)	**$3.4**	**$9.0**
TOC Per Hour (500 Hours)	**$1.6**	**$4.4**
TOC Per Hour (1000 Hours)	**$1.4**	**$3.8**

Prices are in thousands of dollars in constant price 2023—e.g., $3.4 = $3,400.

Note that TOC PH is sensitive to the total number of hours that are flown. If it is assumed that the drone is only flown for 100 hours, TOC PH is significantly higher than O&S cost PH. As the assumed number of hours increases, the TOC PH reduces, eventually approaching the O&S cost PH numbers. Comparing the COTS UAS TOC PHs to the normalized O&S unit cost per hour for helicopter systems, the COTS UAS TOC PH numbers at the 500 Hour assumption are lower than the O&S Cost PH for the MH-139A and the MH-60S, while the COTS UAS Low value is lower than all three helicopters in the data set. This suggests that if small UAS are used in lieu of queuing other manned assets to aid in surface ship missions, the cost per hour of that support is likely to be reduced, even when factoring in procurement costs. However, this is based on several key assumptions, including procurement cost for the UAS, number of hours flown, and UAS O&S cost per hour. If those assumptions are updated with real-world information, this methodology can be used to assess expected savings.

2. Break-Even Calculations and Conclusions

Another calculation that can be considered using the data in Tables 56 and 57 is the point at which the procurement investment in a UAS is paid back or reaches the breakeven point via reductions in O&S cost. This number can be calculated by starting with the COTS

UAS procurement costs and reducing those costs each hour flown by the delta between the O&S cost of the system being substituted and the O&S cost of the UAS. Figure 29 shows the results of those calculations for the high and low COTS UAS assuming the MH-60S is the system being substituted.

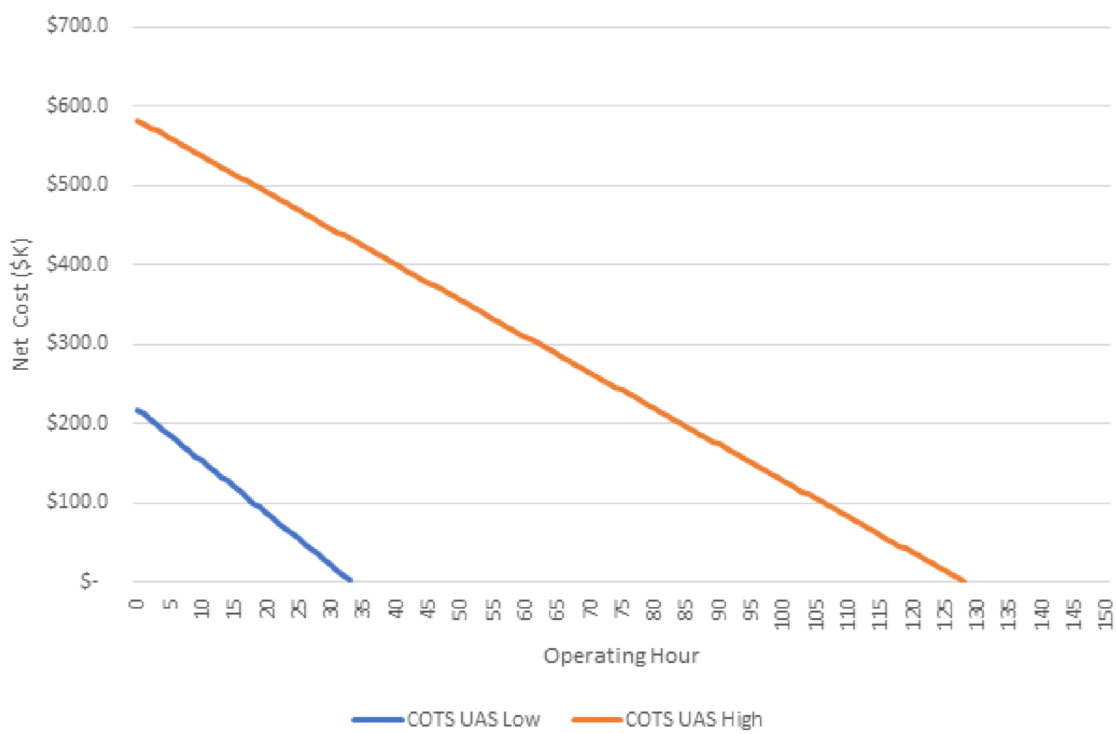
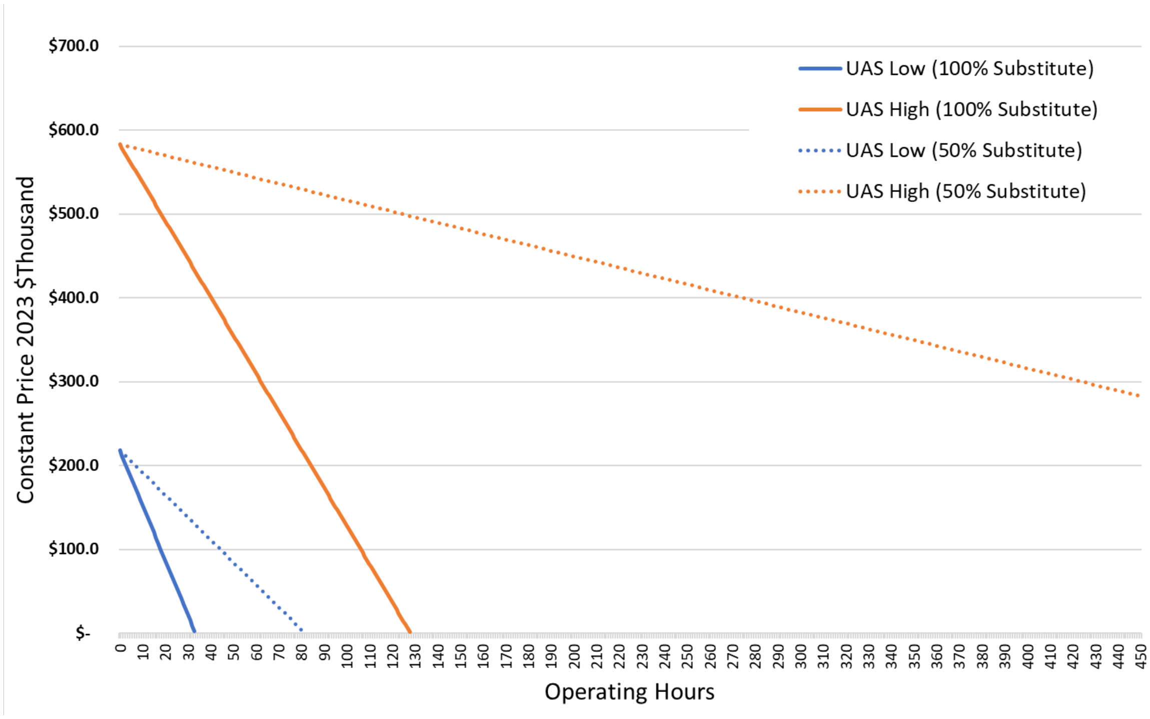


Figure 29. Break-Even Calculation

For the COTS UAS Low case, the breakeven point is achieved in the 34th operating hour. For the COTS UAS High case, which includes a higher procurement cost and a higher UAS O&S cost per hour, the breakeven point is achieved in the 129th hour. This analysis assumes that each UAS hour is effectively replacing an MH-60S hour. Again, this assumption should be validated with real world data. Figure 30 shows how these values change if this assumption is updated to assume that only 50% of the UAV Hours are reducing MH-60S hours.



At higher UAS costs, substitution rate assumed dramatically affects the break-even point. UAS High (50% Substitute) line continues to 834th operating hour.

Figure 30. Break-Even Calculation at 50% Substitution Rate

In this case, the breakeven point for the COTS UAS Low option is extended to the 82nd hour, which is still early in the system's life. However, for the more expensive drone option, the breakeven point is not reached until the 834th hour. This is 683% longer than under the 100% substitution case.

To summarize the analysis and findings with respect to cost, two types of analysis are presented which may be useful in considering the cost impacts of UAS. TOC PH of a future UAS system is an appropriate metric to compare with the costs of existing systems because it includes the investment cost of the new system. Considering TOC PH for two notional drone cost points, when comparing to the MH-60S, this analysis suggests that UAS flight hours are likely less expensive than the existing system. The source of funding may also be interested in understanding the cost breakeven point of acquiring new systems. Here, the analysis shows that for a lower cost system the breakeven point is early in the new system's life. As the COTS UAS solution becomes more expensive to procure and maintain, this breakeven point extends further into the UAS life. Importantly, with respect to savings, the existence of savings is dependent on the number of UAS hours that replace flight hours for existing systems. If most UAS flight hours are not directly replacing flight hours for existing systems, then adding UAS systems to surface ships is unlikely to save money.

V. CONCLUSIONS AND FUTURE WORK

In this chapter, the analyses, methods, and findings resulting from this research are summarized, and the final conclusions drawn from them are presented. Additionally, there have been several future work opportunities identified. These opportunities are also presented along with recommendations on how to go about them based on the foundational work conducted herein.

A. CONCLUSIONS

The Chief of Naval Operations' (CNO) 2021 NAVPLAN [1] includes a goal of achieving a hybrid fleet by the year 2045, though currently there is limited organic (i.e., launched and recovered from the vessel) Unmanned Aerial Systems use on smaller surface ships in both the USCG and USN fleets. Many UAS assets are capable of intelligence, surveillance, and reconnaissance and light-load resupply missions. Utilizing these systems in place of manned alternatives in suitable operations may save crucial time and effort in meeting mission goals. This paper seeks to identify UAS parameters that improve performance for key missions performed by USN and USCG vessels and model UAS behavior and impacts in contrast to alternatives currently employed.

For the ISR scenarios considered, the analysis shows that incorporating a UAS capability can significantly reduce mean time to search an area. This impact is larger for smaller areas, as UAS aerial time is finite while search time increases with the size of the search. The impact of UAS on reducing time also increases as the number of targets in the scenario increases. With respect to UAS parameters for the ISR mission, speed of the UAS is key – if the UAS speed is approaching the speed of the ship, UAS impact is reduced.

In the SAR analysis, UAS capability significantly reduces time to search the box when the UAS is used to increase sensor width. Here, it is discovered that the total amount of UAS aerial time is a key factor, whether this is achieved with additional UAS systems or longer endurance time. UAS sensor width is also a key factor, with wider sensor ranges decreasing the time required to search the box. However, while UAS systems can be used to decrease time to search, the assumed probability of detection for the UAS is important. If the probability of detection is low, this usage pattern lead to fewer overall detections.

The scenario in which the UAS is used to increase the overall scenario probability of detection as opposed to increasing sensor width is also considered. In this scenario, the UAS systems has effectively no impact on scenario time. As in the previous SAR scenario, probability of detection is very important—UAS impact on scenario non-detections is negligible or negative at the lower end of UAS probability of detections considered. At the higher end of the UAS probability of detections considered, a number similar to the assumed ship probability of detection, UAS positively impact the mean number of scenario non-detections (i.e., they decrease non-detections). Finally, UAS systems have negligible impact on non-detections for scenarios with lower total targets to find, but their impact increases as targets are added.

With respect to the benefits of adding UAS to the surface fleet for ISR and SAR missions, the following trends emerged:

- In the ISR case, UAS speed is key parameter.
- In general, more searching with high probability of detection shows favorable results and more searching with low probability of detection increases probability of non-detection. This implies that UAS sensors must be carefully considered when acquiring new systems.
- Counterintuitively, having UAS capability is more impactful to ISR and SAR mission metrics when smaller areas are searched. This is because larger searches take longer and UAS aerial time has a hard upper bound.
- UAS Systems are more likely to be impactful in when there are more targets to find or confirm in ISR and SAR environments.
- Ultimately, it is likely that incorporating UAS into the surface fleet, all else equal, will lead to improved performance in ISR and SAR missions for the metrics considered. However, the UAS must be selected with care.

The cost implications of adding UAS systems into the surface fleet were also considered. The analysis suggests that smaller COTS UAS solutions are likely to be significantly lower cost per hour than traditional manned assets, even when procurement costs are included for the UAS systems. As cost for the COTS UAS increases, their cost approaches the lower end of manned asset costs. This analysis, because fixed procurement costs are included, is dependent on the number of UAS hours flown. The more the UAS asset is flown, the lower its comparative per unit cost will be. This study also considered the number of flight hours at which UAS systems break even, or the procurement investment has paid for itself by reducing the marginal cost of supporting the surface fleet. This analysis assumes that UAS hours replace manned assets. Here, both lower and higher cost COTS UAS systems reach the breakeven point rapidly if it is assumed that all UAS hours are substitutes for manned assets. However, for higher cost systems, this breakeven point is highly dependent on the assumed substitution rate. For the notional higher end COTS UAS system considered, at a 50% substitution rate, the number of flight hours to reach breakeven increased ~680% relative to the 100% substitution rate case

Finally, the UAS Selector Tool considers:

- What generic UAS parameters are most valuable in an operating scenario.
- How performance specific UAS systems achieve on those parameters.
- What ships can support specific UAS systems.

This tool then calculates for each ship type which UAS can operate from it and the relative value of each UAS type. This tool is designed to be easily updated with real-world data for UAS systems, ship types, and stakeholder preferences. Stakeholders can use this tool to guide their further research into specific UAS solutions.

B. FUTURE WORK

Throughout this study, areas of useful additional research and analysis are identified that are either outside of the scope of this study or could not be properly conducted within its timeline. Researchers building upon the foundation of this study can utilize these as examples of how to do so.

Firstly, there is value to be found in expanding the set of specifications that are taken into consideration in the swing weight portion of the Drone Selector Tool. As described in Chapter III, the specifications that are currently weighted in the tool are chosen based upon their relation to each mission type. However, it is possible to include more specifications for these calculations so that a more complete picture of each UAS alternative is drawn for the user. For example, maximum altitude could also be weighted for ISR/SAR missions given that this ostensibly increases the field of view for the UAS. However, there is likely to be a point of diminishing returns for the number of specifications included.

Drawing from the previous suggestion, research can be conducted regarding the effect of increased altitude on target-identifying performance. It is intuitive that with higher altitude comes a wider field of view, thus a higher chance of a target being within that field of view. The caveat here is that with higher altitude *also* comes a greater separation between the sensor and the target, suggesting higher sensor quality and zoom level would be required for an effective identification. The research required may necessitate live tests given each UAS' unique maximum altitudes, sensor qualities, and battery life/loiter time. Relevant questions to consider for each UAS would include:

- How high can the UAS get?
- How fast can the UAS get there?
- How well can the UAS see when it gets there?
- How long can the UAS stay there?
- Does higher altitude meaningfully impact the UAS' ability to successfully identify targets?

The modeling of these factors and the results would improve the understanding of a UAS' value in target-finding missions such as ISR and SAR.

Similarly, research could also be conducted regarding UAS performance in off-nominal environments. This too may require live tests as this study has discovered that the manufacturers of these UAS do not often include performance degradation in high winds, rain, fog, etc. All models and calculations in this study are under the assumption of nominal conditions, and only those metrics reported by the manufacturer are utilized without alteration.

Next, the set of ExtendSim models presented in this study can be expanded. The inclusion of a model scenario in which the UAS flies entirely independently of the ship would be a useful addition. This model would involve predetermining the areas of the search box that the ship would cover, then sending out a UAS to independently search other areas of that operational area. This would serve to further understand the effect UAS may have on the number of targets identified and the time taken to identify them. This model is not included in this study due to the assumption that this would not much improve these factors given the short loiter times of UAS (compared to the ship's search time). However, forethought can be given to intelligently planning the routes that the ship and UAS would take. Perhaps if an appropriate search plan is constructed for each asset some improvements could be noted. There are likely opportunities for several other models to be constructed as well. However, the one discussed here would be beneficial regardless of metric improvements given the foundation it would lay for mission-planning with UAS aboard these vessels.

As a general recommendation, improvements can be made to the Drone Selector Tool's UAS specifications. Namely, there are several UAS without a complete set of specifications—i.e., some are missing maximum altitude, runway length required, storage size, etc. Many attempts were made to source these specifications, but at the time of this paper's writing, they are not publicly listed and attempts to contact the manufacturers were unfruitful. Assumption specifications are used in their place to allow their listed specifications to be considered against each of the other UAS. These assumptions are the least favorable of the available data from the other UAS to not inadvertently bloat their weighting. However, the inclusion of their actual values would further increase the value of the Drone Selector Tool's outputs.

Another useful examination that is not conducted in this study is the impact of mean time between failure, mean downtime, and mean time to repair. With every UAS in this study being a COTS product, there is perhaps some amount of this information already available. However, life cycle considerations are outside the scope of this study, therefore this information is not present herein. Regardless, the understanding of the up-time, maintenance, and impacts to UAS budgeting is valuable to the stakeholders that will make use of these UAS.

Finally, there are many factors regarding real-world UAS use that are not covered by this study. For example, a UAS' loiter time could perhaps be degraded with payloads attached to them—i.e., the return trip for a UAS during a logistics mission may be affected by the additional weight. A model could potentially be built to display this behavior and to examine optimal planning for such effects. For example, releasing the UAS at an opportune time and continuing driving forward to near where its battery/fuel will deplete on the return trip. Similar considerations may also be explored regarding other use-related capability degradations such as fuel depletion rates while operating at maximum speed, or other such concepts.

APPENDIX A. UAS SUITABILITY SCORES

Table 59. UAS Suitability Scores

UAS	ISR/SAR Score	Logistics Score
Phantom 3	12.66	NO PAYLOAD
Vesper	23.89	NO PAYLOAD
X2-D	15.89	NO PAYLOAD
Anafi USA	15.32	NO PAYLOAD
ASW Heavy Lift Multirotor Hexacopter	25.43	24.86
ASW Heavy Lift Multirotor Octocopter	25.43	28.86
Alpha 900	96.29	37.74
AeroVironment Puma LE	130.57	NO PAYLOAD
L3 Harris FVR-90	304.79	57.05
Tekever AR3 Catapult	302.21	48.33
Tekever AR3 VTOL	165.07	48.33
Censys Sentaero BVLOS	52.43	NO PAYLOAD
Deltaquad Pro Cargo	49.71	34.56
Deltaquad Pro View	49.71	34.56
Aerosonde Textron HQ	175.29	66.43
Shield VBAT	293.50	184.52

A higher score here indicates a more suitable match—e.g., the Alpha 900's ISR/SAR score of 96.29 indicates that it is a more suitable ISR/SAR solution than the X2-D with a score of only 15.32. This remains true for the logistics scores as well, where "NO PAYLOAD" indicates that it cannot support logistics missions whatsoever.

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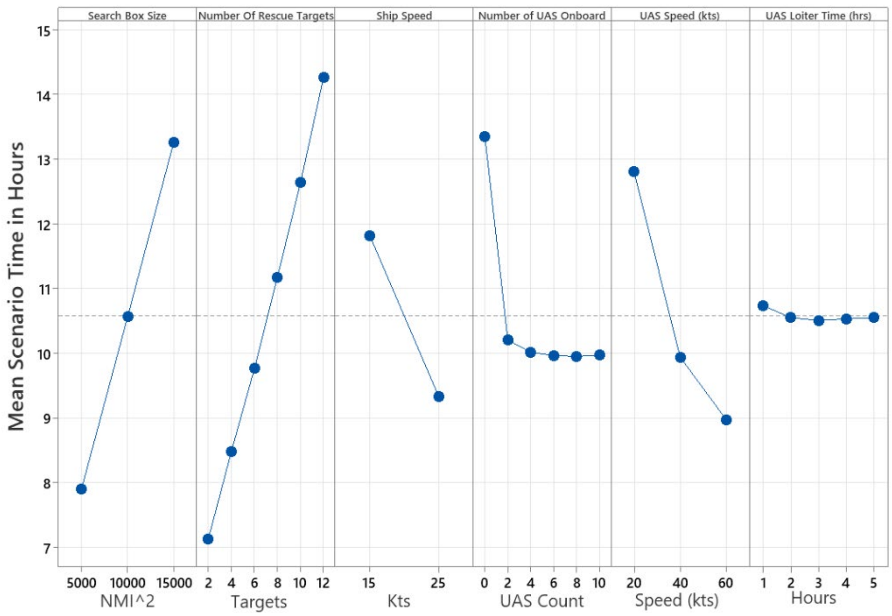
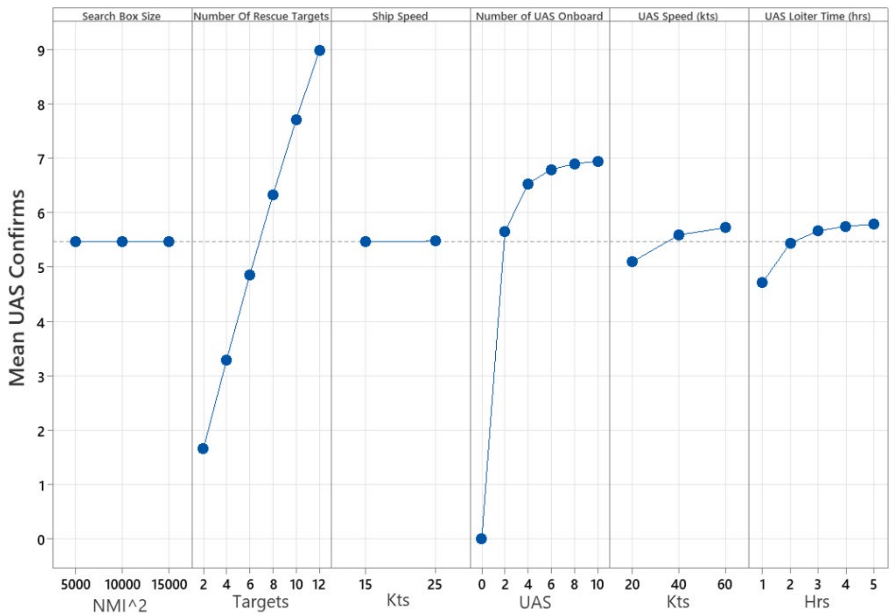
APPENDIX B. ISR MODELING ANALYSIS PLOTS



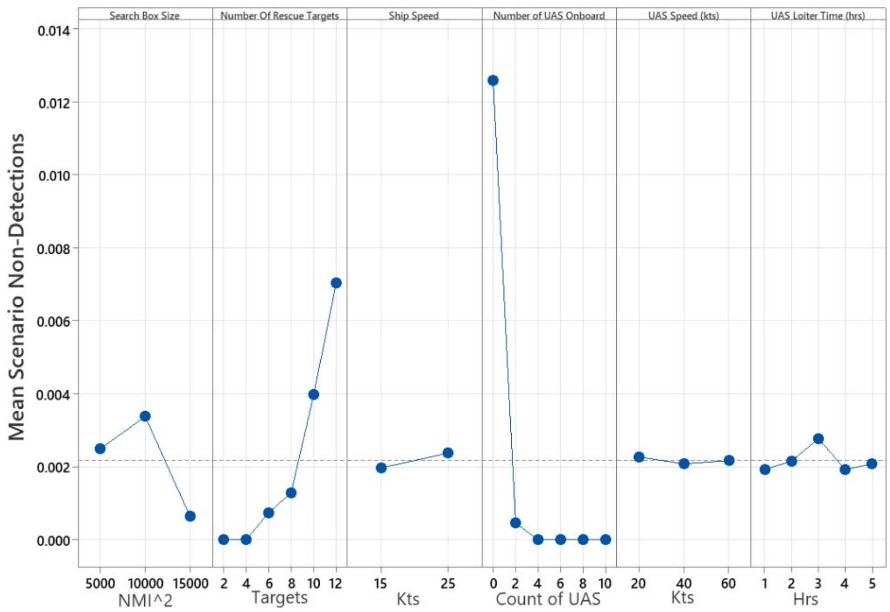
y-axis is scenario time. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in scenario time with changes in distinct variables.

Figure 31. ISR Detect and Confirm Main Effects Plot for Mean Scenario Time in Hours



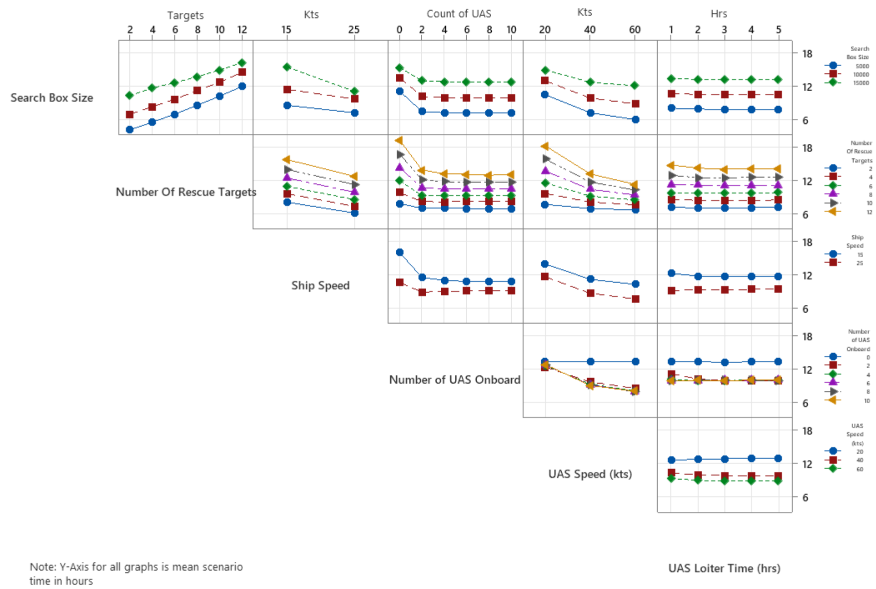
y-axis is mean scenario confirmations by UAS. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in UAS confirmations with changes in distinct variables.

Figure 32. ISR Detect and Confirm Main Effects Plot for Mean UAS Confirmations



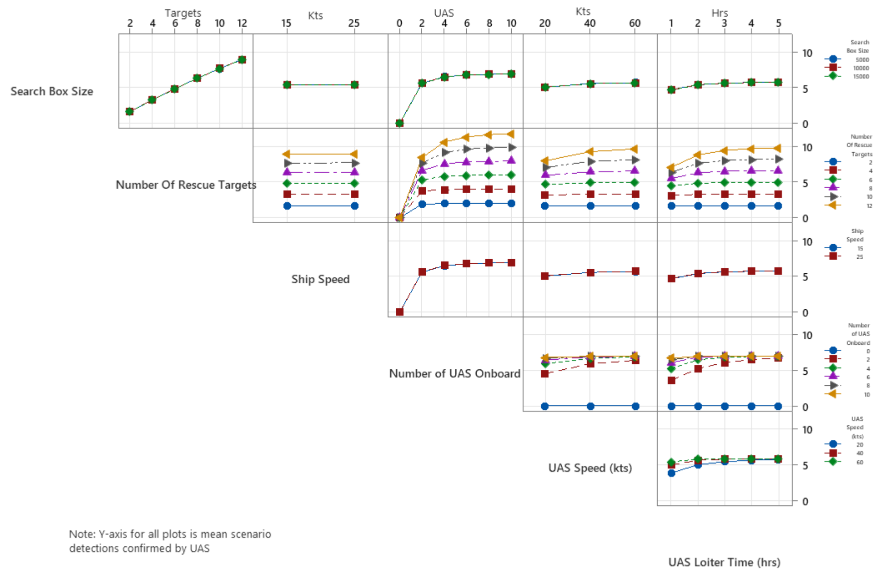
y-axis is mean scenario time. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in the average scenario non-detections with changes in distinct variables.

Figure 33. ISR Detect and Confirm Main Effects Plot for Mean Scenario Non-detections (y-axis) by DOE Input Variables (x-axis, labels at top, units noted at bottom)



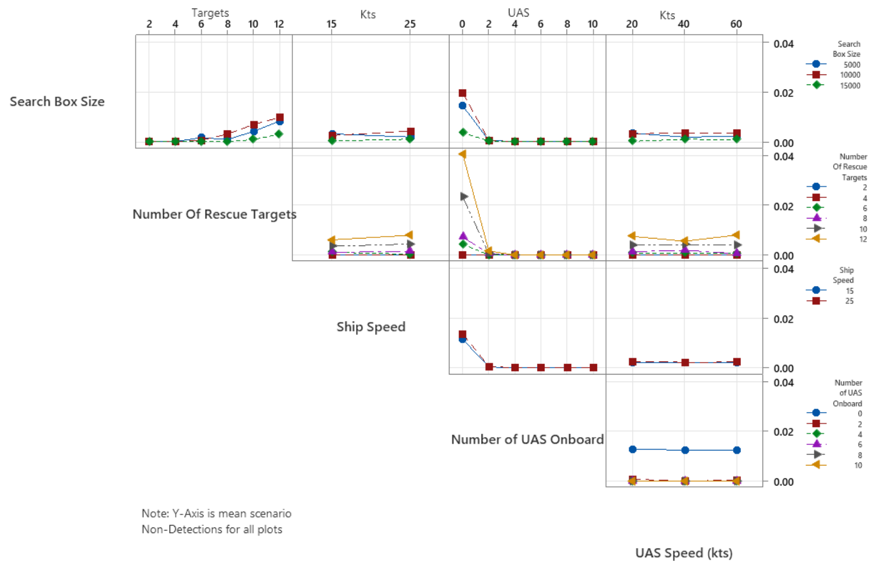
y-axis is mean scenario time. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., "Targets" is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average scenario time with changes in the paired inputs.

Figure 34. ISR Detect and Confirm Interaction Plot for Mean Scenario Time in Hours



y-axis is mean scenario confirmations by UAS. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., "Targets" is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average UAS confirmations with changes in the paired inputs.

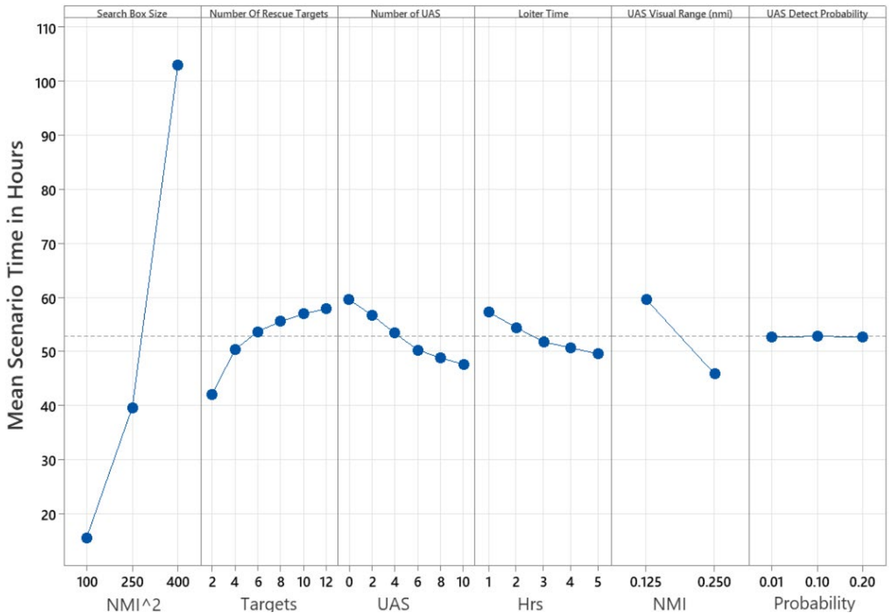
Figure 35. ISR Detect and Confirm Interaction Plot for Mean Scenario UAS Confirmations



y-axis is mean scenario non-detections. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., "Targets" is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average scenario non-detections with changes in the paired inputs.

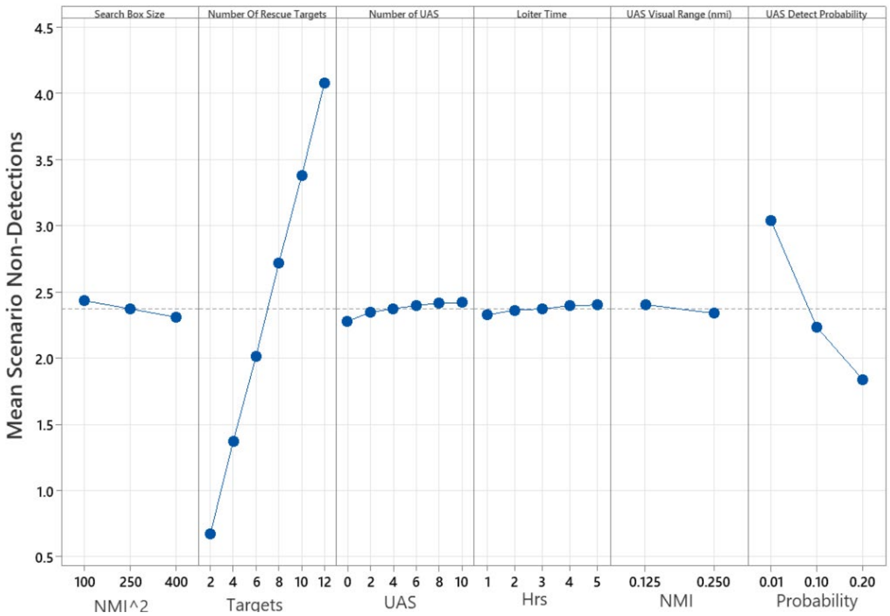
Figure 36. ISR Detect and Confirm Interaction Plot for Mean Scenario Non-detections

APPENDIX C. SAR MODELING ANALYSIS PLOTS



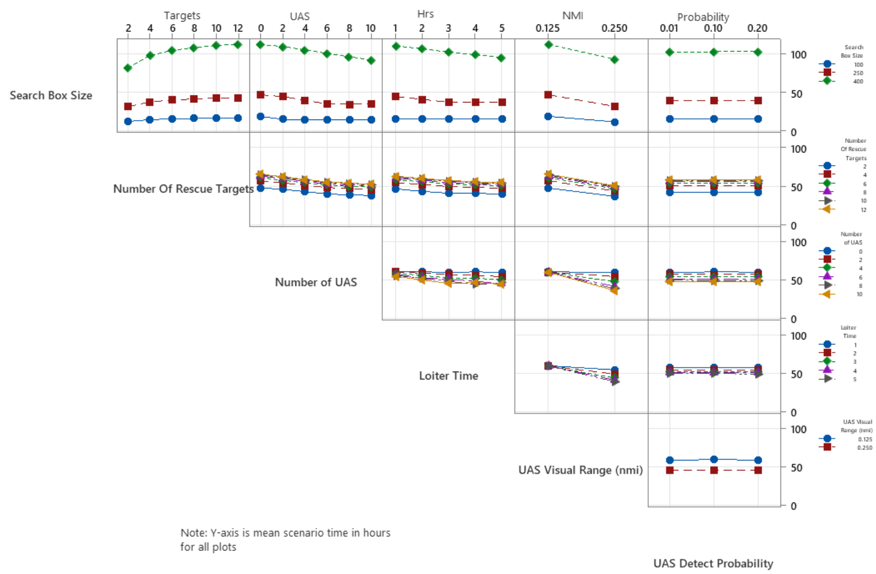
y-axis is the mean scenario time. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in average scenario time with changes in distinct variables.

Figure 37. SAR Decrease Time Main Effects Plot for Mean Scenario Time in Hours



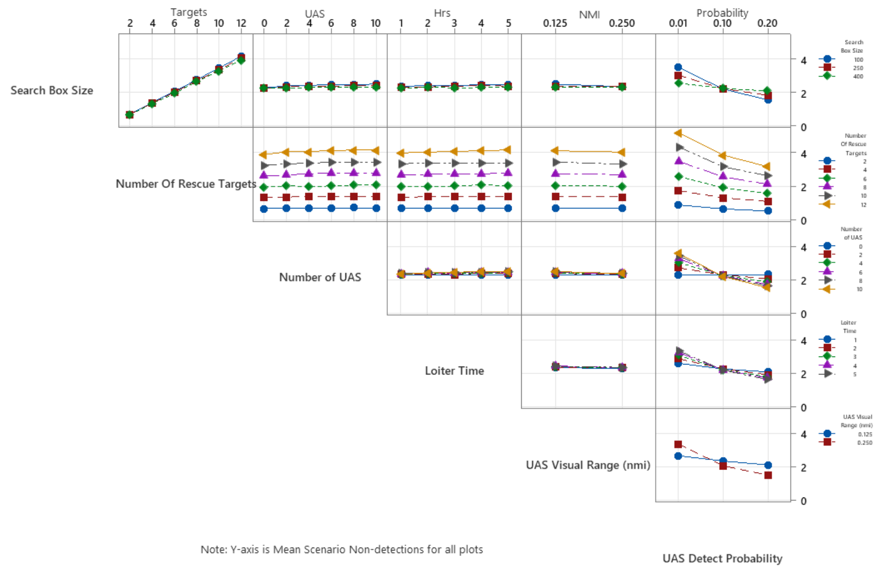
y-axis is the mean scenario non-detections. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in average scenario non-detections with changes in distinct variables.

Figure 38. SAR Decrease Time Main Effects Plot for Mean Scenario Non-detections



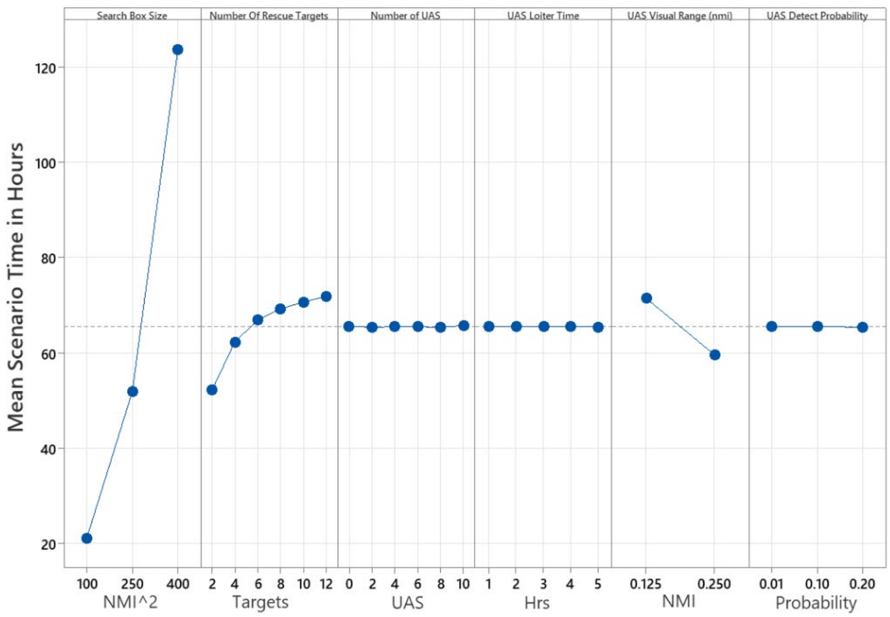
y-axis is mean scenario time. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., “Targets” is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average scenario time with changes in the paired inputs.

Figure 39. SAR Decrease Time Interactions Plot for Mean Scenario Time in Hours



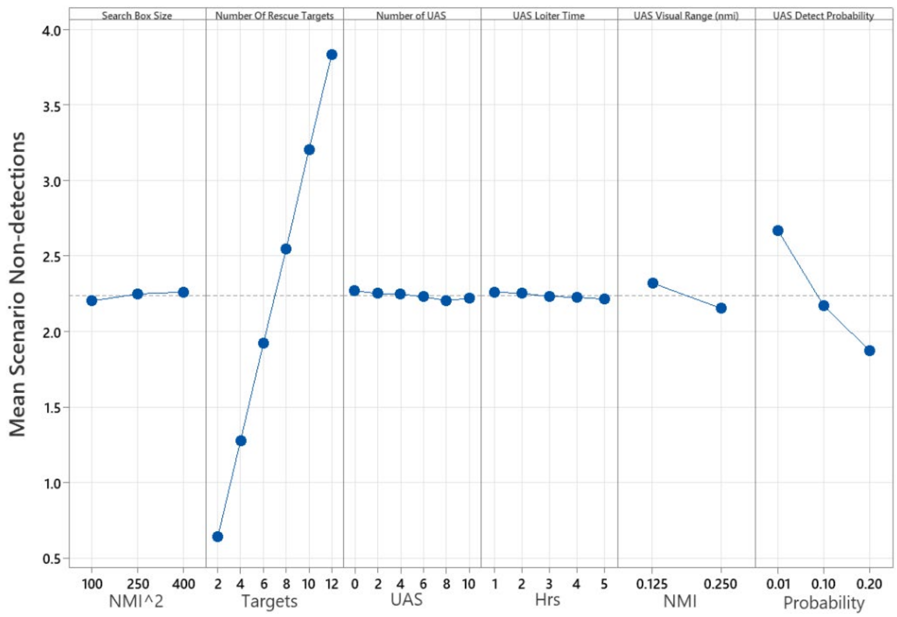
y-axis is mean scenario non-detections. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., "Targets" is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average scenario non-detections with changes in the paired inputs.

Figure 40. SAR Decrease Time Interaction Plot for Mean Scenario Non-detections



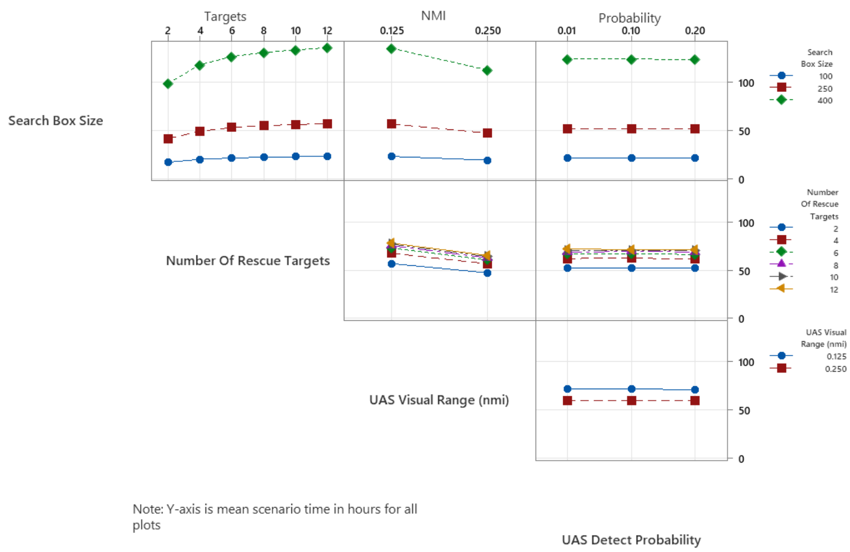
y-axis is mean scenario time. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in average scenario time with changes in distinct variables.

Figure 41. SAR Increase Detections Main Effects Plot for Mean Scenario Time in Hours



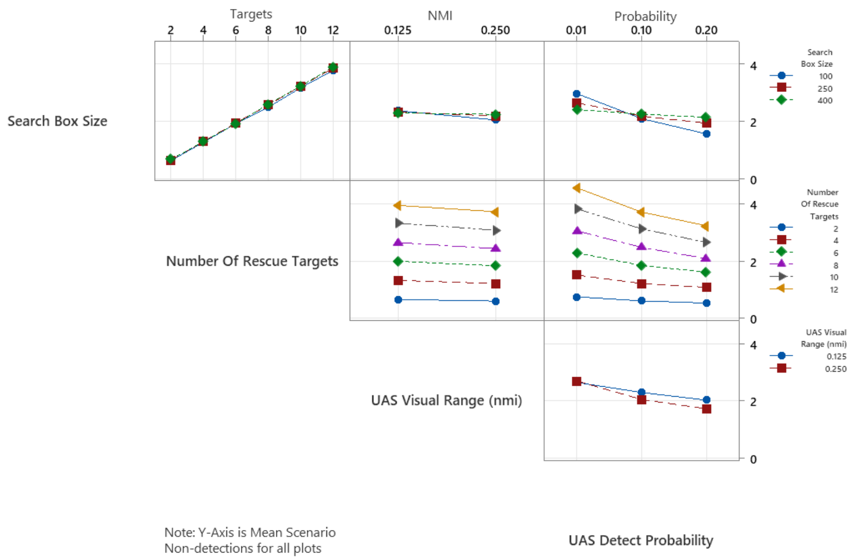
y-axis is mean scenario non-detections. The plot is sectioned by the various design of experiments inputs variables (search box size, ship speed, etc.) and the values for each are varied as depicted on the x-axis with units notated at the bottom. This graph represents the change in average scenario non-detections with changes in distinct variables.

Figure 42. SAR Increase Detections Main Effects Plot for Mean Scenario Non-detections



y-axis is mean scenario time. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., "Targets" is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average scenario time with changes in the paired inputs.

Figure 43. SAR Increase Detections Interaction Plot for Mean Scenario Time in Hours



y-axis is mean scenario non-detections. The plot is sectioned by pairs of mutually varied inputs. The variable notated to the left of a given box is stylized by color and shape, each of which represents the varied value (depicted to the right of the plots). The variable notated to the bottom of a given box is varied according to the numbers that line the top of the box (i.e., "Targets" is varied by 2, 4, 6, 8, 10, and 12). This graph represents the change in average scenario non-detections with changes in the paired inputs.

Figure 44. SAR Increase Detections Interaction Plot for Mean Scenario Non-detections

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