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OPERATIONAL ASSESSMENT OF ALTERNATIVE FUELS FOR UNMANNED AERIAL VEHICLES

by

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March 2023

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13. ABSTRACT (maximum 200 words)

This thesis explores alternative fuel options for unmanned systems in the Department of Defense (DOD). The use of traditional fuels in warfare has become a major concern for the department, prompting a search for alternative fuels that may improve operational performance by increasing the time on station for future systems. To address this challenge, this thesis selected hydrogen, methanol, and ethanol as potential alternative fuel candidates and conducted simulations. A simulation program called ExtendSim was used to conduct simulations and determine the operational availability of systems employing each fuel type. Operational availability is a crucial parameter and outcome in the choice of the best alternative fuel. The simulations were performed under various constraints, including tank weight and volume, launch decks, and refueling spots. The results showed that liquid hydrogen when constrained by the fuel weight of existing systems, had the highest operational availability. Use of hydrogen fuel showed a potential to increase operational availability from 0.74, using traditional propellants, to 0.92 using hydrogen fuel. The study also revealed the impact of the number of refilling spots and obstacles on the overall results, which means they affected the results and outcome of the operational availability. This research provides valuable insights into the development of alternative fuels for unmanned systems in the Department of Defense.

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OPERATIONAL ASSESSMENT OF ALTERNATIVE FUELS FOR UNMANNED AERIAL VEHICLES

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ABSTRACT

This thesis explores alternative fuel options for unmanned systems in the Department of Defense (DOD). The use of traditional fuels in warfare has become a major concern for the department, prompting a search for alternative fuels that may improve operational performance by increasing the time on station for future systems. To address this challenge, this thesis selected hydrogen, methanol, and ethanol as potential alternative fuel candidates and conducted simulations. A simulation program called ExtendSim was used to conduct simulations and determine the operational availability of systems employing each fuel type. Operational availability is a crucial parameter and outcome in the choice of the best alternative fuel. The simulations were performed under various constraints, including tank weight and volume, launch decks, and refueling spots. The results showed that liquid hydrogen when constrained by the fuel weight of existing systems, had the highest operational availability. Use of hydrogen fuel showed a potential to increase operational availability from 0.74, using traditional propellants, to 0.92 using hydrogen fuel. The study also revealed the impact of the number of refilling spots and obstacles on the overall results, which means they affected the results and outcome of the operational availability. This research provides valuable insights into the development of alternative fuels for unmanned systems in the Department of Defense.

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LIST OF ACRONYMS AND ABBREVIATIONS

Ao	Operational Availability
BAMS-D	Broad Area Maritime Surveillance Demonstrator
CBRNE	Chemical, Biological, Radiological, Nuclear, Explosive
CNG	Compressed Natural Gas
CONOPS	Concept of Operations
DGE	Diesel Gallon Equivalent
DOD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DOE	Department of Energy
DON	Department of the Navy
GGE	Gasoline Gallon Equivalent
ISR&T	Intelligence, Surveillance, Reconnaissance, and Targeting
LCS	Littoral Combat Ship
LDUUV	Large Displacement Unmanned Undersea Vehicle
LUSV	Large Unmanned Surface Vessel
MDUSV	Medium Displacement Unmanned Surface Vehicle
MDUUV	Medium Displacement Unmanned Undersea Vehicle
MOE	Measure of Effectiveness
MOP	Measure of Performance
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
MUSV	Medium Unmanned Surface Vessel
NDAA	National Defense Authorization Act
NPS	Naval Postgraduate School
RFI	Request for Information

SAR	Search and rescue
TOS	Time On Station
UAV	Unmanned Aerial Vehicle
U.S.	United States
USV	Unmanned Surface Vehicle / Unmanned Surface Vessel
UUV	Unmanned Undersea Vehicle
UVC	Unmanned Vehicle Carrier
UxV	Unmanned Vehicle
XLUUV	Extra Large Unmanned Undersea Vehicle

EXECUTIVE SUMMARY

The National Defense Authorization Act of 2022 dictates that the U.S. Department of Defense (DOD) invest in alternative and renewable fuels, such as hydrogen and electricity, to support its future systems and operational concepts and to reduce its environmental impact and dependence on traditional fuel chains (U.S. Government Publishing Office 2022). The DOD considers global warming to be a serious security threat and is working to reduce its greenhouse gas emissions by reducing its conventional fuel use and increasing its investment and budget in alternative fuels. The DOD is also testing and certifying cost-competitive alternative fuels to reduce the risk of fuel supply and to integrate alternative energy sources into bases and combat equipment. The Department of Navy (DON) is interested in the viability of a dedicated Unmanned Vehicle Carrier (UVC) to support both traditional and alternative-fueled unmanned systems, where unmanned aerial vehicles (UAV) are expected to provide support for search and rescue (SAR) and intelligence, surveillance, and reconnaissance (ISR). The DON is also pursuing the use of alternative fuels in unmanned undersea and surface vehicles. This thesis informs investment in both alternative fuels and unmanned systems by developing and analyzing a discrete event simulation of UVC operations utilizing multiple candidate alternative fuels.

A. BACKGROUND AND RELEVANT LITERATURE

On March 16, 2021, the U.S. Navy and Marine Corps announced the “Unmanned Campaign Framework,” a strategy aimed at making unmanned systems a reliable and critical part of future combat operations. The framework has several goals including improving manned-unmanned teaming, building a digital infrastructure, incentivizing rapid development and testing of unmanned systems, and creating a sustainable approach for unmanned contributions to the force. The Navy and Marine Corps are working on roadmaps for technological maturity and acquisition. The focus is on defining performance standards, reducing risk, and standardizing autonomy, command and control, and payload interfaces. Unmanned systems are used in various domains including air, sea, and ground. Examples of current unmanned systems in operation include a Broad Area Maritime Surveillance Demonstrator (BAMS-D) unmanned aircraft, the X-47B fighter jet, the Large and Medium Unmanned Surface Vessels, the Long-Range Unmanned Surface Vessel being developed by the Marine Corps, and Small and Medium Unmanned Undersea Vessels.

The DOD has been implementing sustainable energy measures in its military operations and strategies, including the publication of the 2011 and 2016 Operational Energy Strategies, which established energy policies and objectives to reduce reliance on oil and integrate alternative energy sources. The DOD has been testing and certifying the procurement of alternative fuels and released a Request for Information (RFI) in 2021 to gather information on transitioning to 100% carbon-free power (Vergun 2022). The DOD aims to create an electricity sector free of carbon pollution by 2035 and is exploring alternative fuels such as hydrogen, methanol, and ethanol as potential options. This effort by the DOD is crucial in contributing to the fight against global climate change while maintaining U.S. competitiveness in the global energy markets. Realizing these larger goals requires a definition of the operational role that unmanned systems and alternative fuels may have on future operational concepts. Using simulations, this thesis implements those fuels and systems to inform the refinement of the concepts described in the Unmanned Campaign Framework.

B. MODEL DESCRIPTION

In this paper, a simulation model was created using the ExtendSim program to examine unmanned systems operating in the operational environment. The model assumed two classes of UAVs, the MQ-8 and RQ-21, currently operated by the U.S. Navy, and simulated their operation over a 30-day period. The purpose of the simulation was to identify the design parameters and assess the impact of alternative fuels on UAV performance, especially their operational availability. The four types of fuels used in the simulation were gasoline, gaseous hydrogen, liquid hydrogen, and methanol, and the simulation was built in eight distinct configurations based on the type of fuel used and the constraints of volume and weight. Realizing these larger goals requires the definition of the operational role that unmanned systems and alternative fuels may have on future operational concepts. This thesis implements those fuels and systems to inform the refinement of the concepts described in the Unmanned Campaign Framework. Within each configuration, design and operational factors that may impact performance were also varied. Using an efficient experimental design approach, 65 design configurations were developed for each fuel type and each configuration was replicated 30 times within the ExtendSim model. This resulted in a total of 15,600 runs of the ExtendSim model.

C. ANALYSIS AND CONCLUSION

Analysis was conducted to compare the impact of alternative fuels on unmanned operations from a UVC. The model was run with different input variables and fuel combinations to evaluate the operational availability of each fuel. The results showed that gaseous hydrogen and liquid hydrogen, when constrained by weight, had the highest operational availability among the fuels compared, with values of 0.9207 and 0.9211, respectively. The research also identified other factors such as the number of UAVs, number of refueling spots, and presence of obstacles that affect operational availability, and concluded that increasing the number of UAVs and refueling spots and reducing the presence of obstacles could improve operational availability. Regression analysis was conducted, and contour profiles were built to determine the recommended number of UAVs based on the operational availability of each fuel. Using the appropriate fuel type analysis showed that a total of 17 UAVs could be supported by the UVC. Additional analysis of UVC design suggested that doubling the number of refueling spots aboard the UVC (from four to eight) enabled the UVC to support one additional UAV. Finally, an examination of the impact of the environment suggests that varied environmental conditions may reduce the number of UAVs that may be supported from 17 to 15.

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I. INTRODUCTION

A. BACKGROUND

According to the 2022 National Defense Authorization Act (NDAA), the U.S. Department of Defense (DOD) is investigating in alternative and renewable fuels, including electric, hydrogen, or other sustainable fuel technologies, to support future systems and operational concepts. This is motivated by a desire to reduce environmental impact and decouple from traditional fuel chains. The investigation in this thesis extends beyond the DOD. It is estimated that the total U.S. military greenhouse gas emissions between 2018 and 2001 is 1.267 million metric tons (Crawford 2019). Consequently, the DOD has defined global warming as a serious security threat and has been working for decades to address it. To that end, the DOD is reducing its use of conventional fuel with the objective of reducing greenhouse gases and, as a result, is increasing its investment in and budget for alternative fuels.

The DOD has tried to test and certify the procurement of cost-competitive alternative fuels to reduce the risk to fuel supplies and to integrate alternative energy sources into bases and individual combat equipment. The goal is to significantly reduce the need for refueling by increasing the use of energy-harvesting technologies in the surrounding area (Department of the Navy [DON] 2017). This investment in harvesting technologies has been focused on likely areas of operation, notably the Pacific theater. Within this expected area of operations, the DOD is particularly interested in the viability of a dedicated Unmanned Vehicle Carrier (UVC) that can support both traditionally and alternatively fueled unmanned systems.

Within the operating environment described in the previous paragraph, Unmanned Aerial Vehicles (UAV) are expected to provide support for search and rescue (SAR) and intelligence, surveillance, and reconnaissance (ISR). Platforms currently fielded include the MQ-25 and MQ-8. Additionally, the Navy is pursuing both Unmanned Undersea Vehicles (UUV) and Unmanned Surface Vehicles (USV) (DON 2021). Current systems include REMUS, Knifefish, and Sea Hunter, all of which are candidates for use of alternative fuels. Table 1 presents the operational characteristics of the UAVs, USVs, and UUVs that are well-suited to the use of alternative fuels (DON 2021).

Table 1. Operational Characteristics of Unmanned Vehicles.

	UAV		USV	UUV	
	MQ-8B	MQ-25	Sea Hunter	REMUS 6000	Knifefish
Operated by	Navy[1]	Navy[2]	Navy[3]	Navy[4]	Navy[5]
Type	Reconnaissance, fire support, targeting support[1]	Surveillance and Strike[2]	Reconnaissance, Track submarine[3]	Reconnaissance[4]	Reconnaissance, Mine countermeasure[5]
Length (m)	7.3[1]	15.5[2]	40[3]	3.84[4]	6.7[5]
Wingspan (m)	8.4[1]	22.9/9.54[2] (folded)	-	-	-
Height (m)	2.9[1]	3.0/4.79[2] (folded)	-	-	-
Endurance (hr)	8[1]	12[2]	30–90 days[3]	22[4]	25[5]
Range (km)/ Depth (km)	177[1]	930[2]	19,000[3]	6[4]	4.5[5]

Adapted from 1. DON (2021); 2. DON (n.d.); 3. Newswire (2013); 4. Oceanographic Systems Lab (n.d.); and AUVAC (n.d.).

The U.S. Department of Energy (DOE) suggested some alternative fuels that the DOD and the DON can use for recharging the unmanned systems. Table 2 shows which types of fuel are available as alternative fuels and lists the characteristics of each alternative fuel. Table 2 contains a total of seven types of fuel: Gasoline, Biodiesel, Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG), Ethanol, Methanol, and Hydrogen.

Table 2. Fuel Properties Comparison. Adapted from U.S. Department of Energy (DOE) (2021).

	Gasoline	Biodiesel	Compressed Natural Gas (CNG)	Liquefied Natural Gas (LNG)	Ethanol	Methanol	Hydrogen
Chemical Structure	C_4 to C_{12}	C_{12} to C_{22}	CH_4(majority), $C_2H_6$and inert gases	CH_4same as CNG with inert gasses <0.5%	CH_3CH_2OH	CH_3OH	H_2
Fuel Material	Crude Oil	Fats and oils from sources such as soybeans, waste cooking oil, animal fats, and rapeseed	Underground reserves and renewable biogas	Underground reserves and renewable biogas	Corn, grains, or agricultural waste (cellulose)	Natural gas, coal, or woody biomass	Natural gas, methanol, and electrolysis of water
GGE or DGE	1gal = 1.00 GGE 1gal = 0.88 DGE	B100 1gal = 1.05 GGE 1gal = 0.93DGE	1lb. = 0.18 GGE 1lb. = 0.16 DGE	1lb. = 0.19 GGE 1lb. = 0.17DGE	1gal = 0.67 GGE 1gal = 0.59 DGE	1gal = 0.50 GGE 1gal = 0.45 DGE	1lb. = 0.45 GGE 1 lb. = 0.40 DGE 1kg = 1GGE 1kg = 0.9DGE
Energy Content	112,114–124,340 Btu/gal (c)	B100 119,550–127,960 Btu/gal (c)	20,160–22,453 Btu/gal (c)	21,240–23,726 Btu/gal (c)	E100 76,330–84,530 Btu/gal (c)	57,250–65,200 Btu/gal (c)	51,585–65,200 Btu/gal (c)
Physical State	Liquid	Liquid	Compressed gas	Cryogenic liquid	Liquid	Liquid	Compressed gas
Flash Point	-45°F (j)	210° to 338°F (j)	-300°F (j)	-306°F (j)	55°F (j)	52°F (j)	N/A
Autoignition Temperature	495°F (j)	~300°F (j)	1,004°F (j)	1,004°F (j)	793°F (j)	897°F (j)	1,050° to 1,080°F (j)

Note: DGE = Diesel Gallon Equivalent; GGE = Gasoline Gallon Equivalent

Considering the planned operating environment, some of the alternative fuels are not appropriate for application based on their energy efficiency, by-products, safety, and physical state. Among the alternatives presented in Table 2, this thesis focuses on three types of fuel: Hydrogen, Ethanol, and Methanol.

Gasoline Gallon Equivalent (GGE) and Diesel Gallon Equivalent (DGE) are important factors in terms of energy efficiency because this thesis needs to find alternative fuels that are not much different from the efficiency of the diesel or gasoline the DOD is using now. In that respect, the three fuels just mentioned show less efficiency than diesel or gasoline but have higher efficiency than the other alternative fuels. This reduction in efficiency will require that larger quantities of each fuel be available when compared to traditional fuels. Generation and storage requirements will account for that discrepancy and are assessed as part of this thesis.

B. RESEARCH QUESTIONS

The purpose of this thesis is to assess the viability of alternative fuels for unmanned systems currently utilized by the Navy and Marine Corps. This assessment utilizes simulation modeling to assess the impact of changing fuel types in a future operational environment. To achieve this purpose, this thesis focuses on the following questions:

- How does the operational availability (Ao) of unmanned vehicles (UxV) differ depending on the type of alternative fuel?
- Except for the type of alternative fuel, what other factors affect the operational availability of UxVs?

C. SYSTEMS ENGINEERING PROCESS

There are many approaches to systems engineering, including the Waterfall, Vee, and Spiral (Blanchard and Fabrycky 2014). This thesis used a combination of the left-hand side of the Vee model (Figure 1) and the mission engineering approach defined in the work of Beery and Paulo (2019). The mission engineering approach dictates the development of a simulation model to support the steps of the Vee model highlighted in Figure 1. It requires a process of decomposing from the upper system, the UVC, to the lower systems and subsystems such as the Control system, the Launch system, the Maintenance system, and UxVs, and confirming what functions and components are needed for the system.

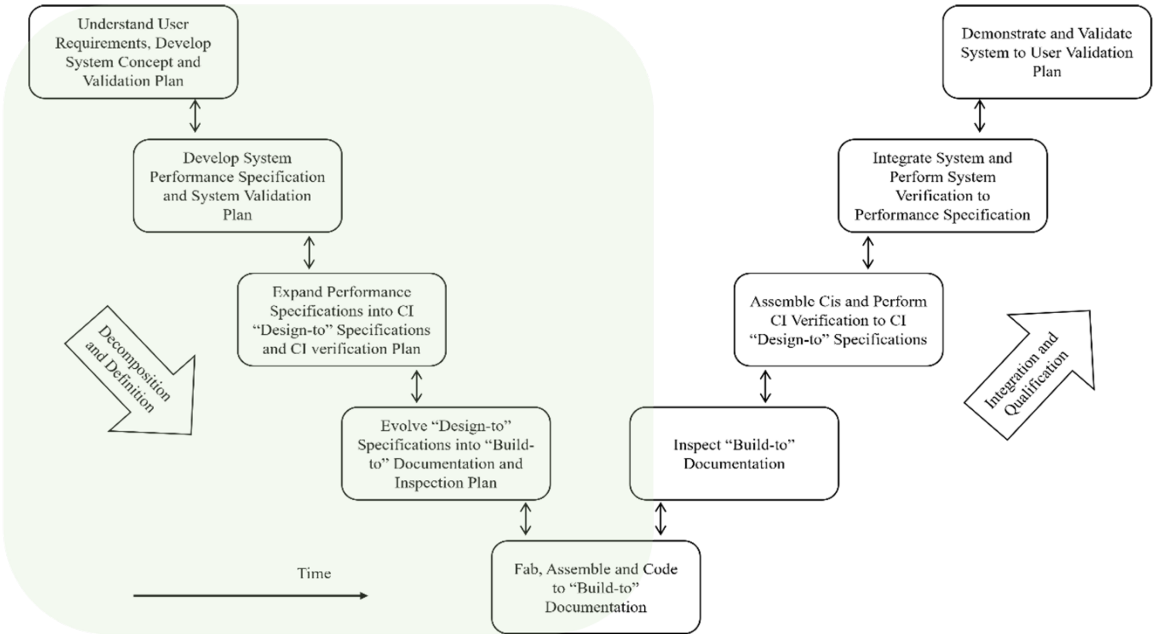

Figure 1. Systems Engineering "Vee." Source: Forsberg and Mooz (1992).

The Department of Defense Architecture Framework (DoDAF) version 1.5, which was published in 2007, said that there are several steps and guidelines to follow when making and designing systems, including the operational view, systems view, technical standards view, and all-views, and each view has its respective products.

In May 2009, the DOD revised the DoDAF and published version 2.0 with more added viewpoints. What version 2.0 emphasizes differently from version 1.5 is the data-centric approach that gives a technical explanation of the meta-model data categories and the model that goes along with them. Architects, program managers, portfolio managers, and other technically minded architecture consumers make up the bulk of the audience. This thesis makes and uses some products of the DoDAF to allow readers to understand the various perspectives and decisions associated with the utilization of alternative fuels aboard a UVC.

D. PROBLEM STATEMENT

The U.S. Navy and U.S. Marine Corps' future operations will become stronger and more complicated by the combination of man and unmanned systems (DON 2021). Moreover, the DOD's energy strategy cannot turn a blind eye to environmental concerns, and it must study and discover alternative fuels that can replace the traditional fuels currently in use (DOD 2017). Motivated by that guidance, this thesis studies alternative fuels that can maximize the efficiency and operational availability of the UxVs in operation by the Navy and Marine Corps.

E. LITERATURE REVIEW

This literature review is organized into three sections. The first section reviews the unmanned campaign framework from the U.S. Navy and U.S. Marine Corps. The second reviews the unmanned systems that are currently in use and the future prototypes planned by the U.S. Navy and U.S. Marine Corps. The third reviews the available alternative fuels for future unmanned systems.

1. Unmanned Campaign Framework

On March 16, 2021, in Washington, DC, the U.S. Navy and the U.S. Marine Corps announced the unmanned campaign framework, a strategy to make unmanned systems a reliable and essential part of combat and warfighting in future battles (DON 2021). The framework has several purposes and goals:

> to advance manned-unmanned teaming within the full range of Naval and joint operations, build a digital infrastructure that integrates and adopts unmanned capabilities at speed and scale, incentivize rapid incremental development and testing cycles for unmanned systems, disaggregate common problems, solve once, and scale solutions across platforms and domains, and create a capability-centric and sustainable approach for unmanned contributions to the force. (DON 2021)

The framework offers a plan for combining various technologies to produce deadly, resilient, and scalable impacts that assist future operations. The Navy and Marine Corps are creating comprehensive roadmaps for technological maturity and acquisition. The goal is to develop answers swiftly for challenging issues associated with ongoing and upcoming conflicts. The strategy for the campaign focuses on how the Navy and Marine Corps will define performance standards and decrease risk and standardize autonomy, command and control, payload interfaces, and networks with specialized prototypes for each unmanned system and the development of capabilities in this way (DON 2021).

The framework describes how unmanned systems are applied and used in various ways to fulfill missions in the air, on the sea, and on the ground. In the air, a Broad Area Maritime Surveillance Demonstrator (BAMS-D) unmanned aircraft equipped with an Intelligence, Surveillance, Reconnaissance, and Targeting (ISR&T) sensor package is in operation that provides maritime surveillance. The MQ-8C (Figure 2, left) provides organic ISR&T to Littoral Combat Ships (LCS) and other air-capable ships. Notably, in 2013, the X-47B (Figure 2, right), one of the U.S. Navy's fighter jets, proved that unmanned aerial vehicles could launch and return from the aircraft carrier, and further succeeded in refueling for the first time in 2015.

Figure 2. UAVs operated by the DOD. MQ-8C (left) and X-47B (right). Source: Grumman (2020) and Cenciotti (2015), respectively.

Recently, Large and Medium Unmanned Surface Vessels (L/MUSV) were developed to provide assets for fleet experimentation, technology development, and demonstration. The LUSV and the MUSV of today are prototype initiatives utilizing Sea Hunter (Figure 3, left) and Overlord, which are the kinds of USVs. The Long-Range Unmanned Surface Vessel (LRUSV) (Figure 3, right) is being developed by the Marine Corps to improve maritime reconnaissance and long-range precision gunfire in support of sea control and denial operations. The undersea domain has been operating using small

UUVs for many years, but as technology advances, small and medium UUVs are being developed and put into operation.

Figure 3. USVs operated by the DOD. Unmanned Sea Hunter (left) and LRUSV (right). Source: Keck (2020) and DON (2022), respectively.

This section has covered the future framework and several unmanned systems that are currently in operation or development by the U.S. Navy and U.S. Marine Corps. In the future, unmanned systems and manned systems will be fully integrated to carry out operations, and their sophistication will increase as technology develops. Although important today, unmanned systems will become even more important in the future.

2. Energy Strategy of the DOD

The DOD's operational energy strategy was first published in 2011 and a new operational energy strategy was published in 2016. The 2011 Operational Energy Strategy contributed to establishing energy policies throughout Services, Combatant Commands, and the Department, and the 2016 Operational Energy Strategy established and embodied three objectives and three goals each.

The DOD 2016 Operational Energy Strategy (Objective 2) stated that the department is continuing to test and certify the procurement of cost-competitive bulk alternative fuels in order to reduce the risk of fuel supply and integrate alternative energy sources into bases and individual combat equipment. The goal is to significantly reduce the need for refueling by increasing the use of energy-harvesting technologies in the surrounding area.

In 2021, the DOD released a Request for Information (RFI) to gather prices and technical information to support the department's transition to buying 100% carbon-free power (Vergun 2022). Deputy Secretary of Defense Kathleen Hicks said, "the DOD has an opportunity to lead the way in the transition to carbon pollution-free electricity as one of the top electrical users in the country" (Vergun 2022). She added that in addition to being crucial for combating the threat posed by climate change, it is also crucial for maintaining U.S. competitiveness in the quickly evolving global energy markets. The RFI, Hicks said, makes it abundantly obvious to the market that the DOD is actively working to support President Biden's Executive Order to create an electricity sector free of carbon pollution by 2035.

The DOD has been actively preparing for future wars by incorporating sustainable energy measures into its military strategies and operations. This includes researching alternative fuels to replace the current reliance on oil and working towards 100% carbon-free power in order to contribute to the fight against global climate change (Vergun 2022). This effort by the DOD is one of the reasons for the study of hydrogen, methanol, and ethanol as potential alternative fuels in this paper.

3. Available Alternative Fuels

As mentioned in Section A, the DOD has studied various types of alternative fuels that can be used in future operations. Specifically, Table I presented seven alternative fuels that may be viable for future use. Based on efficiency and viability in the operational environment relevant to this thesis, three alternative fuels are reviewed in detail in this study. The following sections review these three alternative fuels, which include hydrogen, ethanol, and methanol, showing how they create energy, what their respective combustion equations are, and how alternative fuels can be used.

The physical states of the three fuels—hydrogen, ethanol, and methanol—are liquid and compressed gas, and this affects the storage and charging of fuel. In terms of the environmental aspect, the type of by-product from each fuel should be considered:

hydrogen makes water, and the other two make some amount of carbon dioxide. While this thesis does not consider eco-friendliness as part of the evaluation, consideration will be given to any additional requirements associated with the disposal of any waste products generated during the production of the fuel.

a. Hydrogen (Gas and Liquid)

The mass-energy density of hydrogen is 120 MJ/kg, which is the highest value among various fuels including methane, ethane, propane, gasoline, ethanol, and methanol (Thomas 2000). Also, the gaseous hydrogen has a heat of combustion of 51,585 Btu/gal at 60° F and a pressure of 2,400 psi (Chiaravino 2003). Its Gasoline Gallon Equivalent is 0.45GGE (per 1 lb), which means that almost twice as much gaseous hydrogen is needed to produce the same amount of gasoline-generated energy.

The combustion equation for the gaseous hydrogen is

$$2H_2 + O_2 = 2H_2O.$$

According to the combustion equation, there are no carbon oxides after the combustion of hydrogen compared to traditional fuels such as gasoline and diesel, and therefore, it means that the hydrogen has an eco-friendly characteristic.

One thing to watch out for concerns storing the gaseous hydrogen. The density of gaseous hydrogen is low, requiring approximately 23 times more volume to store the gaseous hydrogen compared to the other gaseous fuels (Thomas 2000). Since hydrogen can be found as a gas, the technique to store the gaseous hydrogen was developed early. Specifically, high-pressure tanks are often required for hydrogen gas storage (350–700 bar or 5,000–10,000 psi).

The U.S. Department of Energy (DOE) states that the energy costs at 350 bars are 2.2 kWh/kg and for 700 bars are 3.2 kWh/kg in 2015. Tanks containing 8 kg of gaseous hydrogen in 90 L were commercially available at 350 bars (Meyen-Faria 2022). Even though liquefying gaseous hydrogen requires some energy, there is also a method of storing it in a liquid state. According to the DOE, in 2009 it would take 12 kWh of power per kilo of hydrogen. The problem is that energy is required, but when storing liquid hydrogen, a 22 L tank is needed to store 8 kg of hydrogen, which requires about 24% volume compared to gaseous hydrogen (Meyen-Faria 2022). The energy density of hydrogen fuel, the lack of hazardous byproducts, and the sophistication of storage technology likely make it viable in the near term for adoption by the DOD, and therefore, it is considered as part of this thesis.

b. Methanol (Liquid)

Methanol, which is also called methyl alcohol, is an organic chemical and the simplest aliphatic alcohol. It has a pronounced alcoholic odor, and it is a colorless, light, volatile liquid that is combustible. Nowadays, industrial production of methanol mostly involves hydrogenating carbon monoxide.

The mass-energy density of methanol is 22 MJ/kg, which is only 18% of that of gaseous hydrogen. Methanol has a heat of combustion of 57,250 Btu/gal, which is like that of gaseous hydrogen, but the GGE of methanol is 0.50GGE (per 1 gallon), which is a better value than that of hydrogen. Methanol is liquid at room temperature, and it is important to handle it more carefully so as not to vaporize it due to its low boiling point (148.5°F). To store 1 kg of methanol, a solvent with a volume of 1.264 L is required.

The combustion equation for the methanol is

$$2CH_3OH + 3O_2 = 2CO_2 + 4H_2.$$

As seen in the equation, methanol produces some carbon dioxide, which is a greenhouse gas and contributes to global warming. However, methanol is attractive as an eco-friendly fuel because it can reduce sulfur oxide (SO_x) by 99%, nitrogen Oxide (NO_x) by 60%, and greenhouse gas by up to 25% (Methanol Institute 2020). There have been many attempts to study methanol as a commercial alternative fuel because it is known to have a positive impact on the environment. In 2015, the Stena Germanica RoPax Ferry (Figure 4) was launched with methanol as the main fuel and marine gas fuel (MGO) as the back-up. The ferry satisfied the International Maritime Organization (IMO) regulation for fuel with a very low sulfur content of 0.1%. The energy density of liquid methanol fuel, the lack of hazardous byproducts, and the sophistication of storage technology likely make it viable in the near term for adoption by the DOD, and therefore, it is considered as part of this thesis.

Figure 4. Stena Germanica RoPax Ferry.
Adapted from Google images (n.d.).

c. Ethanol (Liquid)

Unlike methanol, which is made by the synthesis process, ethanol is made from crops such as sugar cane and sugar corn. Ethanol is eco-friendly and does not do much natural destruction because it can be made from grain. However, it is still considered difficult to use only ethanol as an alternative fuel. The production cost is quite high because it needs time and resources to grow the grain and convert it to fuel. Additionally, the supply of fuel may be unstable because grain yields are greatly influenced by various factors such as weather and climate.

The mass-energy density of ethanol is 26.8 MJ/kg, which is 22% of that of gaseous hydrogen. Furthermore, ethanol has a heat of combustion of 12,754 Btu/gal, which is a quarter of that of gaseous hydrogen. On the other hand, the GGE of ethanol is 0.67GGE (per 1 gallon), which is a better value than all three fuels. Although the GGE of the ethanol is higher than that of methanol, ethanol also has a low boiling point (173.1°F), and a storage container of 1.267 L is needed to store 1 kg of ethanol.

The combustion equation for the ethanol is

$$C_2H_5OH + 3O_2 = 2CO_2 + 3H_2O.$$

Except for the molecular formula of ethanol, the combustion equation of ethanol is like that of methanol, and methanol also emits some amount of carbon dioxide. However, even though there is some carbon dioxide as a byproduct, ethanol is a renewable fuel because it is made from various plant-based materials known as biomass. Additionally, ethanol has a higher-octane number than that of gasoline, which means that it can provide premium blending properties. The energy density of liquid ethanol fuel, the lack of hazardous byproducts, and the sophistication of storage technology likely make it viable in the near term for adoption by the DOD, and therefore, it is considered as part of this thesis.

This section has studied the properties and potential use of hydrogen, methanol, and ethanol as alternative fuels. It has examined their physical characteristics, mass-energy density, GGE, and heat of combination in order to use this information as input data for the analysis in the remainder of this thesis. The suitability of these fuels as future alternative fuels is discussed in later chapters of this thesis.

This chapter presented the background and motivation for the thesis. Chapter II defines the relevant behavioral and structural considerations that impact model development. Chapter III presents a simulation model used to assess the viability of alternative fuels. Chapter IV provides simulation results and analysis. Chapter V concludes the paper with recommendations regarding alternative fuel utilization for a UVC.

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II. SYSTEM DEFINITION

A. NEEDS ANALYSIS

As mentioned in the literature review, the future operations of the U.S. Navy and U.S. Marine Corps should reduce dependence on traditional fuels and should be supportable as the Navy and Marine Corps shift towards concepts that rely on unmanned systems. In addition, the UVC's own fuel (especially alternative fuel) should be capable of independent operation, and its operational efficiency should not be significantly lower than the current efficiency of provided by petroleum, gasoline, and diesel. It is necessary to develop the UVC studied in this thesis so that it can meet the refueling requirements of numerous UxVs while being removed from the logistics chain and having high operational availability.

B. REQUIREMENTS ANALYSIS

Identifying the needs and concerns of the stakeholders is the starting point of the requirements analysis. As discussed in the introduction and literature review sections of Chapter I, this paper has identified the main stakeholders and needs and concerns. The need is what the stakeholders want to get, such as desired end state, goals, and objectives, and the concern is what risk is involved (Table 3).

Table 3. Needs and Concerns of Stakeholders regarding UVC System

Stakeholders	Needs	Concerns
DOD/ DON	Independent operations available Get a high Ao (availability) figure	Cannot succeed in the missions Short duration time or performance
Logistics Team	Do not need external fuel chain	Do not have enough fuel to refuel
Mechanics	Repair damaged components ASAP	Fail to repair components

According to the needs and concerns of the stakeholders, there are several lists of requirements for the system. The requirements are descriptions or representations of how the system should behave or essential functions or attributes of the system. Table 4 includes lists of requirements of the UVC system.

Table 4. The Requirements for the UVC System

	Requirements	Stakeholders
1	The system shall operate the missions by itself	DOD/DON
2	The system shall provide enough operation time	DOD/DON
3	The system shall be refueled by itself	Logistics Team
4	The system shall be repaired by its own mechanics	Mechanics

C. FUNCTIONAL ANALYSIS

The purpose of functional analysis is to present an overall integrated and composite description of the system's functional architecture to establish a functional basis for all subsequent design and support activities. Figure 5 shows the functional hierarchy and decomposition of the UVC, and it allows us to understand what the UVC must do to meet the requirements.

1. Functional Hierarchy

According to Figure 5, the system has three functions, including "Command UxVs," "Launch UxVs," and "Recover UxVs," and each function has sub-functions. The first function, named 'command UxVs,' assigns missions to each UxV and communicates with the UxVs while they are operating on the battlefield. The second function, named "launch UxVs," consists of two sub-functions, including waiting for launch and launch UxVs. Due to spatial constraints, there are not many decks for launching UxVs, and there may be a UxV waiting to launch. After that, when the deck becomes available, UxVs are launched. The third function is "recover UxVs," which includes repairing damaged UxVs and refueling them for the next mission.

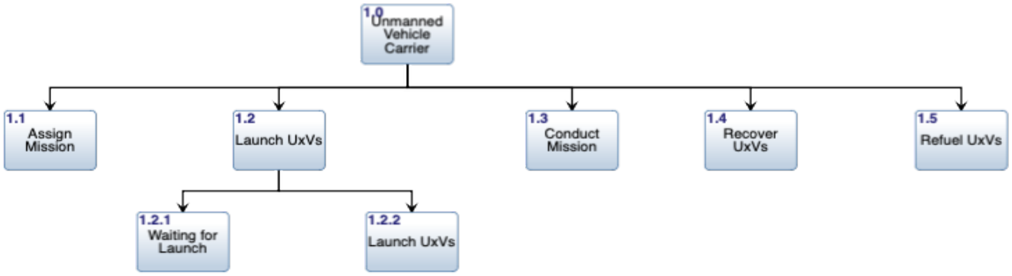


Figure 5. Functional Hierarchy of the UVC System

2. Functional Flow

Functional flow shows how sequentially the system performs its functions and which functions happen when. According to the functional hierarchy, there are identified functions that UVC must do. Figure 6 shows how the functions are connected and the order of the functions within the UVC. Starting with the UVC assigning a mission to the UxV, the UxV that is assigned a mission waits in the queue for launch because the UVC has a limited launch deck. After the UxV is launched, it performs a mission and returns to the UVC, where the UxV goes through a recovery process. If the UxV sustains damage, it will get repaired; otherwise, it will not get repaired. After refueling, the flow is terminated or starts again.

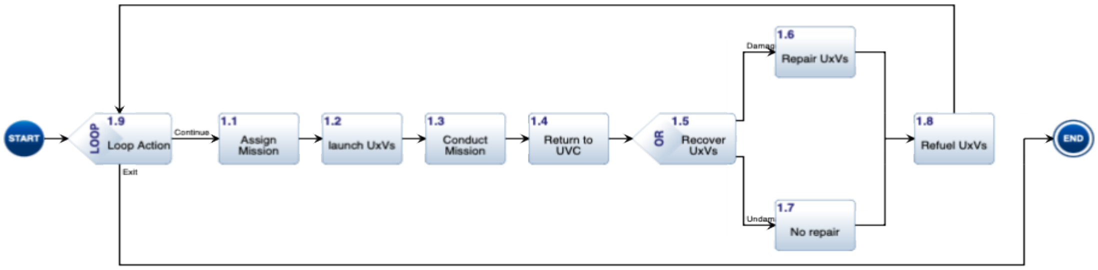


Figure 6. The Functional Flow of the UVC System

3. Operational Activities

The operational activities are defined to identify the operations that humans must perform to fulfill the mission of the systems. In this thesis, as mentioned earlier, the mission of the UVC is to perform its own operations by operating the UxVs without a traditional fuel supply. According to the functional flow, the activities to be performed in terms of operational level are further subdivided. The operational activities are shown in Table 5.

Table 5. Operational Activities of the UVC System.

Numbering	Operational Activities
OA.1.1	Control and command
OA.1.1.1	Identify the missions
OA.1.1.2	Prioritize the missions
OA.1.1.3	Allocate the missions to the sub-systems
OA.1.1.4	Assign the missions to the UxVs
OA.1.1.5	Start and trace the UxVs
OA.1.2	Launch UxVs
OA.1.2.1	Manage the queue
OA.1.2.2	Prepare for the launch
OA.1.2.3	Launch UxVs
OA.1.3	Recover UxVs
OA.1.3.1	Repair the damaged UxVs
OA.1.3.2	Refuel the UxVs

Table 6 presents the operational activity to systems function traceability matrix, similar to a DoDAF SV-5, and it represents the mapping of operational activities to system functions, which identifies the transformation of an operational need into a purposeful action performed by a system. The purpose of this figure is to ensure consistency between the functions that the UVC system will perform and the operations that the crew of the UVC is expected to perform.

Table 6. Operational Activity to Systems Functions Traceability Matrix

	F.1.1	F.1.1.1	F.1.1.2	F.1.2	F.1.2.1	F.1.2.2	F.1.3	F.1.3.1	F.1.3.2
OA.1.1	O	O	O						
OA.1.1.1	O	O							
OA.1.1.2	O	O							
OA.1.1.3	O								
OA.1.1.4	O	O							
OA.1.1.5	O		O						
OA.1.2				O					
OA.1.2.1				O	O				
OA.1.2.2				O		O			
OA.1.2.3				O		O			
OA.1.3							O		
OA.1.3.1							O	O	
OA.1.3.2							O		O

4. UVC System Decomposition

The UVC has several sub-systems, including the control system, the launch system, the maintenance system, and UxVs, as shown in Figure 7. There are two sub-systems under the Maintenance system, which are the fueling system and repair system, and there are UAVs, USVs, and UUVs under the UxVs. The control system directs almost everything that happens within the UVC system. The launch system controls and launches the UxVs to carry out operations to fulfill the missions, and it has a number of launching decks to launch the UxVs. There are two sub-systems under the maintenance system: the first is fueling and refueling the UxVs, and the other is repairing the damaged UxVs. Each of the lowest-level systems presented in this section is represented within the simulation model and assessed as part of the UVC system.

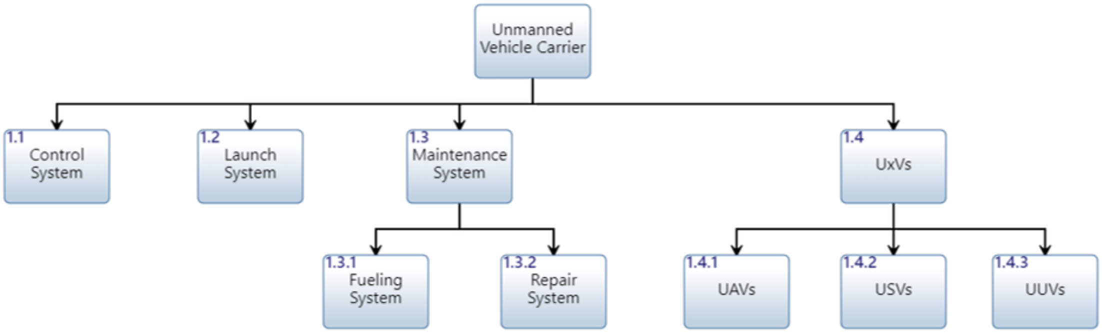


Figure 7. The Decomposition of the UVC System

To implement the UVC in a simulation program, each sub-system was modeled using the program’s activity blocks. In order to implement the control system, UAVs were created using create blocks, and missions were sequentially assigned to the generated UAV. The tasked UAVs were launched through an activity block called launch decks, but due to the limited number of launch decks in the UVC, UAVs were waiting in the launch queue and then subsequently launched. After returning from the mission, the UAVs passed through the activity blocks to refuel and repair, then went back to the beginning and waited for another mission.

III. MODEL DEVELOPMENT

A. ARCHITECTURE DEVELOPMENT

The scenario of this model is represented by the high-level operational concept graphic, OV-1, and it describes what the architecture is supposed to do, and how it is supposed to do it. In this paper, the scenario begins on the coast about 100~200 miles from the land. The enemy is armed with anti-aircraft missiles and anti-ship missiles along the coastline, and torpedoes are installed underwater to block access to our ships. If the Navy can disarm the enemy with its own fighting power, our Army and Marine Corps will be able to land, destroy the enemy's main facilities, and neutralize the enemy forces. For this operation, the Navy has decided to operate the UVC, which will operate several UxVs to effectively neutralize the enemy's combat capabilities. The UxVs will conduct several operations: UAVs conduct reconnaissance and precision strike missions in the air, USVs attack enemies on the ground by approaching what ordinary ships cannot access, and UUVs are tasked with reconnaissance and exploration of threats underwater.

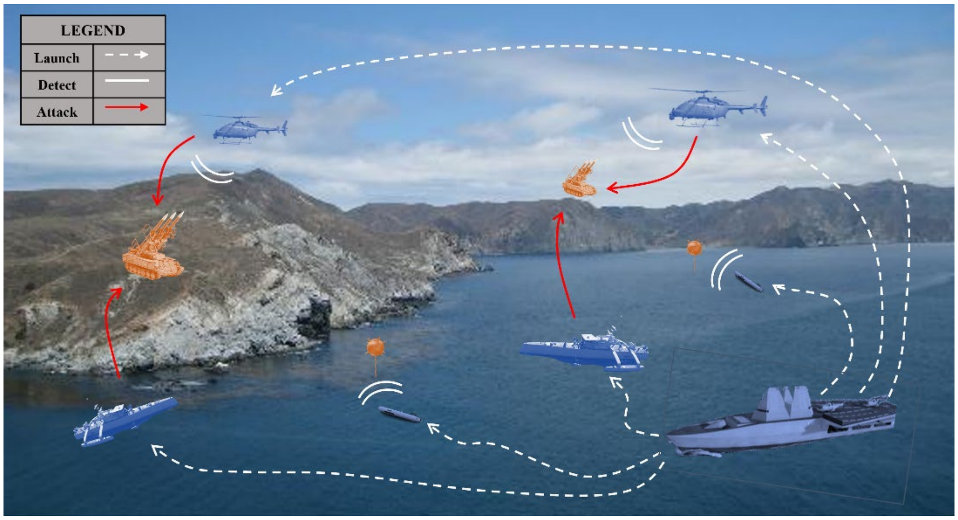


Figure 8. OV-1 of the System. Adapted from Google images (n.d).

B. MODEL DESCRIPTION

This section explains the simulation model, the constraints and assumptions, alternative generation, and experimental design that this thesis used. The simulation model has several steps to conduct the experiment, and there are some constraints and assumptions because this experiment was not conducted under the ideal conditions. The alternative generation describes the characteristics of the UAVs that are used in the simulation model, and the experimental design shows the variables.

1. Simulation Model

As mentioned in the Research Question section, this study leveraged the ExtendSim program to create a model of unmanned systems operating within the context described in OV-1. Figure 9 represents a series of processes in the UVC, and the model created in this paper also follows the process, which is similar to what is described in the functional flow.

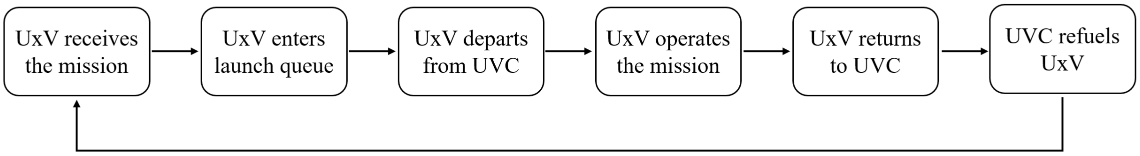


Figure 9. The Sequence of the Model

This paper, due to some realistic constraints and limits, assumes that the UVC carries only two classes of UAVs, which are currently in operation with the U.S. Navy, the MQ-8 and RQ-21, and their specifications are provided in the Alternative Generation section. The model was executed for a 30-day timeframe, meaning that within the model a total of 720 operational hours were simulated.

2. Constraints and Assumptions

There are some constraints and assumptions for the model and scenario because of some restrictions and circumstances which cannot represent the real world. To get more accurate values and outcomes, this paper identified constraints and assumptions as follows.

a. Constraints

- The order and assignment of missions to UAVs are hard to predict.
- The damage to and destruction of the UAVs are difficult to predict exactly.
- The exact specifications of the UAVs and UVC are not publicly available.
- The factors such as environmental conditions that degrade the performance of the UAVs cannot be predicted exactly.

b. Assumptions

- The UAVs are assigned a mission shortly after they are created.
- There is no destruction of the UAVs, and the damage would follow the distribution.
- There is no destruction or loss of the UVC.
- The specifications of the UAVs and UVC have been drawn from other papers or have been calculated.
- The factors that degrade the performance of the UAVs follow a random number between 0.8 and 1.0.
-

C. ALTERNATIVE GENERATION

The simulation model created for this paper was used to identify design parameters according to the type of alternative fuel and to assess the impact of alternative fuels. In the model, the parameters are the performance of the UAV according to the type of UAV and the type of alternative fuel. According to the type of alternative fuel, the characteristics such as TOS and Time for Refuel are different.

The data about the UAVs used in the simulation are summarized in Table 7 and are already used in other papers or calculated by the author. There are four types of fuels, including traditional (gasoline), gaseous hydrogen, liquid hydrogen, and methanol. The values of the Time On Station (TOS, endurance) and Time for Refuel are used and calculated based on traditional fuel, comparing the characteristics of the hydrogen and methanol.

A baseline simulation model was developed using traditional (gasoline) fuel. The baseline model was developed for both volume and weight-constrained traditional fuel. Similarly, six distinct simulation files were created to simulate the different types of fuels used by the UAVs (three different fuel types constrained by either volume or weight). Subsequently, an experimental design focused on system and operational characteristics was defined and executed for each simulation file. As mentioned in the previous paragraph, the simulation used three alternative fuels, each of which was constrained in volume and weight. The TOS (endurance) refers to the time during which a UAV's mission is carried out, which depends on how much fuel the UAV has. If the volume is constrained, the TOS is determined by the number of molecules entering the same volume, and if the weight is constrained, it is determined by the number of molecules entering the same mass. Within each of those configurations, the design and operational factors that may impact performance were also varied. The eight different configurations are defined as volume-constrained and weight-constrained implementations of traditional (gasoline), gaseous hydrogen, liquid hydrogen, and methanol.

Table 7. Characteristics of UAVs Used in the Simulation, by Fuel Type

		MQ-8 Fire Scout			RQ-21 Scan Eagle		
(hours)		Traditional	H2(G/L)	Methanol	Traditional	H2(G/L)	Methanol
MTBM		25[1]	25[4]	25[4]	100[2]	100[4]	100[4]
MTBF		30[1]	30[4]	30[4]	45[3]	45[4]	45[4]
MTTR Corrective		2.5[1]	2.5[4]	2.5[4]	0.5[3]	0.5[4]	0.5[4]
MTTR Preventive		1.6[1]	1.6[4]	1.6[4]	3.5[2]	3.5[4]	3.5[4]
TOS (endurance)	Volume	12[1]	2.13/8.51[4]	3.42[4]	10[3]	1.77/7.09[4]	2.85[4]
	Weight	12[3]	31.30[4]	5.74[4]	10[3]	26.09[4]	4.78[4]
Time for Refuel	Volume	0.75[4]	0.8/0.4[4]	0.75[5]	0.3[4]	0.2/0.1[4]	0.3[5]
	Weight	0.75[4]	15.4/4.8[4]	0.75[5]	0.3[4]	0.1[4]	0.3[5]
Launch Time		0.5[4]	0.5[4]	0.5[4]	0.5[4]	0.5[4]	0.5[4]
Recovery Time		0.5[4]	0.5[4]	0.5[4]	0.5[4]	0.5[4]	0.5[4]
Mission Frequency		6[2]	6[4]	6[4]	6[2]	6[4]	6[4]

[1] (Anderson 2016)
[2] (Arnold 2021)
[3] (Office of the Secretary of Defense 2015)
[4] (Lee 2021)
[5] Assumed or calculated value

D. EXPERIMENTAL DESIGN

The experimental design consists of two sub-sections: design of experiment factors and design of experiment approach.

1. Design of Experiment Factors

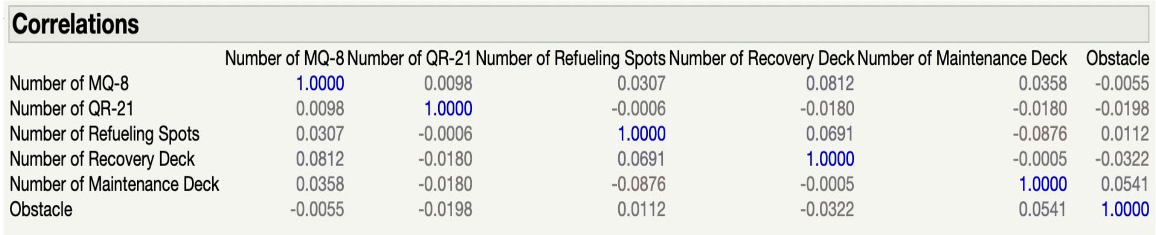
Based on the performance experimental design approach was developed using the Nearly Orthogonal Latin Hypercube designs defined in (Sanchez and Upton 2022). Table 8 shows the input variables which are used in the ExtendSim model: Number of MQ-8, Number of RQ-21, Number of Refueling Spots, Number of Recovery Decks, Number of Maintenance Decks, and Obstacles. Each factor has a minimum value and a maximum value, and these values were used to define simulation configurations that were explored in ExtendSim (Appendix A). Additionally, the scatterplot shows the selected design points which are covering the entire design space (Appendix B).

Table 8. Input Variables of the Model.

Factor	Min	Max	Description
Number of MQ-8s	8	16	The number of MQ-8s carried on the UVC
Number of RQ-21s	2	6	The number of RQ-21s carried on the UVC
Number of Refueling Spots	4	8	The number of refueling spots on the UVC
Number of Recovery Decks	2	4	The number of recovery decks on the UVC
Number of Maintenance Decks	2	4	The number of maintenance decks on the UVC
Obstacle	0.8	1.0	The factors that degrade the UxVs' performance

2. Design of Experiment Approach

The important point is that there should be no correlation between these input variables because what this paper wants to confirm is the operational availability and effects of the fuel types. If the correlation between input variables affects the results, it will not be a good result and conclusion. This study used the JMP program to check whether there are correlations between input variables. Figure 10 shows the correlation between the input variables, with the highest relationship being between the number of MQ-8s and the number of Recovery Decks at 8.12%, and the lowest being the number of RQ-21s and the number of Refueling Spots at almost 0%. In normal cases, if the correlation is less than 10%, it is said to have little effect.



Correlations

	Number of MQ-8	Number of QR-21	Number of Refueling Spots	Number of Recovery Deck	Number of Maintenance Deck	Obstacle
Number of MQ-8	1.0000	0.0098	0.0307	0.0812	0.0358	-0.0055
Number of QR-21	0.0098	1.0000	-0.0006	-0.0180	-0.0180	-0.0198
Number of Refueling Spots	0.0307	-0.0006	1.0000	0.0691	-0.0876	0.0112
Number of Recovery Deck	0.0812	-0.0180	0.0691	1.0000	-0.0005	-0.0322
Number of Maintenance Deck	0.0358	-0.0180	-0.0876	-0.0005	1.0000	0.0541
Obstacle	-0.0055	-0.0198	0.0112	-0.0322	0.0541	1.0000

Figure 10. Correlations between Input Variables

IV. ANALYSIS

A. ANALYSIS APPROACH

To conduct analysis, a baseline simulation model for both volume and weight constrained traditional fuel and six alternative fuel models were built. The models were coded as models 1 to 8, corresponding to the type of fuel: model 1 and model 2 are traditional fuels constrained by volume and weight, respectively; model 3 and model 4 are gaseous hydrogen fuels constrained by volume and weight, respectively; model 5 and model 6 are liquid hydrogen fuel constrained by volume and weight, respectively; and model 7 and model 8 are methanol fuel constrained by volume and weight, respectively.

Using the experimental design approach defined in Chapter III, a total of 65 model configurations were defined for each of the eight models. This resulted in a total of 520 candidate designs for exploration. To capture the variability within each run, each of the 520 designs was repeated 30 times, for a total of 15,600 simulation runs. Each run was conducted for a simulation timeframe of 720 hours (30 days). After running all simulations, it was possible to derive the operation availability value for each fuel type.

B. MODEL ANALYSIS RESULTS

There are some results from the simulation model, including the operational availability, least squares regressions, and contour profilers, that are used to analyze the results.

1. Mean of Operational Availability for Each Fuel Type

Operational availability is a measure of how often a system is ready to perform its intended mission and can be affected by factors such as fuel consumption, maintenance, and downtime. By analyzing the operational availability of each model run, it is possible to determine which fuel would provide the greatest benefit in terms of system performance, readiness, and reliability.

Table 9 shows the mean of operational availability for each fuel type obtained from the simulations. The highest values are for gaseous hydrogen constrained by weight and liquid hydrogen constrained by weight, and the lowest value is for gaseous hydrogen constrained by volume. The distributions of the operational availability are shown in the histogram explaining the range of operational availability for each fuel type (see Appendix C).

Table 9. Operational Availabilities by Fuel Type

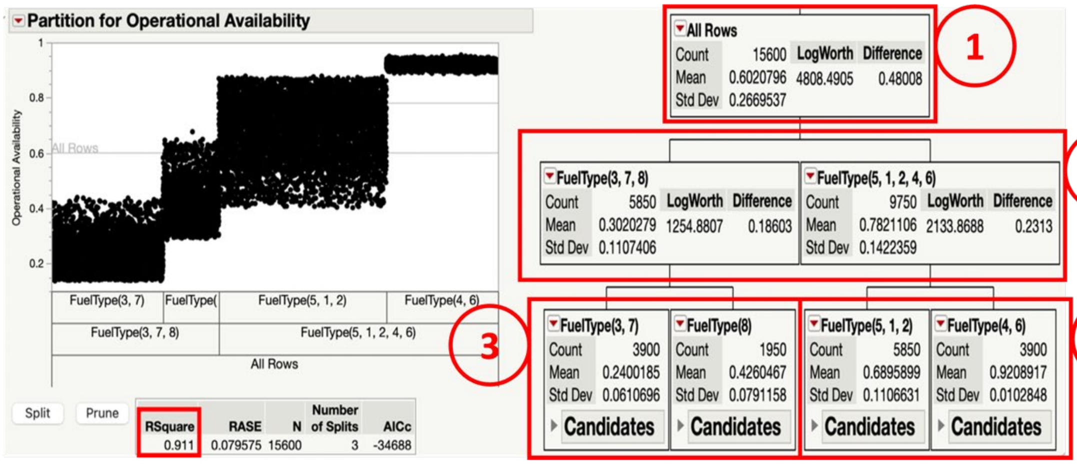
Fuel Type		Operational Availability
Traditional Fuel (Gasoline)	Model 1	0.7405
	Model 2	0.7405
Gaseous Hydrogen	Model 3	0.1991
	Model 4	0.9207
Liquid Hydrogen	Model 5	0.5877
	Model 6	0.9211
Methanol	Model 7	0.2809
	Model 8	0.4260

2. Partition Tree Analysis

JMP is the data analysis tool used by engineers and scientists to verify their results involving large volumes of data. It enables them to see how their data are connected to each other and find out what affects the outcomes. In this case, the outcomes are the operational availability depending on the type of alternative fuel. Additionally, JMP helps engineers do a regression analysis to test hypotheses and shows the R-Square value which explains how much of the dependent variable data, operational availability in this thesis, is explained by the independent variables, which are the fuel types in this thesis. As a starting point for analysis, this research used the partition tree function in JMP, which builds a sequential decision tree based on the statistical impact of each decision variable.

Figure 11 shows the decision tree from the JMP, and it shows 0.911 as an R-Square value. This high R-Square value indicates that the underlying model is explaining a substantial amount of the variability in the underlying data and can be used with high confidence. The partition tree analysis also presents which combination of fuels has better operational availability than the other combinations, and the combination can be analyzed by dividing it incrementally.

The average operational availability in the model is 0.60 (denoted as 1 in Figure 11). Using fuel types 1, 2, 4, 5, or 6 results in an average operational availability of 0.78. while fuel types 3, 7, and 9 result in an average operational availability of 0.30 (denoted as 2 in Figure 11). Among the low-performing fuels, fuel type 8 (average operational availability of 0.42) outperforms both fuel types 3 and 7 (average operational availability of 0.24; denoted as 3 in Figure 11). Within the high-performing subset of fuels, fuel types 4 and 6 (average operational availability of 0.92) outperform fuel types 1, 5, and 2 (average operational availability of 0.68; denoted as 4 in Figure 11). Finally, the highest operational availability is achieved when fuels 4 and 6 are used, and the lowest is when fuels 3 and 7 are used.



RSquare	RASE	N	Number of Splits	AICc
0.911	0.079575	15600	3	-34688

All Rows

		LogWorth	Difference
Count	15600		
Mean	0.6020796	4808.4905	0.48008
Std Dev	0.2669537		

FuelType(3, 7, 8)

		LogWorth	Difference
Count	5850		
Mean	0.3020279	1254.8807	0.18603
Std Dev	0.1107406		

FuelType(5, 1, 2, 4, 6)

		LogWorth	Difference
Count	9750		
Mean	0.7821106	2133.8688	0.2313
Std Dev	0.1422359		

FuelType(3, 7)

Count	3900
Mean	0.2400185
Std Dev	0.0610696

FuelType(8)

Count	1950
Mean	0.4260467
Std Dev	0.0791158

FuelType(5, 1, 2)

Count	5850
Mean	0.6895899
Std Dev	0.1106631

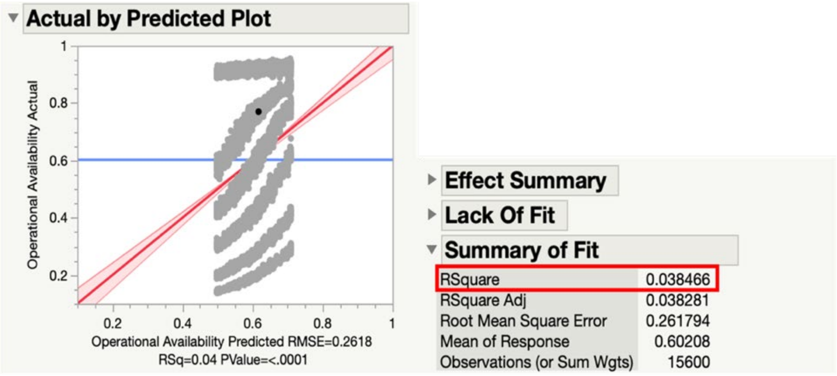
FuelType(4, 6)

Count	3900
Mean	0.9208917
Std Dev	0.0102848

Figure 11. Decision Tree

3. Least Squares Regression—Fuel Type Removed

Beyond the insights related to fuel type generated by the partition tree analysis, traditional least squares regression was conducted to develop additional insights regarding the design and operational factors that had the largest impact on operational availability. This regression analysis was conducted without the variables corresponding to fuel type because the results of the partition tree analysis suggest that they will dominate the regression equation if included. It was possible to identify which variables were important by removing unimportant variables using stepwise regression. JMP was used to fit least squares regression equations and assess the correlation between operational availability and other variables. However, the result showed that the value of R-Square was too low to show meaningful correlation between operational availability and other variables without fuel type. Figure 12 shows the R-Square value as 0.0385. This low R-Square value means that there are no definitive conclusions that should be developed using regression analysis that ignores fuel type.



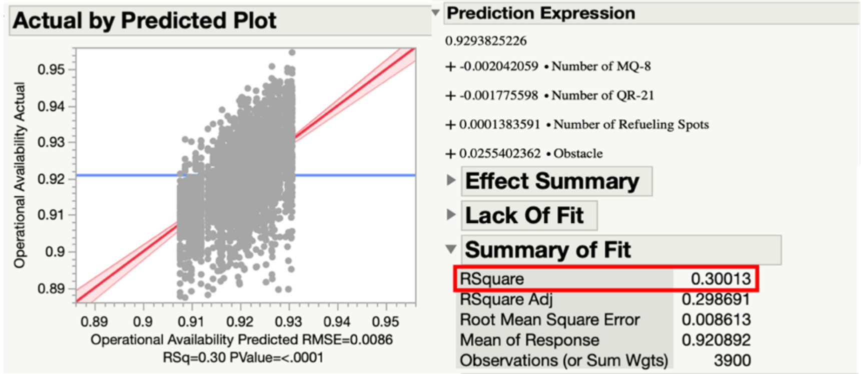
RSquare	0.038466
RSquare Adj	0.038281
Root Mean Square Error	0.261794
Mean of Response	0.60208
Observations (or Sum Wgts)	15600

Figure 12. Fit Least Squares (all fuels included)

4. Least Squares Regression—Preferred Fuel Types

The second approach segmented the data into data points where fuel type results in high operational availability for fuel types 4 and 6, and all other fuel types result not only in low availability but determine which other variables matter. To analyze this, the results for fuel types 4 and 6 were taken by an indicator column created in Excel to eliminate statistically insignificant variables for each case. The process was the same as the first approach, and least squares regression equations were used again. Figure 13 shows that the R-Square value of the recommended fuel types (fuel types 4 and 6) is 0.3001, indicating that some conclusions may be developed, but those conclusions should be general rather than specific. Figure 14 shows that the R-Square value for the regression equation using fuel types other than 4 and 6 is 0.0929, which is a much lower value compared to the recommended fuel types. This means that there are no definitive conclusions that should be developed using regression analysis that focuses exclusively on low-performing fuel types.

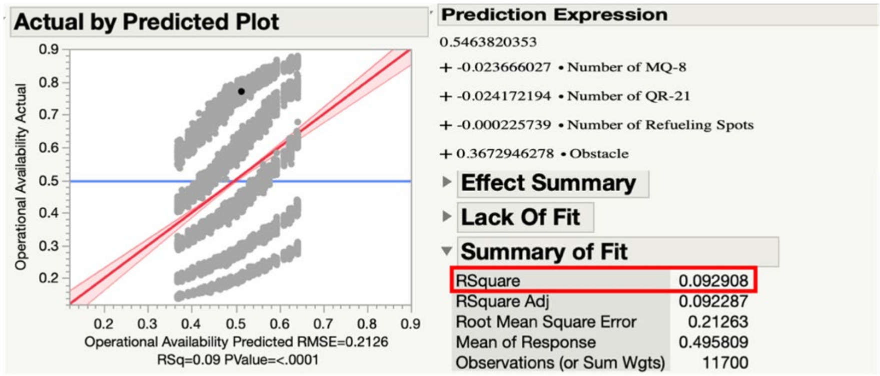
Figures 13 and 14 also show the prediction expressions that represent the variables that impact performance. While the R-Square values are not high, there is an interesting overlap between the regression equations. Both figures indicate that the number of MQ-8s, the number of RQ-21s, the obstacle, and the number of refueling spots are the most significant factors impacting operational availability in both cases. Due to the commonality in the regression equations, contour profilers were generated to develop general insights regarding the impact that those variables may have on operational availability.



```
Prediction Expression
0.9293825226
+ -0.002042059 • Number of MQ-8
+ -0.001775598 • Number of QR-21
+ 0.0001383591 • Number of Refueling Spots
+ 0.0255402362 • Obstacle

Summary of Fit
RSquare                        0.30013
RSquare Adj                   0.298691
Root Mean Square Error        0.008613
Mean of Response              0.920892
Observations (or Sum Wgts)        3900
```

Figure 13. Fit Least Squares (fuel types 4 and 6)



```
Prediction Expression
0.5463820353
+ -0.023666027 • Number of MQ-8
+ -0.024172194 • Number of QR-21
+ -0.000225739 • Number of Refueling Spots
+ 0.3672946278 • Obstacle

Summary of Fit
RSquare                       0.092908
RSquare Adj                   0.092287
Root Mean Square Error         0.21263
Mean of Response              0.495809
Observations (or Sum Wgts)       11700
```

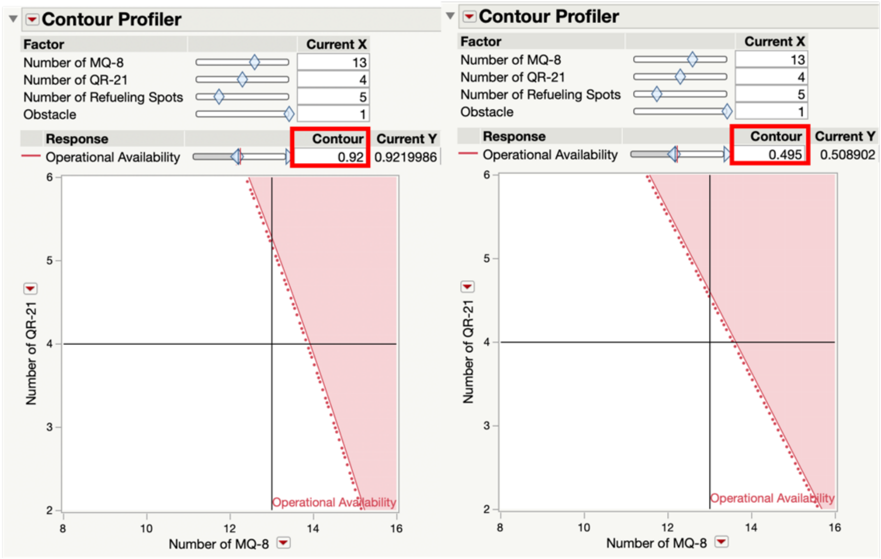
Figure 14. Fit Least Squares (all other fuel types)

5. Contour Profiler Analysis

This approach is described in the work of MacCalman, Beery, and Paulo (2016) and is a useful method of identifying combinations of design alternatives that may be pursued rather than specific design recommendations using a predictive regression equation.

a. *Contour Profiler Analysis—Fuel Type*

Figure 15 presents a contour profiler with two graphs, one on the left showing fuel types 4 and 6 which had high operational availability and one on the right showing fuel types with low operational availability. A threshold value is imposed on both graphs corresponding to the average operational availability achieved in each set of configurations. This means that there is a threshold operational availability of 0.92 for the left graph and a threshold operational availability of 0.495 for the right graph. The white area represents a region that is not possible, while the red area represents another infeasible area. The x-axis indicates the number of MQ-8s, and the y-axis shows the number of RQ-21s. These regions are subject to the obstacle setting and the number of refueling spots, both of which remain unchanged in these visualizations. The obstacle is a factor that impacts UAVs' performance in their mission, such as weather conditions, UAV failure rate, and enemy attacks. As the number of refueling spots and obstacles are fixed, the operational availability can only affect the white area. In both cases, the recommended total number of unmanned systems is 17, and each figure includes a crosshair corresponding to 13 MQ-8s and 4 RQ-21s. Other combinations of 17 or fewer unmanned systems can meet the threshold values for operational availability but increasing beyond 17 total systems results in an inability to meet the threshold performance.



Contour Profiler

Factor	Current X
Number of MQ-8	13
Number of QR-21	4
Number of Refueling Spots	5
Obstacle	1

Response	Contour	Current Y
Operational Availability	0.92	0.9219986

Contour Profiler

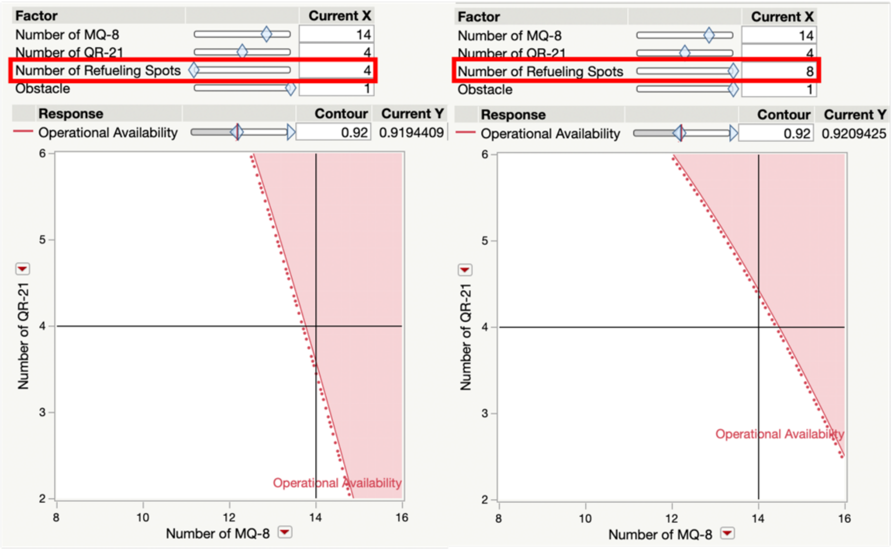
Factor	Current X
Number of MQ-8	13
Number of QR-21	4
Number of Refueling Spots	5
Obstacle	1

Response	Contour	Current Y
Operational Availability	0.495	0.508902

Figure 15. Contour Profilers for High Performing and Low Performing Fuel Alternatives

b. Contour Profiler Analysis—Refueling Spots and Obstacle with High Performing Fuel Type

The following sections focus exclusively on high-performing alternatives using fuel types 4 and 6. For all subsequent graphs, there is a performance threshold for operational availability of 0.92. Figure 16 illustrates the relationship between the number of refueling spots and a combination of the number of RQ-21s and MQ-8s. As the number of refueling spots increases, the white area in the graph expands, meaning that there are additional combinations of RQ-21s and MQ-8s that can meet the performance threshold of 0.92. The graph on the left indicates that the combination of 14 RQ-21s and four MQ-8s is not possible when there are only four refueling spots available. However, when the number of refueling spots is increased to eight, as shown in the graph on the right, the combination of 14 RQ-21 and four MQ-8 units becomes feasible. The number of refueling spots appears to be impacting the combination of the RQ-21s and MQ-8s that can be utilized, as demonstrated by the changes in the white area in Figure 16. In general, it appears that increasing the number of refueling spots aboard the UVC from four to eight increases the total number of unmanned systems that may be supported from 17 to 18.



Factor	Current X
Number of MQ-8	14
Number of QR-21	4
Number of Refueling Spots	4
Obstacle	1

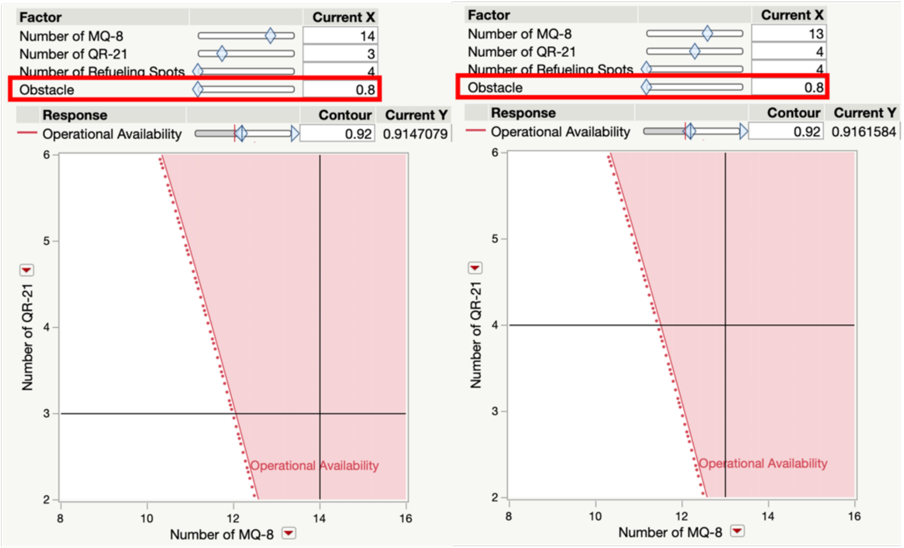
Response	Contour	Current Y
Operational Availability	0.92	0.9194409

Factor	Current X
Number of MQ-8	14
Number of QR-21	4
Number of Refueling Spots	8
Obstacle	1

Response	Contour	Current Y
Operational Availability	0.92	0.9209425

Figure 16. Contour Profilers Depending on the Number of Refueling Spots: Four (left) and Eight (right)

Beyond the impact of the number of refueling spots aboard the UVC, it is also useful to examine the impact that the obstacle variable has on the number of unmanned systems that can be supported by the UVC. Recall that the obstacle variable is scaled from 0 to 1 and is implemented as a degrading factor on flight duration. Note that each of the following analyses restricts the number of refueling spots to four, rather than increasing the number of spots to eight as in the previous analysis. Figure 17 displays the combinations of RQ-21 and MQ-8 units that are feasible given an obstacle value of 0.8. Obstacles refers to factors that can impact UAV performance, including weather conditions, UAV failure rate, and enemy attacks. This variable is multiplied by the performance of the UAV, and the closer it is to 1, the less it affects the performance of the UAV. The feasible area decreases as the obstacle value decrease, meaning the UAV performance is negatively impacted. A comparison of Figure 16 and Figure 17 reveals a noticeable discrepancy in the white area, and this means that the feasible combinations become limited. As a result, the possible combination of RQ-21 and MQ-8 units becomes infeasible when the obstacle value is set to 0.8, reducing the combination to less than 17. In general, it appears that changing the impact of the obstacle impact from 1 to 0.8 decreases the total number of unmanned systems that may be supported from 17 to 15.



Factor	Current X
Number of MQ-8	14
Number of QR-21	3
Number of Refueling Spots	4
Obstacle	0.8

Response	Contour	Current Y
Operational Availability	0.92	0.9147079

Factor	Current X
Number of MQ-8	13
Number of QR-21	4
Number of Refueling Spots	4
Obstacle	0.8

Response	Contour	Current Y
Operational Availability	0.92	0.9161584

Figure 17. Contour Profilers Depending on the Presence of Obstacles

6. Analysis Summary

This thesis has used partition tree analysis, least squares regression, and contour profiler analysis to analyze the results from the simulation. Using the partition tree analysis, it is determined that fuel types 4 and 6 have the highest operational availability. The least squares regression shows that the most significant factor in determining the performance of the UAV is fuel type, rather than other input variables. The contour profiler analysis was used to find that up to 17 UAVs could achieve an operational availability of 0.92 when fuel types 4 or 6 were used. This analysis also revealed that increasing the number of refueling spots from four to eight allowed the UVC to support one additional UAV, and that changing the impact of the obstacle variable reduced the number of UAVs that could be supported from 17 to 15.

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V. CONCLUSION AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSION

Recent guidance from the U.S. Department of Defense (DOD 2016) and the U.S. Department of the Navy (DON 2017) has focused on developing and integrating unmanned systems and manned systems as well as adopting renewable energy sources to prepare for future warfare. The goal of these efforts is to improve the capabilities and efficiency of military operations by reducing dependence on traditional fossil fuels. The DOD is also exploring ways to integrate current unmanned systems with new energy technologies to enhance its capabilities. This work is described in the background and literature review sections of Chapter I.

This research described in this thesis used a software simulation called ExtendSim to create the model that examined the impact of alternative fuels to support unmanned operations from a UVC. Input data was obtained by referencing existing papers or by direct calculation. The model simulated various processes such as launch, mission execution, and refueling, and it was run with various combinations of input variables to analyze the results. The run time and several variables were also considered in the model. Operational availability was one of the key considerations used to evaluate the effectiveness of alternative fuels and determine which one would be the best for future military operations.

Table 9 in this paper compares the operational availability of various alternative fuels under different constraints, such as weight and volume. The results showed that gaseous hydrogen constrained by weight and liquid hydrogen constrained by weight produces the highest operational availability among the fuels compared, with 0.9207 and 0.9211, respectively. This indicates that these fuels are most efficient when there is a limit on the weight of the alternative fuel. The operational availability of methanol constrained by weight, with a value of 0.4260, is also relatively high but not as good as gaseous hydrogen and liquid hydrogen. Hence, methanol is less efficient than those mentioned before and not a strong enough replacement for traditional fuel.

In addition to the type of fuel, the paper also identified other factors that affect operational availability when simulating the performance of unmanned systems. The number of MQ-8 and RQ-21 units, the number of refueling spots, and the presence of obstacles were identified as the main factors. While the presence of an obstacle is an uncontrollable variable in operation, it was systematically varied as a controllable factor within the simulation models to aid in the development of conclusions and recommendations that can be sensitive to changing environmental conditions. The results showed that these factors had a significant impact on operational availability when simulating the use of gaseous hydrogen and liquid hydrogen, which had the highest operational availability among the fuels compared. The same result was obtained when all fuels were targeted. Increasing the number of unmanned systems and refueling spots and reducing the number of obstacles can help to improve operational availability.

Contour profilers were used to determine the appropriate number of MQ-8 and RQ-21 units based on the operational availability associated with each fuel. As can be seen from Figure 15, the recommended area is shown in white, while the non-recommended area is shown in red. The results are similar even if the area on the left is smaller than the area on the right, as the number of UAVs is rounded to the nearest integer. The appropriate number of MQ-8 and RQ-21 units in combination is 17, but this may vary depending on the UVC's capabilities. As the UVC system's capabilities increase, the number of UAVs that can be operated simultaneously also increases, which can lead to a reduction in waiting time, maintenance time, and refueling time. This results in an increase in the appropriate number of UAVs.

B. RECOMMENDATIONS

This paper has some limitations and many considerations. With that in mind, a follow-up study might well address the following.

1. Alternative Cost Analysis

It would be beneficial to include an analysis of the cost of various alternative fuels and how they compare with traditional fuels. Operational efficiency is a critical factor for the military, as it directly impacts the ability to perform missions effectively and efficiently. However, cost is also a major consideration, as the military operates on a limited budget and has limited resources. The use of alternative fuels such as gaseous hydrogen and liquid hydrogen may provide a higher level of operational efficiency, but they may also be more expensive than traditional fuels.

2. Environmental Impact

A study of the environmental impact of various fuels in terms of emissions and pollution would be useful in assessing their overall sustainability. While the literature review may have included information on the chemical formulas of the alternative fuels, it did not delve into the specifics of their environmental impact. This is because the purpose of this paper was to focus exclusively on the operational efficiency of alternative fuels in comparison to traditional ones. In a follow-up study, therefore, it would be important to examine the substances generated when each alternative fuel is burned and the potential impact they have on environment, which can help the DOD and DON meet the requirements of the National Defense Authorization Act of 2022.

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APPENDIX A. DOE TRIALS

Run	Number of MQ-8s	Number of RQ-21s	Number of Maintenance Decks	Number of Refueling Spots	Fuel Rate	Number of Recovery Decks	Obstacles	Maintenanc e Probability
1	14	2	2	5	0.003	3	0.953125	0.5
2	16	5	3	4	0.003	3	0.85	0.5
3	15	3	3	8	0.003	2	0.971875	0.5
4	13	6	2	7	0.003	3	0.884375	0.5
5	15	4	2	5	0.003	2	0.83125	0.5
6	12	6	2	5	0.003	3	0.93125	0.5
7	14	3	3	6	0.003	2	0.865625	0.5
8	15	5	3	8	0.003	3	0.984375	0.5
9	14	2	3	4	0.003	4	0.921875	0.5
10	16	5	2	6	0.003	4	0.85625	0.5
11	12	2	2	8	0.003	3	0.8875	0.5
12	16	4	2	7	0.003	4	0.8125	0.5
13	12	3	3	5	0.003	3	0.896875	0.5
14	14	4	3	6	0.003	4	0.99375	0.5
15	13	3	3	7	0.003	4	0.84375	0.5
16	13	4	2	6	0.003	3	0.990625	0.5
17	15	4	3	6	0.003	2	1	0.5
18	13	5	3	5	0.003	3	0.890625	0.5
19	14	4	4	6	0.003	3	0.978125	0.5
20	13	5	3	7	0.003	2	0.834375	0.5
21	15	3	4	6	0.003	2	0.875	0.5

Run	Number of MQ-8s	Number of RQ-21s	Number of Maintenance Decks	Number of Refueling Spots	Fuel Rate	Number of Recovery Decks	Obstacles	Maintenance Probability
22	14	5	3	4	0.003	2	0.940625	0.5
23	16	4	4	7	0.003	3	0.825	0.5
24	13	6	3	7	0.003	3	0.90625	0.5
25	13	3	4	4	0.003	3	0.946875	0.5
26	14	5	4	5	0.003	4	0.8375	0.5
27	15	2	3	7	0.003	4	0.98125	0.5
28	15	5	4	7	0.003	4	0.8625	0.5
29	16	3	3	5	0.003	3	0.840625	0.5
30	14	6	4	5	0.003	3	0.996875	0.5
31	13	3	4	7	0.003	3	0.88125	0.5
32	15	5	3	8	0.003	4	0.928125	0.5
33	12	4	3	6	0.003	3	0.9	0.5
34	10	6	4	7	0.003	3	0.846875	0.5
35	8	3	3	8	0.003	3	0.95	0.5
36	9	5	3	4	0.003	4	0.828125	0.5
37	11	2	4	5	0.003	3	0.915625	0.5
38	9	4	4	7	0.003	4	0.96875	0.5
39	12	2	4	7	0.003	3	0.86875	0.5
40	10	5	4	6	0.003	4	0.934375	0.5
41	10	3	3	4	0.003	3	0.815625	0.5
42	11	6	3	8	0.003	2	0.878125	0.5
43	8	3	4	6	0.003	2	0.94375	0.5
44	12	6	4	4	0.003	3	0.9125	0.5

Run	Number of MQ-8s	Number of RQ-21s	Number of Maintenance Decks	Number of Refueling Spots	Fuel Rate	Number of Recovery Decks	Obstacles	Maintenance Probability
45	8	4	4	5	0.003	2	0.9875	0.5
46	12	5	3	7	0.003	3	0.903125	0.5
47	10	4	3	6	0.003	2	0.80625	0.5
48	11	5	3	5	0.003	2	0.95625	0.5
49	11	4	4	6	0.003	3	0.809375	0.5
50	9	4	3	6	0.003	4	0.8	0.5
51	12	3	3	7	0.003	3	0.909375	0.5
52	10	4	2	6	0.003	3	0.821875	0.5
53	11	3	3	5	0.003	4	0.965625	0.5
54	9	5	2	6	0.003	4	0.925	0.5
55	10	3	3	8	0.003	4	0.859375	0.5
56	8	4	2	5	0.003	4	0.975	0.5
57	11	2	3	5	0.003	3	0.89375	0.5
58	11	5	2	8	0.003	3	0.853125	0.5
59	10	4	2	7	0.003	2	0.9625	0.5
60	9	6	3	5	0.003	2	0.81875	0.5
61	9	3	2	6	0.003	2	0.9375	0.5
62	9	5	3	8	0.003	3	0.959375	0.5
63	10	2	2	7	0.003	3	0.803125	0.5
64	11	6	2	5	0.003	3	0.91875	0.5
65	9	3	3	4	0.003	2	0.871875	0.5

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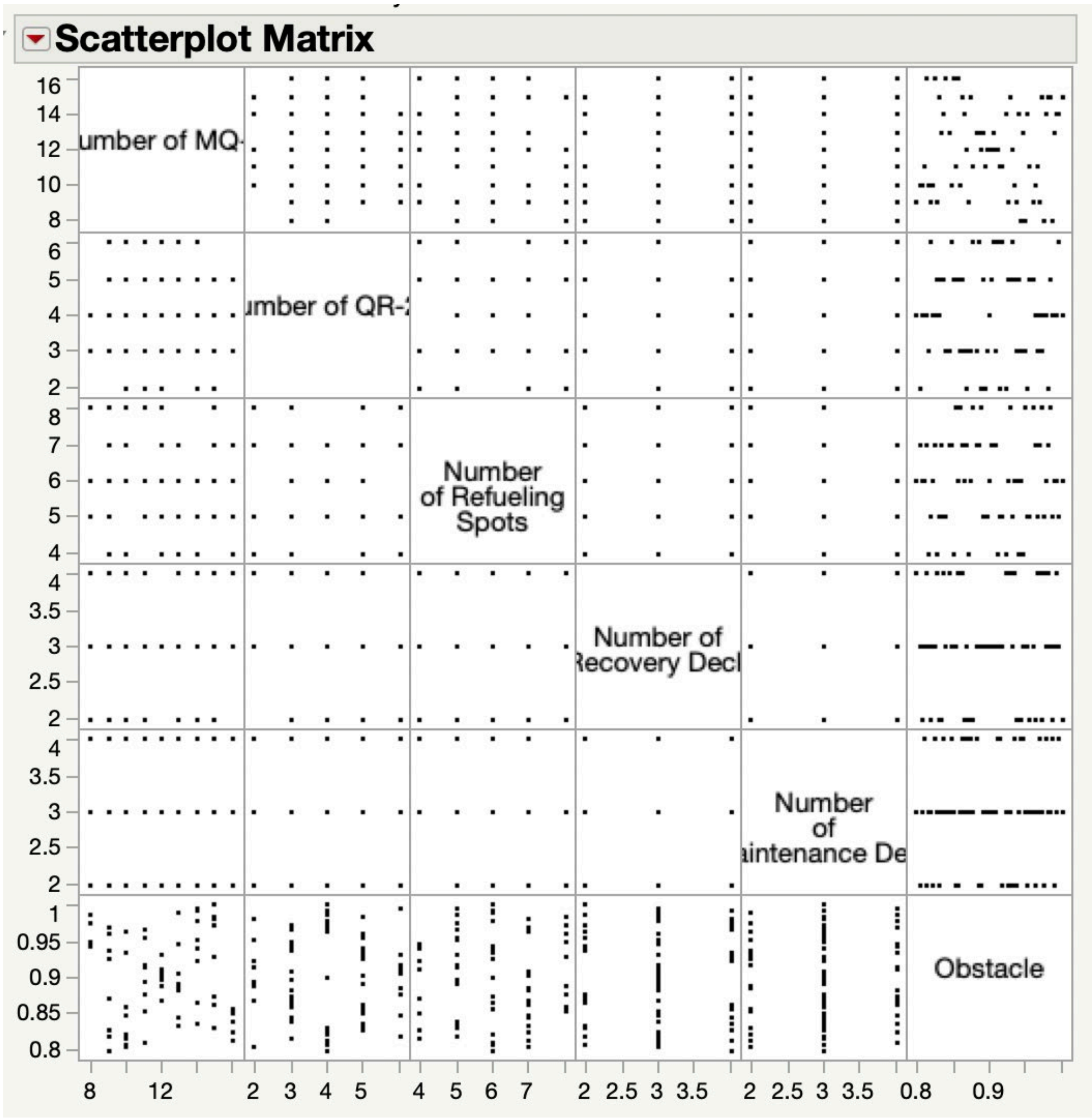
APPENDIX B. DOE SCATTERPLOT MATRIX



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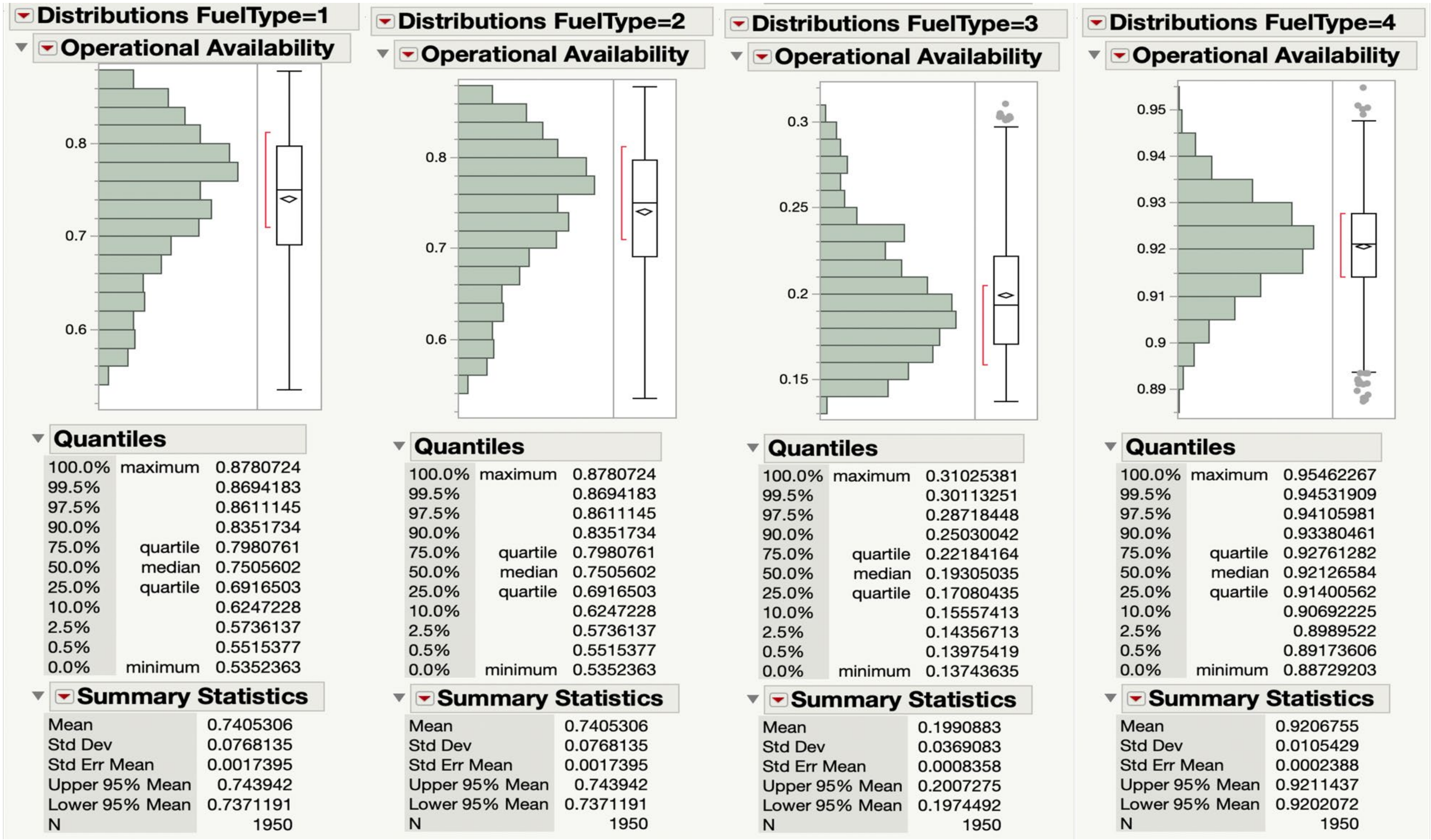
APPENDIX C. DISTRIBUTION OF OPERATIONAL AVAILABILITY BY FUEL TYPE



Distributions FuelType=1

Operational Availability

Quantiles

100.0%	maximum	0.8780724
99.5%		0.8694183
97.5%		0.8611145
90.0%		0.8351734
75.0%	quartile	0.7980761
50.0%	median	0.7505602
25.0%	quartile	0.6916503
10.0%		0.6247228
2.5%		0.5736137
0.5%		0.5515377
0.0%	minimum	0.5352363

Summary Statistics

Mean	0.7405306
Std Dev	0.0768135
Std Err Mean	0.0017395
Upper 95% Mean	0.743942
Lower 95% Mean	0.7371191
N	1950

Distributions FuelType=2

Operational Availability

Quantiles

100.0%	maximum	0.8780724
99.5%		0.8694183
97.5%		0.8611145
90.0%		0.8351734
75.0%	quartile	0.7980761
50.0%	median	0.7505602
25.0%	quartile	0.6916503
10.0%		0.6247228
2.5%		0.5736137
0.5%		0.5515377
0.0%	minimum	0.5352363

Summary Statistics

Mean	0.7405306
Std Dev	0.0768135
Std Err Mean	0.0017395
Upper 95% Mean	0.743942
Lower 95% Mean	0.7371191
N	1950

Distributions FuelType=3

Operational Availability

Quantiles

100.0%	maximum	0.31025381
99.5%		0.30113251
97.5%		0.28718448
90.0%		0.25030042
75.0%	quartile	0.22184164
50.0%	median	0.19305035
25.0%	quartile	0.17080435
10.0%		0.15557413
2.5%		0.14356713
0.5%		0.13975419
0.0%	minimum	0.13743635

Summary Statistics

Mean	0.1990883
Std Dev	0.0369083
Std Err Mean	0.0008358
Upper 95% Mean	0.2007275
Lower 95% Mean	0.1974492
N	1950

Distributions FuelType=4

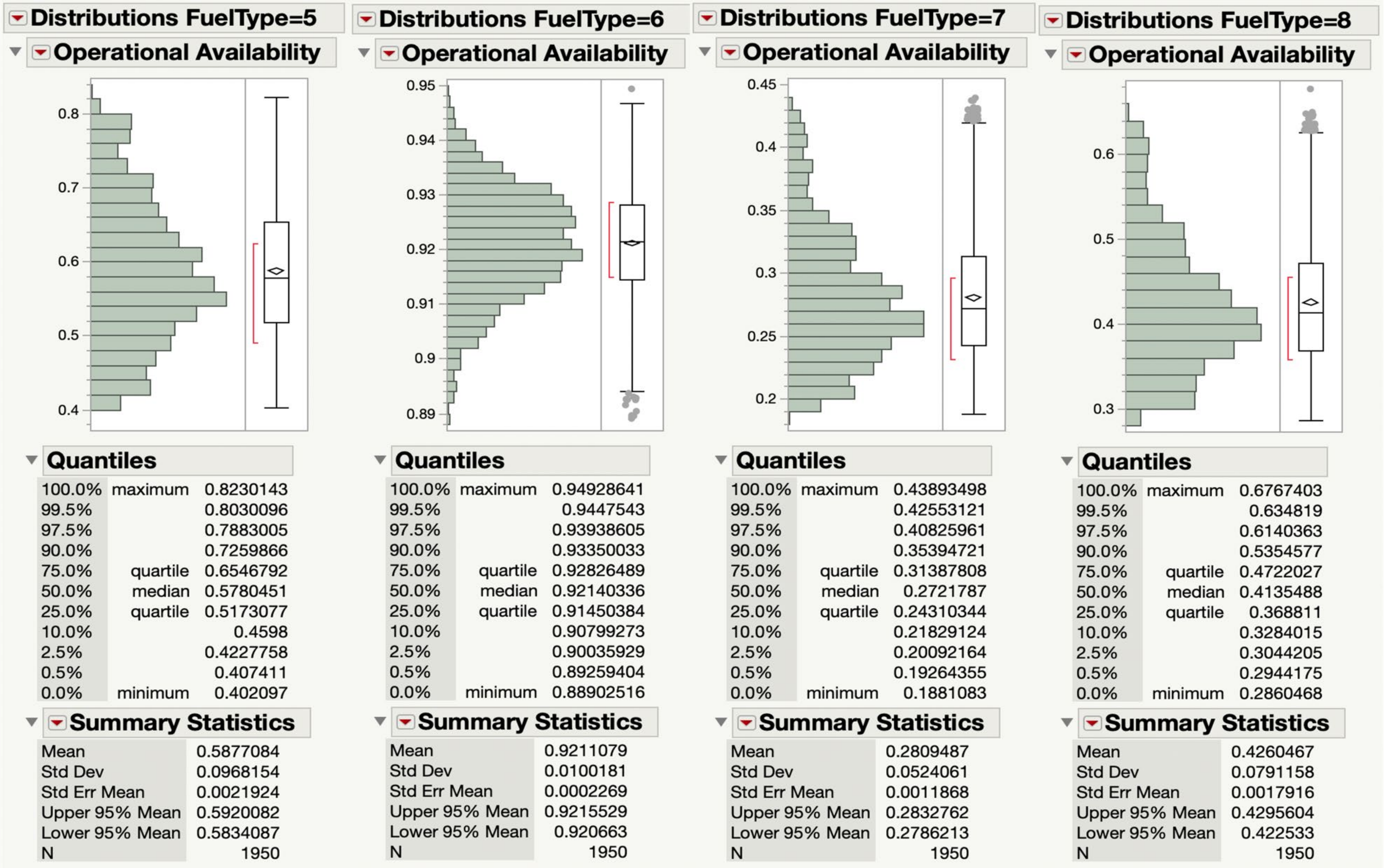
Operational Availability

Quantiles

100.0%	maximum	0.95462267
99.5%		0.94531909
97.5%		0.94105981
90.0%		0.93380461
75.0%	quartile	0.92761282
50.0%	median	0.92126584
25.0%	quartile	0.91400562
10.0%		0.90692225
2.5%		0.8989522
0.5%		0.89173606
0.0%	minimum	0.88729203

Summary Statistics

Mean	0.9206755
Std Dev	0.0105429
Std Err Mean	0.0002388
Upper 95% Mean	0.9211437
Lower 95% Mean	0.9202072
N	1950



Distributions FuelType=5

Operational Availability

Quantiles

100.0%	maximum	0.8230143
99.5%		0.8030096
97.5%		0.7883005
90.0%		0.7259866
75.0%	quartile	0.6546792
50.0%	median	0.5780451
25.0%	quartile	0.5173077
10.0%		0.4598
2.5%		0.4227758
0.5%		0.407411
0.0%	minimum	0.402097

Summary Statistics

Mean	0.5877084
Std Dev	0.0968154
Std Err Mean	0.0021924
Upper 95% Mean	0.5920082
Lower 95% Mean	0.5834087
N	1950

Distributions FuelType=6

Operational Availability

Quantiles

100.0%	maximum	0.94928641
99.5%		0.9447543
97.5%		0.93938605
90.0%		0.93350033
75.0%	quartile	0.92826489
50.0%	median	0.92140336
25.0%	quartile	0.91450384
10.0%		0.90799273
2.5%		0.90035929
0.5%		0.89259404
0.0%	minimum	0.88902516

Summary Statistics

Mean	0.9211079
Std Dev	0.0100181
Std Err Mean	0.0002269
Upper 95% Mean	0.9215529
Lower 95% Mean	0.920663
N	1950

Distributions FuelType=7

Operational Availability

Quantiles

100.0%	maximum	0.43893498
99.5%		0.42553121
97.5%		0.40825961
90.0%		0.35394721
75.0%	quartile	0.31387808
50.0%	median	0.2721787
25.0%	quartile	0.24310344
10.0%		0.21829124
2.5%		0.20092164
0.5%		0.19264355
0.0%	minimum	0.1881083

Summary Statistics

Mean	0.2809487
Std Dev	0.0524061
Std Err Mean	0.0011868
Upper 95% Mean	0.2832762
Lower 95% Mean	0.2786213
N	1950

Distributions FuelType=8

Operational Availability

Quantiles

100.0%	maximum	0.6767403
99.5%		0.634819
97.5%		0.6140363
90.0%		0.5354577
75.0%	quartile	0.4722027
50.0%	median	0.4135488
25.0%	quartile	0.368811
10.0%		0.3284015
2.5%		0.3044205
0.5%		0.2944175
0.0%	minimum	0.2860468

Summary Statistics

Mean	0.4260467
Std Dev	0.0791158
Std Err Mean	0.0017916
Upper 95% Mean	0.4295604
Lower 95% Mean	0.422533
N	1950

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