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The Potential Benefits of Adopting the Single Fuel Concept at Sea in the Brazilian Navy

December 2022

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ABSTRACT

One of the Brazilian Navy's critical challenges is monitoring and guarding its extensive Blue Amazon maritime area. Fuel management, which is highly complex and requires the expenditure of significant financial resources, is a fundamental factor for successfully fulfilling naval objectives. Currently, the Brazilian Navy uses diesel to fuel ships and aviation kerosene for aircraft. The purpose of this study is to examine the potential impacts of the Brazilian Navy adopting a single fuel concept (SFC) for its ships in the Blue Amazon protection zone. This concept means using kerosene to fuel both ships and aircraft. We used the Monte Carlo simulation methodology to model and observe the reduction in mission risk due to the SFC implementation in different scenarios. Our results demonstrate a substantial decrease in mission risk from the status quo to the SFC policy, increasing the effectiveness of Brazilian Navy patrol operations. We conclude that the employment of SFC improves the protection of the Blue Amazon's maritime wealth.

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LIST OF ACRONYMS AND ABBREVIATIONS

CCIM	Centro de Controle do Inventário da Marinha (Brazilian Navy Inventory Control Center)
COMRJ	Centro de Obtenção da Marinha no Rio de Janeiro (Brazilian Navy Procurement Center in Rio de Janeiro)
DAbM	Diretoria de Abastecimento da Marinha (Navy's Supply Systems Command)
DOD	Department of Defense
EEZ	exclusive economic zone
EMA	Estado-Maior da Armada (Brazilian Navy's General Staff)
F-76	military specification diesel fuel marine
GDP	gross domestic product
JP-5	military specification kerosene-based shipboard jet fuel
JP-8	military specification kerosene-based universal (air and ground) fuel
MGO	marine gas oil
MTU	Motoren and Turbinen Union
OMC	organização militar consumidora (consumer military unit)
OMF	organização militar fornecedora (military supply unit)
PEM 2040	Plano Estratégico da Marinha 2040 (Brazilian Navy's Strategic Guidance 2040)
RCL	requisição de comubustíveis e lubrificates (fuel requisition)
RDI	research, development, and innovation
SAbM	Sistema de Abastecimento da Marinha (Brazilian Navy Supply System)
SFC	single fuel concept
SGM	Secretaria-Geral da Marinha (General-Secretariat of the Brazilian Navy)
SINGRA	Sistema de Informações Gerenciais do Abastecimento (Supply Management Informations System)

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I. INTRODUCTION

With 4,600 miles of coastline, Brazil has an immense ocean area of 2.2 million square miles under its jurisdiction, called the Blue Amazon. This Brazilian heritage, full of unexplored natural resources and rich biodiversity, constitutes a critical interest from the country's environmental and strategic point of view (Gomes & Saldanha-Corrêa, 2021). To protect this vast area under its responsibility, the Brazilian Navy needs its logistical support system to provide the proper flow of supplies without interruption, maximizing the availability of its resources during short- or long-term naval operations (Estado-Maior da Armada [EMA], 2003). According to Axe (2011), fuel supply proved to be a decisive factor in several military campaigns of major conflicts throughout history. In this context, the Brazilian Navy uses two types of fuel aboard — diesel fuel maritime for the ships' propulsion and JP-5 for aircraft turbines. This configuration minimizes the endurance of the ships, exacerbates the difficulty of managing resources, and increases the need for fuel storage. To mitigate the problems, this research investigates the possibility and impact of adopting a single fuel at sea.

Existing literature points out that the Blue Amazon is one of the most promising areas for developing biogenetics and exploring mineral resources at great depths. Moreover, it provides about 85% of the oil, 75% of the natural gas, and 45% of the fish production, and it accounts for 95% of the Brazilian international trade (Pereira, 2019). The protection of this heritage depends on facing threats that may jeopardize the economic-strategic objectives of the Brazilian nation. Therefore, the Brazilian Navy must be prepared to ensure Brazilian sovereignty. Among the various scenarios regarding the Brazilian Navy employment, the Brazilian Maritime Strategic Planning (EMA, 2020) highlights, for instance, the possibility of assault against energy production facilities; pirate attacks on international trade, navigation, and even offshore; illegal, unreported, or unregulated fishing; biopiracy activities; organized crime movements; and episodes of terrorism. These characteristics demonstrate the magnitude of the responsibility of the Brazilian Navy in defense of the Blue Amazon. Therefore, it is imperative to investigate the possibilities of expanding and improving the employment capacity of the Brazilian Navy and, when suitable and feasible, implement them.

Not many studies have explored how to enhance the surveillance power over the Blue Amazon from the supply chain's perspective. Wiesebron (2017), for instance, presents recent purchases of nuclear-powered submarines and new fighter aircraft as two strategic acquisition programs that add more weapons systems to the Brazilian armed forces. Despite the great importance of renovating and increasing the number of military assets, the more effective use of existing means can also improve control over the national exclusive economic zone (EEZ). In addition, the Brazilian Navy's Strategic Plan reiterates the importance of the supply logistics function to increase logistical capacity for national defense EMA (2020) and suggests that military leaders should research innovative solutions in the supply chain to accomplish their institutional missions. As an example of this type of initiative, Jimenez et al. (2020) argue that the U.S. Navy is considering the numerous advantages of adopting a single fuel at sea. Following this line of thought, the purpose of this study is to examine the potential impacts of the single fuel concept adoption by Brazilian Navy ships on Blue Amazon protection.

Our paper approaches this issue through the risk analysis perspective, using Monte Carlo Simulation to demonstrate the impact on mission risk of using the single fuel concept. According to Doerr and Ferrer (2018), fuel sharing between military units beyond resupply balances their stockout risk and increases the probability of mission success. Following this rationale, we built a model using the Microsoft Excel add-in Crystal Ball based on two Brazilian Navy patrol scenarios and simulated two scenarios: the current dual fuel policy and the alternative single fuel concept. The simulation evaluates the probability that the ship-aircraft set accomplishes the naval patrol mission for the pre-established period without needing refueling. Comparing the mission success of both scenarios made it possible to measure the percentage risk reduction derived from ship and aircraft fuel sharing.

This study aims to respond to the logistical challenge of guarding an immense maritime area by recommending innovative solutions. The suggested measures intend to improve the Brazilian logistical capacity for national defense by answering the following question: What are the potential benefits of adopting the single fuel concept at sea for the Brazilian Navy? This knowledge will help the Brazilian Navy identify new alternatives to amplify its capabilities to deal with the numerous threats that could thwart the Brazilian economic-strategic goals over its maritime heritage.

Following this chapter, Chapter II provides a fundamental background for a better understanding of the main topics. Chapter III highlights previous debates through a literature review. Chapter IV presents the methodology that we employ in our research. Chapter V details the parameters, calculations, and assumptions regarding the model built. Chapter VI analyzes the impact of adopting the single fuel concept in the given scenarios. Finally, Chapter VII presents the discussion and recommendation.

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II. BACKGROUND

Before discussing how to improve the protection over the Brazilian jurisdictional waters, it is essential to explain the Blue Amazon context, the Brazilian Navy fuel supply procedures, the Brazilian petroleum supply chain, and the concepts regarding the single fuel adoption at sea.

A. THE BLUE AMAZON: THE WEALTH AND THREATS

The Blue Amazon, the enormous Brazilian maritime area that contains the country's exclusive economic zone (EEZ) limits, is a national asset of significant geopolitical, socioeconomic, and environmental importance. According to Gerhardinger et al. (2018), it covers the EEZ and continental shelf, which together are approximately eight times the size of the state of Texas.

In 2004, Admiral Guimarães Carvalho, then Commander of the Brazilian Navy, strategically introduced the term Amazônia Azul (Blue Amazon), taking advantage of the public familiarity with the Amazon rainforest that has similar dimensions and is known as an epicenter of high biodiversity (Carvalho, 2004). Thus, he called society's attention to the wealth of the domestic sea.

One main reason the Blue Amazon is an asset of high strategic value for Brazil is the oil and natural gas reserves (EMA, 2020; Marroni, 2014). Stimulated by the discovery of new repositories in the pre-salt layer in 2006, World Population Review (2022) shows that the country is currently the world's eighth-largest producer of crude oil with 2,852,000 barrels per day. Figure 1 illustrates the dizzying pace of oil production increase as a consequence of recent petroleum prospecting (Our World in Data, 2022). The nation has the potential to become one of the major players among fossil fuel producers in the future.

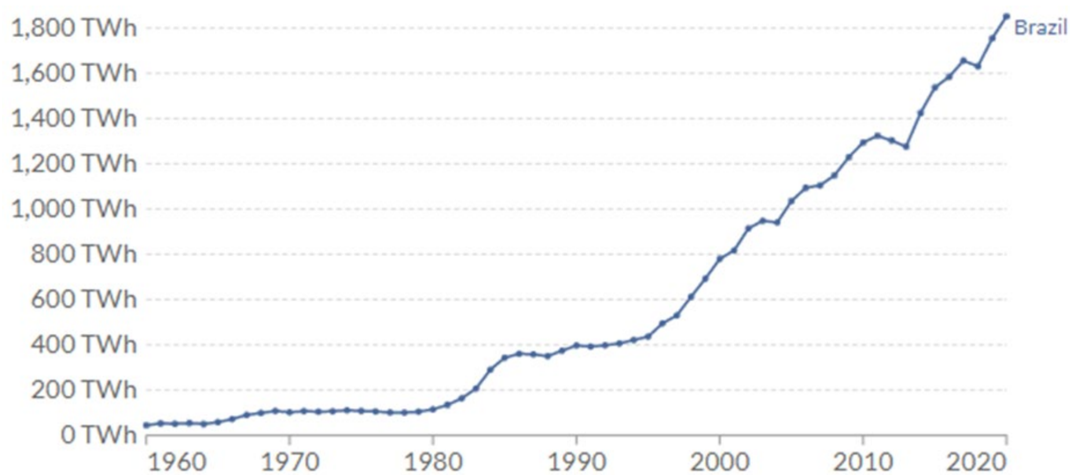

Figure 1. Oil Production in Brazil.
Source: Our World in Data (2022).

Maritime transportation is another factor that reinforces the Blue Amazon's economic importance to Brazil. Most Brazilian international trade occurs through the ocean. In 2021, it represented 32% of GDP (The World Bank, 2022). Moreover, coastal navigation integrates the critical Brazilian market regions with very low logistics costs (EMA, 2020). Furthermore, in January 2022, the Brazilian Congress enacted a specific law stimulating the industry to adopt cabotage as its main transportation mode (Costa & França, 2022). Given these facts, use of the Brazilian waterways is expected to increase, and consequently, the perceived value of the Blue Amazon will also increase.

The Brazilian maritime coast also has a vast repository of natural resources, especially fish and other seafood (Marroni, 2014). Moreover, Brandini (2021) points out that approximately one million Brazilians are artisanal fishers, proving it is an activity of great social relevance. Brandini also emphasizes the importance of maintaining the ecosystem's balance so that the fishing activity, even on a large scale, prospers with sustainability. The study also reveals that the living resources of the Brazilian sea are rich in substances that can be used in the pharmaceutical industry, reducing the volume of expensive drug imports into the country. Finally, coastal tourism and renewable energy sources from wind, waves, and tides complete the non-exhaustive list of the Blue Amazon's riches.

The management of all assets present in Brazilian jurisdictional waters requires knowledge of the threats that may jeopardize the continued use of resources. In 2019, an oil spill reached a large part of the Brazilian coast. According to Soares et al. (2022), the accident affected several species of marine life. Due to water and fish contamination, the hotel sector and artisanal fisheries have suffered a sharp reduction in revenues, according to the authors. In the international context, Barros-Platiau & Barros (2022) point out that the failure to identify the ship that caused the spill has worsened Brazil's reputation worldwide even more. This episode emphasizes the importance of proper surveillance of the national maritime area and how the country can safeguard itself and respond against similar occurrences.

The Brazilian Navy Strategic Guidance 2040 (Plano Estratégico da Marinha 2040 [PEM 2040]) lists some potential threats and advises how to build a robust defense system at sea. The directive recommends establishing a powerful patrolling and monitoring group to dissuade those who could plan different types of attacks such as cyber, via drones, or piracy (EMA, 2020). According to the guidance, an extensive presence in the ocean would also minimize drug trafficking, enhance security and safety, and reduce the risk of vandalism on offshore platforms that could interrupt energy sourcing. These reasons plausibly urge the Brazilian Navy leaders to find alternatives that increase the effectiveness of the national weapon systems' usage to provide as much protection as possible to the Blue Amazon.

B. BRAZILIAN NAVY FUEL LOGISTICS MANAGEMENT

One way to seek more efficient management of the Brazilian Navy's resources is by studying the consequences of embracing the single fuel concept on the fleet's ships. Accordingly, this section explains the Brazilian Navy fuel supply management system.

In line with the Supply Execution Rules, all consumer military units (organizações militares consumidoras-OMC) submit the fuel demand forecast for the following year to the respective Controlling Commands. These controllers consolidate the quantities of fuel from their subordinates and sends them to the Redistributor Commands (Secretaria-Geral da Marinha [SGM], 2020). Subsidies for the entire Brazilian Navy are then received by the

Navy's Supply Systems Command (Diretoria de Abastecimento da Marinha-DAbM). As the Brazilian Navy Supply System (Sistema de Abastecimento da Marinha-SabM) general management organization, DAbM prepares the draft of the maximum authorized consumption (consumo máximo autorizado-CMA), which the Brazilian Navy Commander ratifies after preliminary analysis by the Brazilian Navy's General Staff (EMA) and the General-Secretariat of the Brazilian Navy (SGM).

At the same time, in possession of the demand and product stock data, the Brazilian Navy Inventory Control Center (Centro de Controle de Inventário da Marinha-CCIM) informs the Brazilian Navy Procurement Center (Centro de Obtenção da Marinha no Rio de Janeiro-COMRJ) of the specificity, quantity, and locations of fuel supply. Subsequently, COMRJ centralizes the obtention of fuels, issuing purchase orders by military fuel supply units (organização militar fornecedora-OMF) and contracted companies. The OMFs, which are spread throughout the national territory, register each fuel requisition (requisição de combustíveis e lubrificantes-RCL) in the Supply Management Information System (Sistema de Informações Gerenciais do Abastecimento-SINGRA) to replenish their inventories or those of supported units such as ships (SGM, 2020).

After the contracts are in place, ships receive fuel quotas based on the approved CMA that represent limits on orders that can be placed in the financial year. Marine diesel oil and aviation kerosene must be ordered in multiples of 5,000 liters to be transported by the OMF or directly by the contractors (SGM, 2020). This is one of the situations in which the single fuel concept (SFC) can provide advantages. The following sections will explain that with the proper level of detail.

C. SINGLE FUEL CONCEPT

The SFC involves using a single fuel for all warfare systems that operate together (Garret, 1993). Although studies and tests date back much further, the United States first implemented the SFC in 1988, when DOD directive 4140.43 established that ground vehicles and land-based aircraft operating together would use JP-8 as the power source (Likos et al., 1988). Since then, surveys, field demonstrations, and battlefield experiences have increased the knowledge spectrum about the advantages and disadvantages of the concept (Jimenez et al., 2020). However, the potential logistical benefits remain the most significant driver for operating with just one type of fuel on the battlefield. According to Bowden (1988), The SFC simplifies logistical flow, fuel storage, and refueling operations, thus reducing the cost of sustaining a military force in combat.

The U.S. Navy, however, was not included in the 1988 single-fuel doctrine because of the high temperature of its ships during operations (Garret, 1993). Land-based military aircraft are usually JP-8 powered, which has a flash point as low as 100°F. The temperature of Navy vessels easily overcomes that point, however, such that the use of JP-8 would pose a high fire risk. As a result, naval operating aircraft use JP-5 due to its higher flash point (minimum of 140°F). Therefore, for adopting the SFC for operations at sea, the only suitable fuel among the currently used power sources is JP-5 (Jimenez et al., 2020). Although it cannot use the same fuel as land operations, the U.S. Navy showed interest in applying the SFC in naval operations as early as 1967, when the first studies were carried out on the possibility of using JP-5 in marine propulsion (Sermarini, 2000). At that time, however JP-5`s high cost and low availability hindered the implementation of the SFC in naval operations.

The ambition of moving toward the SFC has continued among the Navy's engineers and logisticians. Hence, studies and experiments also advanced. The Navy has promoted, for instance, a two-phased feasibility study (Giannini et al., 2002; Guimond, 2007) in addition to some reports and master's theses published by the Naval Postgraduate School from 2018 to 2022 that point out that adopting the SFC would be beneficial to the success of naval operations (Jimenez et al., 2020; Kube & Kinser, 2021).

D. CONCLUSION

Although there is no representative body of literature about the use of a universal fuel for all naval systems in the Brazilian literature, the U.S. DOD has sponsored many studies that suggest this matter could be helpful to Brazil's current and future challenges. Therefore, Brazilian researchers must investigate it as a promising alternative to expand and improve the employment capabilities of the Brazilian Navy in defense of the Blue Amazon.

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III. LITERATURE REVIEW

This chapter integrates the results of previous research on the SFC. It addresses the compatibility of diesel motors with JP-5, the impacts of the SFC on maintainability noticed during tests and deployments by U.S. military branches, and the expected logistical implications of the SFC at sea. Ultimately, the literature review demonstrates that previous researchers agree that the SFC can provide significant logistical benefits while it does not harm the ships' maintenance.

A. TECHNICAL FEASIBILITY

The potential implementation of the SFC using JP-5 as the only source of power at sea has as its basic premise the compatibility of this fuel with the current diesel engines of Brazilian Navy vessels. The first point of compatibility is that the Brazilian Navy standard procedures for receiving, storing, handling, and quality control of marine and aeronaval fuels, managed by the Brazilian Naval Engineering Headquarters (2021), provide for JP-5 as the recommended fuel for frigates and corvettes.

Besides that, a study by Guimond (2007) surveyed the original equipment manufacturers of the U.S. Navy vessels' engines to learn their experiences and recommendations on using JP-5. According to the research, most manufacturers consider JP-5 suitable for their marine engines. For instance, Motoren and Turbinen Union (MTU) mentioned that some of their machines use embedded sensors capable of automatically adjusting the burn to the different fuels. Nonetheless, Yanmar Co. Ltd., Westerbeke Corporation, and Onan stated that adjustments would be necessary on their engines due to the low lubricity of JP-5 compared to other fuels. These brands' engines operate with variations of rotary fuel injection pumps that are lubricated internally by fuel. Thus, they are more likely to have problems when running with JP-5. Therefore, there should be more precautions when migrating engines that use these types of injection pumps to JP-5 usage.

That said, Guimond (2007) also consulted Navy diesel inspectors about their expertise in operating with JP-5, and none of them reported critical issues due to the kerosene-based fuel usage. Some cited longer-lasting fuel filters and cleaner burning during JP-5 utilization. A few mentioned that they had experienced slightly higher engine and exhaust temperatures due to the fuel's lower lubricity, but they also highlighted that it was not a harmful problem. Research by Tosh et al. (1992) at Belvoir Fuels and Lubricants Research Facility supported the same idea when they reported that the U.S. Navy ran solely on JP-5 in the Indian Ocean between 1982 and 1983, as well as that U.S. Army vehicles were JP-5 powered while operating in the Panama area from 1980 to 1983, without reporting any problems in both situations.

According to Le Pera (2005), the many field tests done by the DOD on diesel engines using kerosene-based fuel resulted in no performance downgrade, part wear, or noteworthy changes in temperature operation, which endorses the compatibility between jet fuels and diesel-powered machines. However, Le Pera also mentioned that recent combat experiences in Afghanistan and Iraq pointed to lubricity problems in rotary-distribution pumps. Although these observations were made on land-based diesel vehicles, they reinforced the likelihood of lubricity problems with specific weapon systems. Hence, a plan for implementing the SFC in the Brazilian armed forces should encompass an investigation of the impact of the lower lubrication content of JP-5 on engines used in Brazilian systems to determine when and to what extent the addition of fuel lubricants will be necessary.

Another critical concern regarding the compatibility of diesel engines with kerosene fuel like JP-5 is the possibility of increased maintenance costs. Several studies have addressed this issue, and the findings suggest the exact opposite of that mindset. For instance, the laboratory tests developed by Likos et al. (1988) at Belvoir Research Facility concluded that using jet fuel in diesel engines tends to reduce corrosion, decrease deposits on fuel injectors, extend useful life, and improve thermal fuel efficiency.

Agreeing with Likos et al.'s understanding that JP-5 does not jeopardize ships' maintenance, Sermarini's (2000) study on the universal fuel at sea also concluded that JP-5 use would not reduce engine durability and, in some cases, will provide a slight improvement in maintainability. According to these results, the benefits come from a reduction in lubricant oxidation, metal wear, top ring corrosion, and solid particle disposal at the combustion chamber and fuel injector. Furthermore, Giannini et al. (2002) added that using JP-5 as the ship's single power source grants a cleaner fuel burn, meaning it releases significantly fewer impurities into the propulsion system, thus positively impacting shipboard maintenance. Therefore, there is enough evidence to reject the claim that a kerosene-based fuel will damage a diesel engine. More than that, previous research indicates a likely enhancement in diesel engine maintainability.

Additionally, because kerosene runs cleaner in diesel engines than diesel-based fuel, fewer fuel filter refills are expected in the long term. According to research by Guimond (2007), JP-5 has a cleaner burn because it presents lower levels of sulfur, resulting in fewer engine particle emissions. Moreover, U.S. Coast Guard cutters have used JP-5 since the 1970s without reporting any trouble, often interspersing diesel fuels such as F-76 and marine gas oil.

Nonetheless, Coast Guard engineering personnel state that alternating between JP-5 and diesel fuel may cause variations in the filter replacement rate. As related in the study, tanks that routinely store diesel fuels tend to accumulate particles on metallic surfaces and JP-5, due to its characteristics and additives, acts as a solvent dissolving these deposited particles, which are captured by fuel filters. For this reason, Coast Guard vessels carry extra filters when exposed to multi-type fuel replenishment.

Sermarini (2000) adds that JP-5 has less reactivity to water than diesel fuels and additives that guarantee better resistance to the proliferation of microorganisms in the tanks, while diesel contains higher levels of alkane, which are essential nutrients for the development of certain types of microorganisms. As it dissolves sediments deposited in the tanks in contact with diesel, JP-5 acts as a microbicide, causing the contamination to be captured by the filters.

Although it guarantees some degree of flexibility to the rigor of supplying exclusively by jet fuel, due to contamination the alternate use of diesel and kerosene fuels brings critical limitations to the ships during operations. As Tosh et al. (1992) mentioned, storers must maintain the strict requirements for aviation fuel. Consequently, if the Brazilian Navy chooses to maintain the supply of diesel fuel in specific cases, ships must keep at least one tank exclusively for JP-5 storage, thus avoiding contaminating the fuel used by aircraft. Besides that, vessels operating with mixed or contaminated systems should expect to carry more fuel filters than they currently do. In contrast, if the objective is to fully achieve the benefits brought by the expansion of aviation fuel storage capacity and the potential reduction in maintenance costs of naval propulsion engines, implementing universal fuel at sea must avoid multi-type fuel replenishment.

B. LOGISTICAL IMPACT

In addition to establishing the technical feasibility of using JP-5 for ship propulsion, the previous literature on the SFC has focused on demonstrating the logistical benefits of replacing diesel fuel with kerosene-based jet fuel. Positive logistical impacts include ease of handling, reduced possibility of cross-contamination with another fuel type, improved inventory rotation, reduced transportation risks, improved fuel supply chain resiliency, and increased flexibility and availability of weapon systems.

The report commissioned by the Belvoir Fuels and Lubricants Research Facility (Tosh et al., 1992) points out that operating with a single fuel would reduce the crews' workload, given that they would carry out fewer refueling procedures in the same replenishment. Additionally, the authors state that there would be less frequent periodic cleaning and purging routines between charges due to the reduced risk of inter-fuel contamination; hence sailors would be less occupied by these activities. Finally, Tosh et al. conclude that the most significant benefits from SFC implementation at sea would come from the logistics perspective since it simplifies the fuel supply chain.

Sermarini (2000) also recognizes that simplified logistics brings significant enhancements and that pooling ship and aircraft fuels increases fuel demand predictability making it easier to manage. Therefore, the author agrees that there are logistical benefits in converting to the SFC at sea. However, Sermarini disagrees that those are the most relevant impacts it could provide. According to his study, the principal justification for SFC implementation is the opportunity to expand JP-5 production and reduce the probability of shortage in future contingencies. In fact, the JP-5's minimum ignition flash point is a characteristic restriction that other fuels do not have, so it is much more difficult to produce or replace JP-5 in an unforeseen event. Scholars may disagree on what is the main benefit of SFC application. Nonetheless, the recognition of such benefits by different researchers is sufficient reason to consider the SFC alternative and carry out further studies.

Another vital aspect cited by Sermarini (2000) and exemplified by Jimenez et al. (2020) is that the SFC reduces the frequency of refueling needed by warships. Consequently, a smaller infrastructure for refueling would be necessary to provide the same level of service and readiness of U.S. Navy assets, freeing up support and escort resources for other tasks. Furthermore, Sermarini points out that the lower recurrence of replenishments also reduces the volume of communications needed and results in fewer visits to ports for logistical purposes, thus bringing significant operational and economic gains. All this corroborates that we must analyze the SFC as a desirable option to increase the capabilities of the Brazilian Navy.

Therefore, the literature provides enough evidence that it is not only technically feasible to use JP-5 in diesel engines regularly and satisfactorily, but it is also an excellent opportunity for improvement for the Brazilian Navy. According to our predecessors, there is no significant harm to the maintainability of these engines. Furthermore, the review showed that the SFC would provide logistical benefits by simplifying the number of items managed on the battlefield, stimulating the JP-5 production, and freeing up valuable assets for other tasks.

Previous researchers did not present arguments about whether the SFC would increase the capabilities of a regionally centered navy such as the Brazilian Navy, considering its comparably smaller size. Thus, this study simulates and analyzes the impact of SFC implementation on the probability of mission success of a set of one ship and one aircraft operating in Blue Amazon naval patrols, investigating whether it is beneficial even to such a small particle.

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IV. METHODOLOGY

Our thesis analyzes the impacts of implementing the SFC on a vessel-helicopter joint use in a coastal patrol operation. This type of mission faces considerable uncertainties, such as the number of radio contacts to vessels in the area, the nautical miles navigated to reach them, and the nature of the interventions needed. The military assets alter their engine regime to respond to this demanding environment, thus varying their fuel consumption rate. To illustrate the probability of accomplishing the mission before and after implementing the SFC, we developed a Monte Carlo simulation model that enabled us to perform a significant number of trials and to account for the uncertainty of these operations.

A. MONTE CARLO SIMULATION

Balakrishnan (2017) highlights some characteristics of simulation that contribute to our research. The author states, for instance, that simulation models allow us to reproduce different scenarios; thereby, we can set diverse situations with either low or high consumption rates in both dual and single fuel configurations.

Simulation can also handle complexity quite well, using probability distributions as input (Balakrishnan, 2017). This feature makes the model more realistic, as the consumption rates vary according to countless factors to which the naval assets are susceptible. Consequently, the results are also probability distributions, creating a way of measuring the risk of not achieving an objective.

Balakrishnan (2017) also emphasizes that another critical advantage is that simulation runs apart from the real world. For this reason, the Brazilian Navy can consider the SFC without investing money in converting its vessels' engines to burn JP-5, keeping the ships in operation while the studies evolve. Appropriately, the Brazilian Navy can allocate scarce resources to research, development, and innovation (RDI) while maintaining adequate levels of operational availability.

Finally, Leonelli (2021) explains that Monte Carlo Simulation "uses repeated sampling to obtain the statistical properties of some phenomenon" (chapter 5). We used a

Microsoft Excel add-in named Crystal Ball to process multiple fuel consumption estimates, contrasting them against the fuel tank's capacity for numerous theoretical missions. We chose this tool because its flexibility allows us to easily vary the missions' length, averages and standard deviations of consumption per fuel type, and the JP-5 efficiency loss factor, providing the model replicability to diverse military assets and scenarios. In addition, Crystal Ball offers valuable charts that enable users to perform proper comparisons and sensitivity analysis.

B. RISK ANALYSIS

Since Brazilian naval patrol missions do not generally refuel at sea, ships must perform their assigned tasks before they need replenishment, returning to port only at the end of their mission. Therefore, for this study, we defined mission risk as the probability that the ship-aircraft set needs refueling before completing its patrol mission.

Risk analysis gives researchers the benefit of assessing a range of possible outcomes instead of giving just one numerical answer to the problem. To take advantage of this characteristic and to get as close as possible to what could happen in the real world, we established that the data related to the fuel consumption of both the ship and the aircraft would be modeled as probabilistic distributions. Those probabilistic distributions provided the model with a range of possible outcomes, making our analysis more realistic than a simple calculation of fixed values.

After that, we established a set of constant parameters as input to introduce constraints to the model's behavior. These parameters are diesel tank capacity, JP-5 tank capacity, JP-5 efficiency loss factor, and high/low tempo probability. The fuel capacities are defined as a percentage of the total tank capacities available in a mission to represent the limitations imposed by the Brazilian Navy's replenishment policy. Also, the efficiency loss parameter accounts for the potential increase in consumption due to the application of kerosene-based fuel in diesel engines mentioned in previous research. Finally, the probability of high/low tempo introduces the variations in the fuel consumption rate generated by the different occurrences in the naval patrol.

With the simulation model, we can run each scenario for 200,000 replications, a very large number that can produce significantly smooth probabilistic distributions as output. Those distributions represent mission fuel consumption for a given patrol mission type in two different situations: the first using the current policy of two different fuels and the second applying the SFC at sea, which can then be used to perform the risk analysis. Ultimately, we could evaluate the difference between the probabilities of the fuel policies' mission risk and, hence, measure the potential impacts of implementing the SFC in Brazilian Navy missions from the risk analysis perspective.

C. MODEL APPROACH

Figure 2 demonstrates the reasoning behind the simulation model in Crystal Ball. This flowchart illustrates how the chosen variables interact with each other to generate the probabilistic data that this study analyzed. The key elements of this process flow diagram are arrows, boxes, repetition/loop structures, diamonds, and nodes. They represent the direction processing flow from one action or decision to another, processes executed by the model, a group of actions to be repeated within a single replication, decision points that allow only one exiting flow, and split points that represent the beginning of parallel processing flows, respectively.

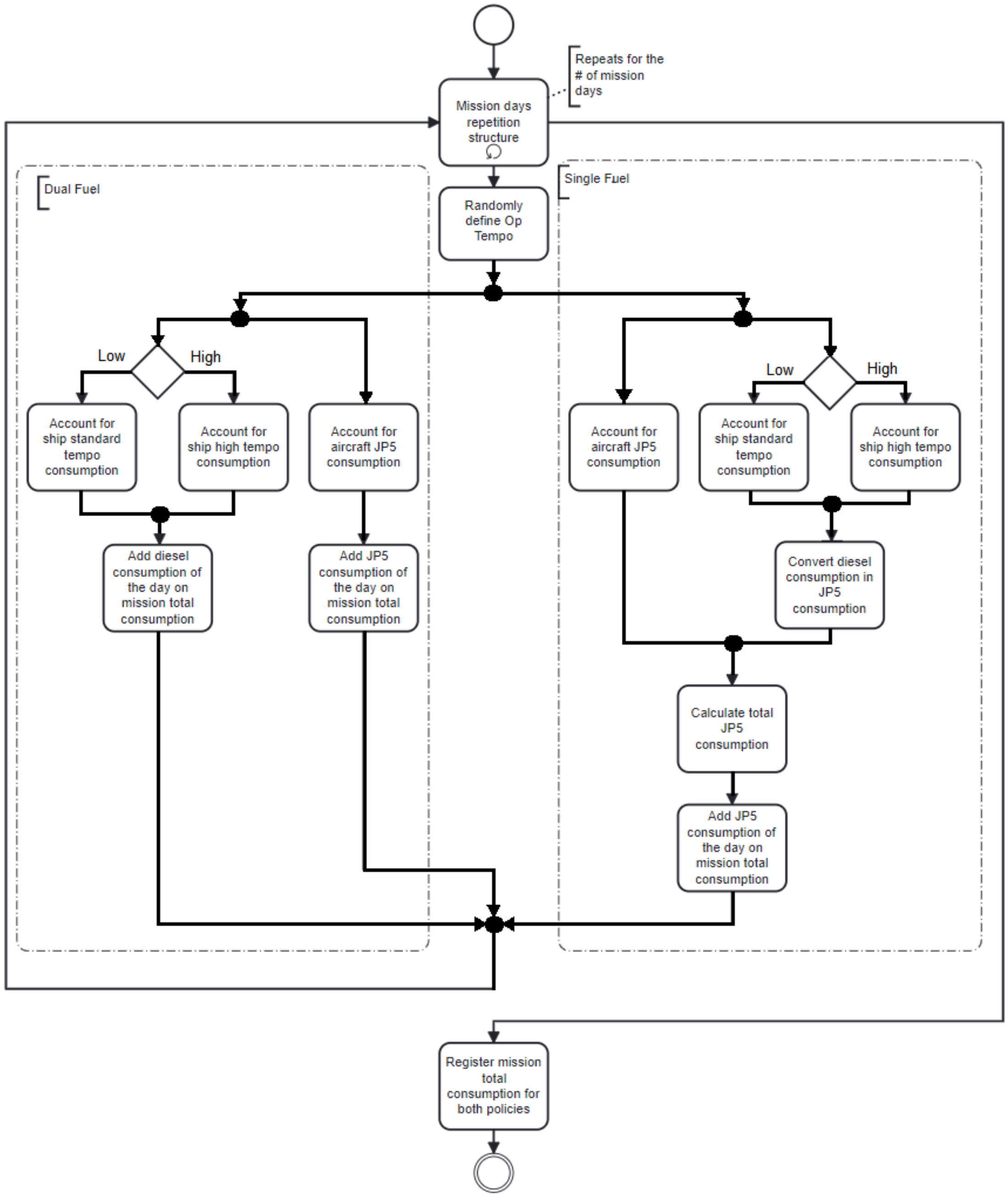

Figure 2. Model reasoning flowchart.

The model was structured to simulate the total mission fuel consumption by calculating and aggregating the fuel consumption of each mission day, incorporating the randomly defined operational tempo for that day. The operational tempo affects the engine employment regime demanded in a mission. For example, a naval patrol typically operates in a low op tempo; however, when a threat or need is detected, the ship operates in a high op tempo environment, increasing speed and fuel consumption rate. As shown in Figure 2, both dual fuel and single fuel calculations are given the same random number to ensure they follow the same op tempo on each day of the simulated mission. Then, the model processes two activity blocks simultaneously, with one modeling the fuel consumption under the dual fuel policy and the other under the single fuel policy.

1. Dual Fuel

When entering the dual fuel policy activity block in Figure 2, a split dot divides the flow to simultaneously process the ship's and aircrafts' fuel consumption. On the side of ship calculation, a decision point divides the processing into two excluding branches: one for high and another for low tempo. Therefore, only the path corresponding to the op tempo determined by the common random number will be followed through the flowchart. The model then simulates the ship's fuel consumption according to a random draw from the probabilistic distribution of consumption for that op tempo. Then, the model records that simulated diesel consumption for that mission day. For the aircraft branch, the model calculates the aircraft's fuel consumption by multiplying random draws from the probabilistic distributions for fuel consumption per hour by the aircraft and hours flown per mission day. After that, like what happened with ship consumption, the model records the simulated JP-5 consumption for that mission day. Those values represent the diesel and JP-5 amount consumed in one mission day in the op tempo specified by the random number drawn.

2. Single Fuel

Simultaneously to the previously described dual fuel block, entering the single fuel part in Figure 2, the processing flow also splits into two parallel processing branches to calculate the daily consumption in the single fuel policy. The first branch simulates the aircraft's fuel consumption by multiplying the simulated values based on probabilistic distributions of fuel consumption per hour and hours flown per mission day. The second one, in the same way as the dual fuel block, is divided into a decision point that simulates the ship's fuel consumption according to the probabilistic distribution of consumption for the specified op tempo. Due to the expected loss of efficiency, we assumed a higher consumption of JP-5 in the single fuel than diesel consumption in the dual fuel policy. Therefore, the model converts the simulated diesel consumption for the vessel into JP-5 consumption by multiplying that value by the efficiency loss factor entered as the input variable. Then, after gathering both consumption values, the model calculates the combined total consumption of JP-5 of the ship and aircraft set and records the amount of JP-5 consumed in one mission day in the op tempo specified by the random number drawn.

3. Output

The actions contained in the dual fuel and single fuel processing blocks of Figure 2 are repeated for the number of days established for a specific mission. Each interaction records the total fuel consumption of one simulated mission in both fuel policies. The model, then, simulates 200,000 missions. At the end of the simulation, the model builds three distributions of outcomes: ship dual-fuel diesel consumption, aircraft dual-fuel JP-5 consumption, and combined single-fuel consumption. Then, those distributions are tested against the respective tank capacity and demonstrate the probability of mission success for the two approaches. For the dual fuel capacity, the likelihood of mission success is given by the most restrictive fuel type. On the other hand, the SFC mission`s success is provided by the straightforward comparison of the capacity of the tanks with the consumption probability distribution. Finally, comparing the mission success probability data allows the model to demonstrate the impact of SFC implementation on the likelihood of patrol mission success in the Brazilian Navy.

D. SCENARIOS

The Brazilian naval military doctrine (EMA, 2017) dictates that the naval patrol consists of limited use of the military force whose purpose is to implement and monitor compliance with laws, regulations, treaties, and mandates in the Brazilian jurisdictional area. The Brazilian Navy's naval patrols over the Blue Amazon are typically conducted by patrol ships using organic aircraft and grouped in two different scenarios: standard patrol missions and quick response missions. The main factors that differentiate these categories are the mission's motivation and the employment regime of the naval assets.

1. Standard Patrol Missions

The first scenario is driven by the need to be present in the maritime jurisdictional area to nullify or minimize the risks and possible effects of threats of any kind. The ship-aircraft duo, then, remains on patrol in a predetermined region for seven days executing activities such as detecting, tracking, inspecting, and mitigating threats. For this purpose, Brazilian Navy's ships employ a variable engine regime alternating between low and high tempo as needed to address any threats. This type of operation aims to perform a naval patrol within a designated area using an efficient fuel rate. If a suspect vessel is reported, the deck officer commands *full ahead*, increasing the ship's speed and fuel consumption rate.

2. Quick Response Missions

The second scenario occurs in a very high tempo situation when the Brazilian Navy receives an alert from the intelligence sector to rapidly intercept a threat, for example, a vessel committing illegal activities within the Brazilian exclusive economic zone (EEZ). This kind of mission requires the ship-aircraft duo to arrive at the scene as fast as possible; otherwise, the criminals can flee the Brazilian jurisdictional area, escaping from the adequate correction measure. From the fuel perspective, the consequence of this type of operation is that both ship and helicopter are burning a lot more fuel to augment their chances of reaching their target. However, these missions are not required to last seven days.

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V. MODEL DESCRIPTION

This chapter provides the detailed data and calculations of the model described in section C of the previous chapter.

Both fuel consumption and storage capacity data of the ship and aircraft considered in this study are registered in classified documents of the Brazilian Navy. For this reason, after gathering the data, we applied some adjustments to the actual values, keeping them within a realistic range for the characteristics of military assets performing maritime patrol while masking the actual values. Regardless, the model could be applied in a secure environment with confidential data.

We established normal probability distributions to represent variations in fuel consumption, as this is the distribution that best represents possible variations around a central value. Considering that the Brazilian Navy tends to prioritize the use of standard speeds depending on the op tempo and that speed is the input parameter of Brazilian Navy assets' consumption curve, the normal distribution is the more reasonable option to portray the behavior of the variables related to the consumption of its naval assets.

A. STANDARD PATROL MISSION PARAMETERS

Following are the parameters regarding this scenario as represented in Figure 3:

Index and Set

i = Mission day [1, 2, …, 7] (1: first day; 2: second day; …; 7: seventh day)

We kept the eighth-day cell blank to indicate that other users can adapt this model to other cases.

Input Data

D_i = Ship diesel consumed (in liters) on day i

r = Random number drawn from Uniform (0, 1) distribution

D_L = Ship diesel consumed in one day (in liters) at a low fuel consumption rate, drawn from ~N (M = 15,000, SD = 1,500). The consumption is defined by a normal distribution. ~N (M = *mean*, SD = *standard deviation*).

D_H = Ship diesel consumed in one day (in liters) at a high fuel consumption rate, drawn from ~N (M = 21,000, SD = 2,500)

J_i = Aircraft JP-5 consumed (in liters) on day i

J_h = Hourly aircraft JP-5 consumption (in liters), drawn from ~N (M = 167, SD = 27)

h = Number of flight hours in one day, drawn from ~N (M = 2, SD = 1) truncated at zero

E = JP-5 efficiency loss factor; a ratio that accounts for the extra consumption of JP-5 in diesel engines compared to the original fuel. After testing, the Belvoir Fuel and Lubricants Research Facility technically observed that JP-5 consumes 2.6% more than F-76, on average (Tosh et al., 1992).

C_D = Diesel tank capacity (in liters); set as 122,500, after considering the replenishment point (35% of the total fuel storage capacity of the ship for standard patrol missions as the current policy in the Brazilian Navy).

C_J = JP-5 tank capacity (in liters); set as 10,500 after considering the replenishment point

C_C = Combined fuel tank capacity (in liters)

$C_C = C_D + C_J$

Output Data

D_T = Total ship diesel consumed during the mission under the dual fuel approach

$D_i = D_L$ if $r < 0.8$, D_H otherwise

$D_T = \sum_{i=1}^{7}(D_i)$

J_T = Total aircraft JP-5 consumed during the mission

$J_i = J_h \times h$

$J_T = \sum_{i=1}^{7}(J_i)$

T_S = Total JP-5 consumed during the mission under the SFC

$T_S = (D_T \times E) + J_T$

The model has some Excel functions embedded that enable the simulation of low and high tempo. The function RAND() applied to the "r" column in Figure 3 generates uniformly distributed random numbers (r) varying from zero to less than one. If the number is less than 0.8, the ship operates at an efficient fuel rate; otherwise, there is a high tempo situation. The result is that on 80% of the days there is a low consumption rate (D_L), and on 20% of the days, there is a high consumption rate (D_H), which automatically calculates the values of the "D_i" column cells using the IF function. The summation of these cells equals the quantity of diesel the ship consumes (D_T) in each of the 200,000 simulated missions.

Both the hourly fuel consumption rate of the aircraft (J_h) and the number of flight hours in one day (h) can vary. Regardless of this consideration, the cells in the columns "J_h" and "h" from the AIRCRAFT (JP-5) field are multiplied and result in the values in cells of the "J_T" column, whose summation represents the total aircraft consumption. After adding all ship consumption per day, the total ship consumption is multiplied by the "JP-5 Efficiency Loss Factor" value (E) to consider the JP-5 loss of efficiency when used as the fuel of the ship's engines. Finally, we obtained T_S by summing the total consumption of ship and aircraft.

It is important to mention that Crystal Ball generates values in the cells highlighted in green according to the probability distribution from the parameters we input in the "Define Assumption" function. In blue, Crystal Ball highlights the cells used as model output from the "Forecast" function. Then, the software creates the charts we compared and analyzed.

Standard Patrol Mission

Diesel (Ship) & JP-5 (Aircraft) Status Quo

SHIP (Diesel)					AIRCRAFT (JP-5)			
Day (i)	D_L	D_H	D_i	r	Day (i)	J_h	h	J_i
1	14,286	19,880	14,286	0.41	1	159.61	1.44	229.78
2	12,465	22,638	12,465	0.23	2	138.5331	2.36	326.93
3	15,638	21,534	21,534	0.85	3	128.4809	0.61	78.19
4	16,833	22,537	16,833	0.20	4	121.6424	2.08	253.30
5	16,442	19,811	19,811	0.97	5	176.1922	1.30	229.75
6	15,297	20,654	15,297	0.07	6	206.5833	2.39	493.72
7	15,125	17,902	15,125	0.17	7	188.3666	1.85	347.80
8					8			
		D_T	115,351				J_T	1,959

Capacity (35%)

Diesel (C_D) 122,500 liters

JP-5 (C_J) 10,500 liters

Combined (C_C) 133,000 liters

JP-5 Only (Ship & Aircraft) Single Fuel Concept

JP-5 Efficiency Loss Factor (E) 1.026

T_S 120,310

Figure 3. Standard Patrol Mission model.

B. QUICK RESPONSE MISSION PARAMETERS

Following are the parameters regarding this scenario:

Index and Set

i = Mission day [1, 2, …, 7] (1: first day; 2: second day; …; 7: seventh day)

Input Data

D_i = Ship diesel consumed on day i (in liters) at a very high fuel consumption rate, drawn from ~N (M = 23.500, SD = 1,500); the relatively small standard deviation reflects the stable ship's behavior. It will keep high speed to reach the threat as fast as possible.

J_i = Aircraft JP-5 consumed (in liters) on day i

J_h = Hourly aircraft JP-5 consumption (in liters), drawn from ~N (M = 167, SD = 27)

h = Number of flight hours, drawn from ~N (M = 6, SD = 2)

E = JP-5 efficiency loss factor

C_D = Diesel tank capacity (in liters); set as 140,000, after considering the replenishment point (40% of the total fuel storage capacity of the ship for quick response missions as the relaxed policy in extreme cases)

C_J = JP-5 tank capacity (in liters); set as 12,000 after considering the replenishment point

C_C = Combined fuel tank capacity (in liters)

$C_C = C_D + C_J$

<u>Output Data</u>

D_T = Total ship diesel consumed during the mission under the dual fuel approach

$D_T = \sum_{i=1}^{7}(D_i)$

J_T = Total aircraft JP-5 consumed during the mission

$J_i = J_h \times h$

$J_T = \sum_{i=1}^{7}(J_i)$

T_S = Total JP-5 consumed during the mission under the SFC

$T_S = (D_T \times E) + J_T$

Figure 4 presents a model that is simpler than the first one but with specific nuances. The critical difference is that the ship fuel consumed on a day (Di) is now a direct draw from a different normal distribution. Therefore, D_L, D_H, and r do not apply to this case.

Quick Response Mission

Diesel (Ship) & JP-5 (Aircraft) Status Quo

SHIP (Diesel)		AIRCRAFT (JP-5)			
Day (i)	**D_i**	**Day (i)**	**J_h**	**h**	**J_i**
1	23,872	1	180.37175	6.71	1,211
2	23,443	2	164.25008	6.35	1,042
3	23,325	3	176.40443	4.97	877
4	24,901	4	177.43044	8.03	1,424
5	21,720	5	132.03854	6.06	800
6	21,820	6	166.43636	8.86	1,474
7	23,149	7	173.08849	4.02	696
8		8			
D_T	162,229			**J_T**	7,525

Capacity (40%)

Diesel (C_D)
140,000 liters

JP-5 (C_J)
12,000 liters

Combined (C_C)
152,000 liters

JP-5 Only (Ship & Aircraft) Single Fuel Concept

JP-5 Efficiency Loss Factor (E) 1.026

Ts 173,972

Figure 4. Quick Response Mission model.

VI. RESULTS AND ANALYSIS

After running the model through Crystal Ball, we obtained charts showing the probability of fuel consumption during a mission. They contrast with each other regarding the type of fuel, amount of fuel available, and level of engine usage, and use fuel capacity as thresholds to determine the probabilities of accomplishing the operation and the associated mission risk. Finally, we compared them to analyze the impact of adopting the SFC in different scenarios. Additionally, we compared JP-5 and diesel prices over the last ten years to identify if their behaviors indicate a possible financial advantage of transitioning toward the SFC at sea.

A. STANDARD PATROL MISSION

1. Diesel and JP-5 Status Quo

Figures 5 and 6 represent our simulation results for the standard patrol mission in the dual fuel policy. The chart in Figure 5 describes the probability distribution of the ship's diesel consumption (D_T). The threshold that separates the areas representing the probability of mission risk and success is 122,500 liters (C_D). Using this parameter, Crystal Ball calculates that ships do not need replenishment before accomplishing their seven-day standard patrol mission 87.1% of the time under the dual fuel policy. Figure 6, using the same reasoning, describes that the aircraft has a 100% chance of enduring the same type of mission under the same policy. Since the dual fuel policy requires Brazilian Navy to maintain a minimum inventory level for both fuel types individually, mission success only occurs if diesel and JP-5 consumption are below the respective available capacity. So, to assess the mission risk, we must first check which fuel is the most restrictive.

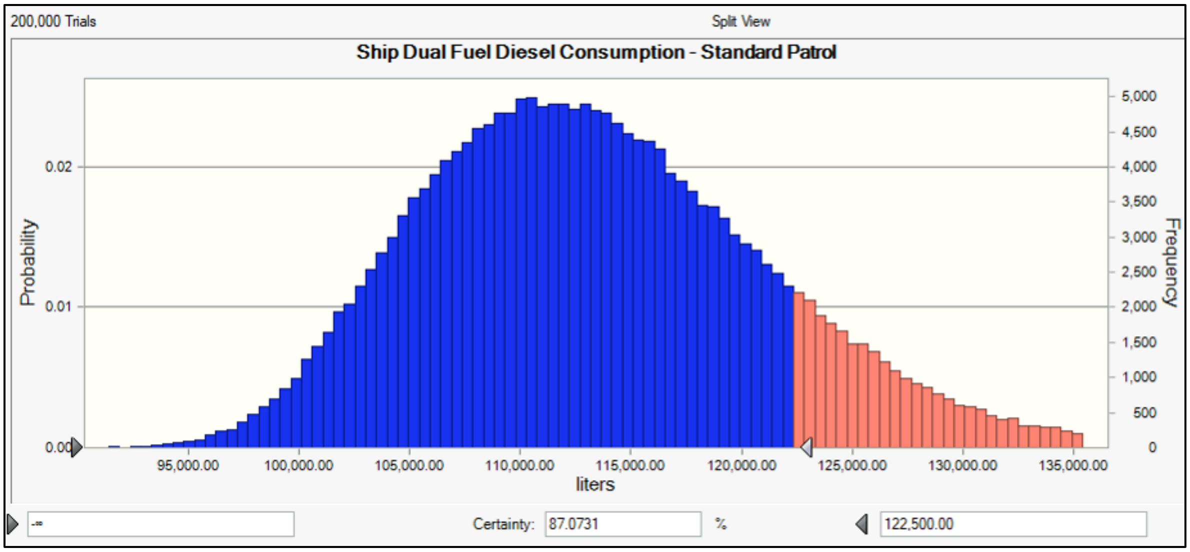

Figure 5. Diesel consumption during standard patrol mission (status quo).

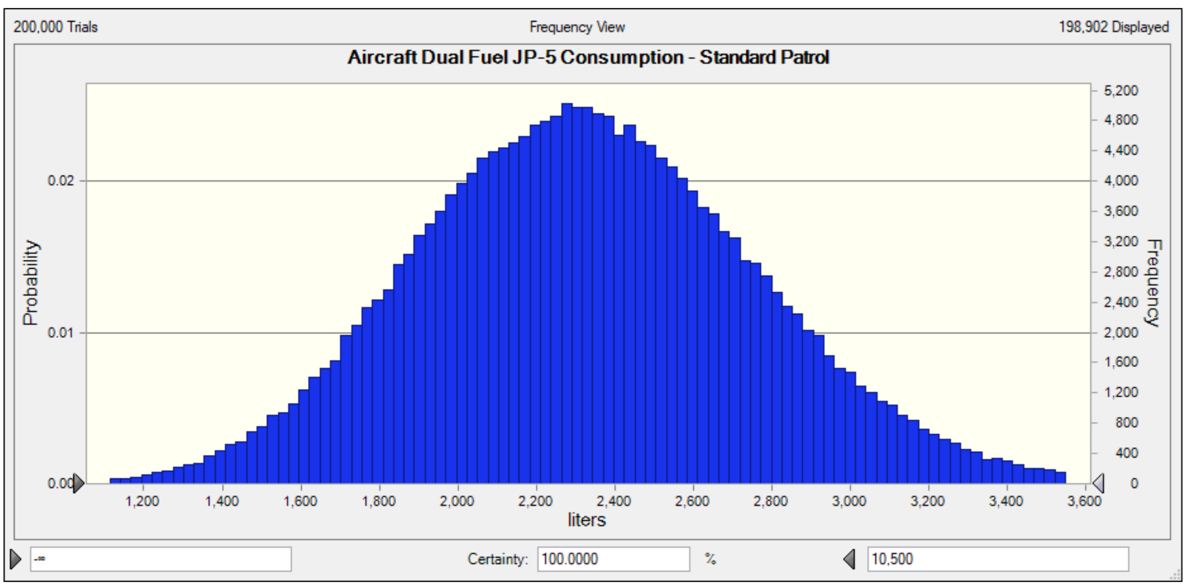

Figure 6. JP-5 consumption during standard patrol mission (status quo).

Comparing both outputs, we identified that the ship diesel consumption chart has the most prominent red area, meaning the ship has the highest probability of consuming all the capacity available. Hence, diesel is the most restrictive fuel type in this case. Actually, the chances of burning all aviation kerosene available are extremely low. Consequently, we selected Figure 5 to represent the probability of mission success or the mission risk for a standard patrol mission using the dual fuel policy (status quo). Therefore, the model points out that approximately 87% of the standard patrol missions will be accomplished through the dual fuel approach. In other words, in this case, the mission risk is around 13%.

2. Single Fuel Concept

Figure 7 demonstrates the results for the standard patrol mission under the SFC policy. The chart depicts the probability distribution of ship and aircraft's JP-5 consumption (T_s). Since ship and aircraft share the same fuel type in the SFC, the threshold that separates the areas representing the probability of mission risk and success is given by combined fuel tank capacity (C_C), 133,000 liters. Therefore, Figure 7 demonstrates that there is roughly a 95% chance of mission success or 5% of mission risk.

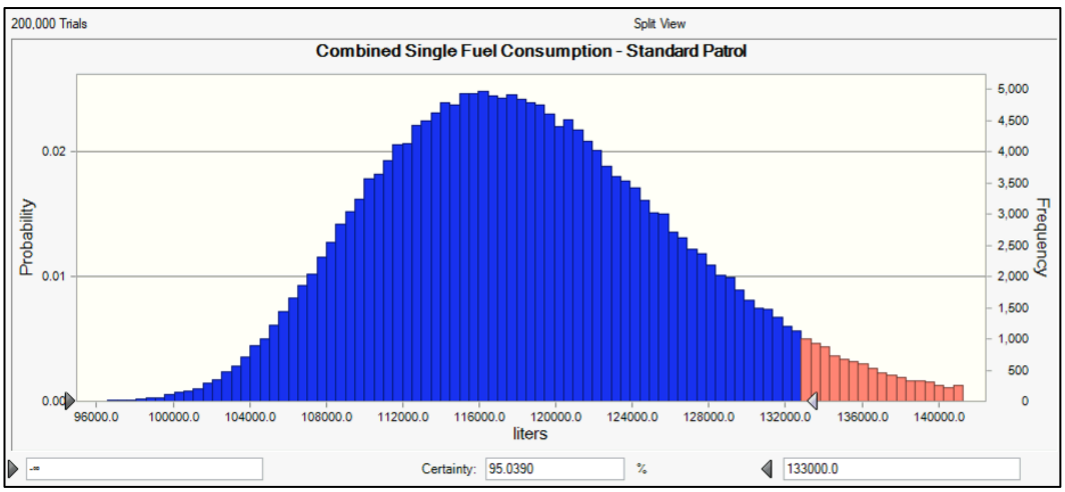

Figure 7. JP-5 consumption during standard patrol mission (SFC).

3. Status Quo vs. Single Fuel Concept

The simulation model outcomes described in Figures 5 and 7 demonstrate that SFC adoption significantly reduced the standard patrol mission risk. The 13% risk associated with the dual fuel approach drops to 5% after implementing the SFC. Accordingly, the probability of staying at sea for seven days without needing replenishment increases by 8%, representing a significant improvement in the Brazilian Navy's patrolling power over the Blue Amazon.

B. QUICK RESPONSE MISSION

We simulated quick response missions for the same seven-day mission period we used for standard patrol operations. Although there is an insignificant risk of needing replenishment for the aircraft during the operation (Figure 9), the red area in Figure 8 demonstrates that the higher ship consumption rate caused a massive likelihood of not enduring seven days at sea without resupply under the dual fuel approach. Since Figure 8 confirms that diesel is the most restrictive fuel, the results depict a non-acceptable mission risk probability of nearly 100%. Likewise, Figure 10 shows that the mission risk would not reduce perceptibly even after adopting the SFC for a seven-day quick response mission.

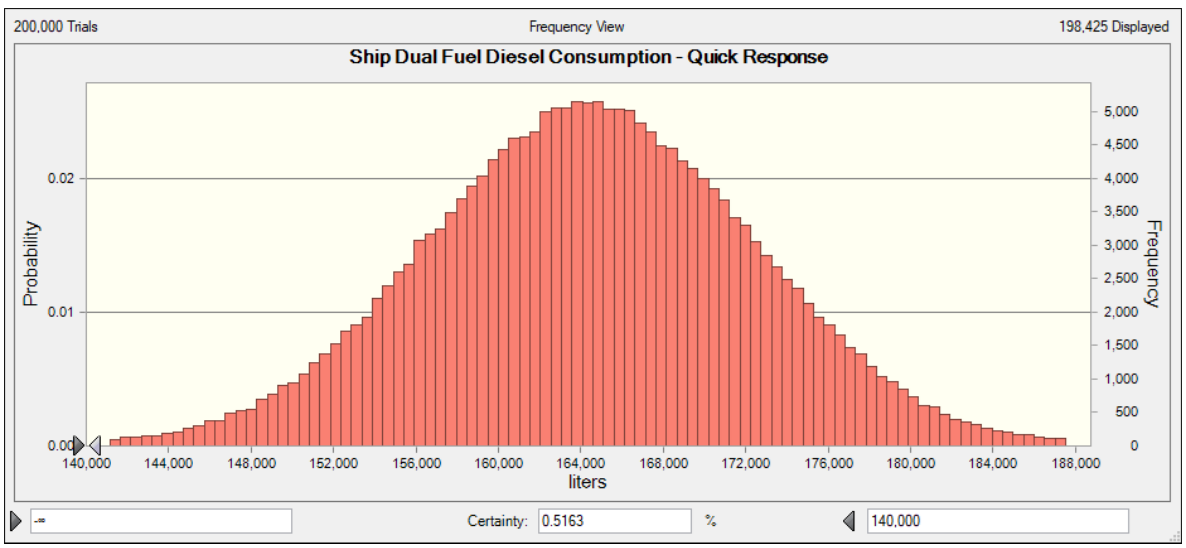

Figure 8. Diesel consumption during a quick response mission (dual fuel).

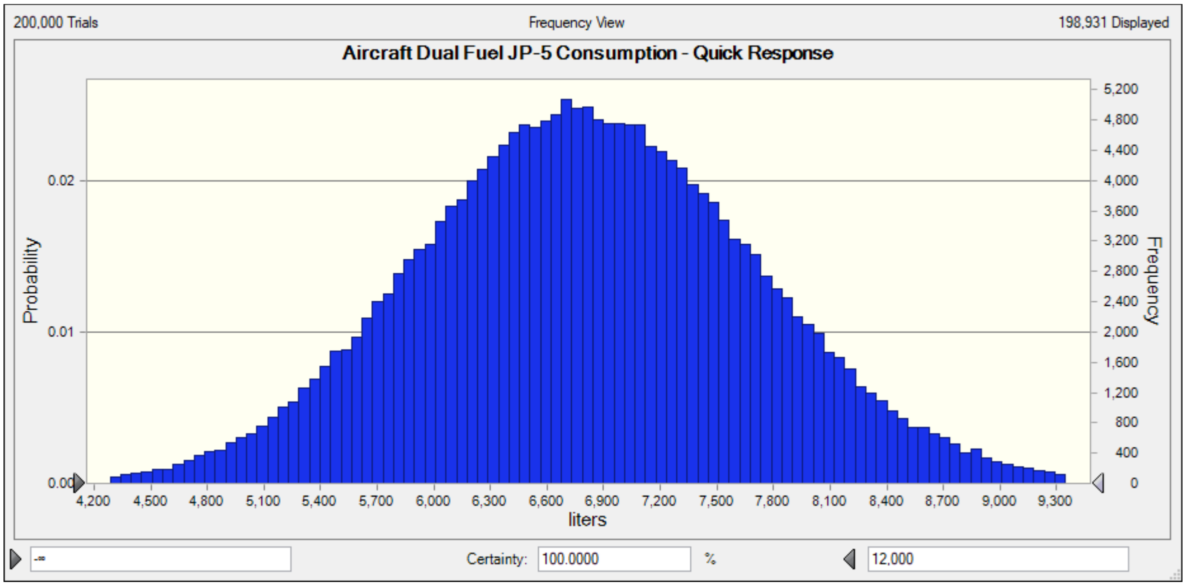

Figure 9. JP-5 consumption during quick response mission (status quo).

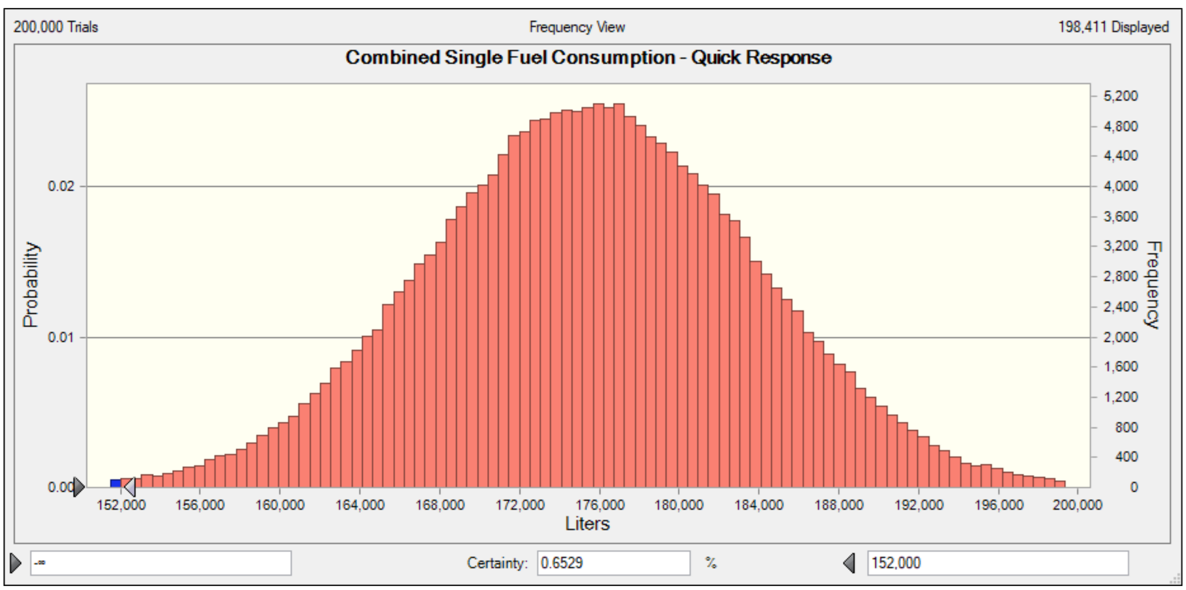

Figure 10. JP-5 consumption during a quick response mission (SFC).

The mission risk associated with the different approaches was so elevated that it became evident that a seven-day quick response mission was not reasonable with these naval assets. As explained before, quick response missions are not required to last seven days. They are actually expected to last less than a standard patrol mission due to their higher fuel consumption rate. Thus, we needed to adapt the model (Figure 11) to establish a reasonable mission length for quick response missions. Then, we could evaluate if adopting the SFC impacts Brazilian Navy in this specific scenario.

1. Mission Length

Since our new question relies on the reasonable mission length, we created new output data to forecast the length of the simulated missions. The new parameter is defined in accordance with the following:

L_D = length of mission (in days) determined by the average 7-day diesel fuel consumption for the status quo (dual fuel approach)

$L_D = C_D / (\sum_{i=1}^{7}(D_i)/7)$

L_C = length of mission (in days) determined by the average 7-day JP-5 combined fuel consumption after SFC adoption

$L_C = C_C / [(\sum_{i=1}^{7}(D_i)/7 \text{ X E}) + (\sum_{i=1}^{7}(J_i)/7)]$

Quick Response Mission

Diesel (Ship) & JP-5 (Aircraft) Status Quo

SHIP (Diesel)			AIRCRAFT (JP-5)			
Day (i)	**D_i**		**Day (i)**	**J_h**	**h**	**J_i**
1	23,872		1	180.372	6.7	1,211
2	23,443		2	164.25	6.3	1,042
3	23,325		3	176.404	5	877
4	24,901		4	177.43	8	1,424
5	21,720		5	132.039	6.1	800
6	21,820		6	166.436	8.9	1,474
7	23,149		7	173.088	4	696
8			8			
		L_D				
D_T	162,229	6.04			**J_T**	7,525

Capacity (40%)

- **Diesel (C_D)** 140,000 liters
- **JP-5 (C_J)** 12,000 liters
- **Combined (C_C)** 152,000 liters

JP-5 Only (Ship & Aircraft) Single Fuel Concept

JP-5 Efficiency Loss Factor (E) 1.026

		L_C
Ts	173,972	6.12

Figure 11. Length of the operation model.

Figure 12 demonstrates the probability distribution of the maximum length of a quick response mission (in days) under the dual fuel approach. We selected the 87.1% mission success probability depicted on the standard mission under dual fuel (Figure 5) as the threshold to calculate the reasonable quick response mission length. Using this parameter, we identified that 5.65 days is a reasonable mission length according to the status quo risk tolerance concurrent to our model development.

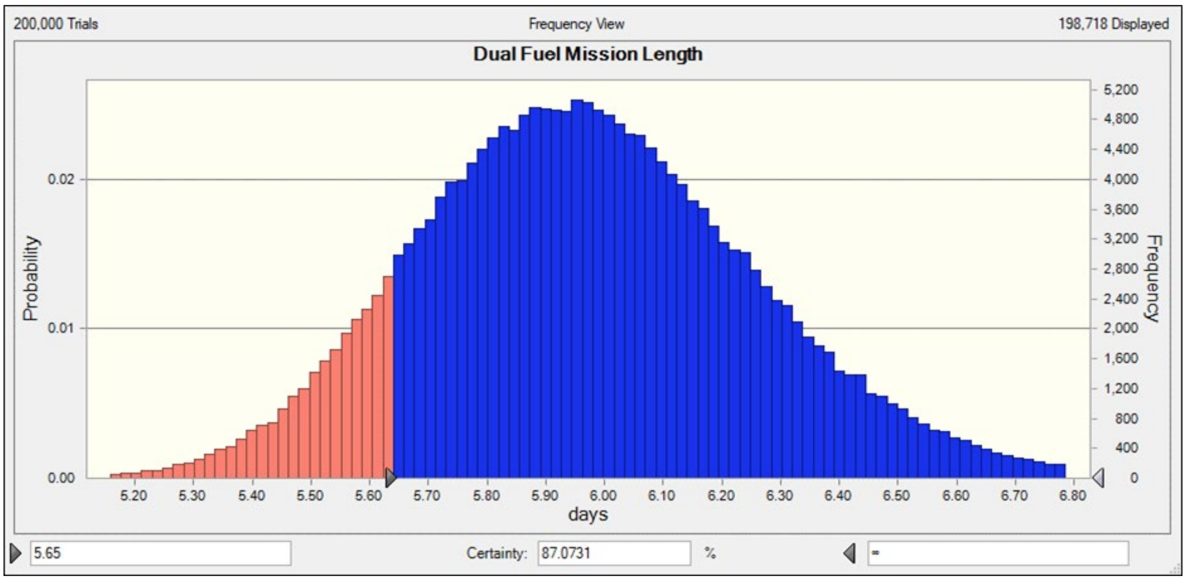

Figure 12. Length of the operation for a quick response mission (status quo – dual fuel).

Then, we adjusted the equations to get the corresponding values of D_T and J_T:

Equations

$$D_T = \sum_{i=1}^{5}(D_i) + (0.65 \times D_6) \quad (1)$$

$$J_T = \sum_{i=1}^{5}(J_i) + (0.65 \times J_6) \quad (2)$$

2. Diesel & JP-5 Status Quo

Figures 13 and 14 represent the simulated quick response missions' output considering the dual fuel policy. Once more, results demonstrate that diesel is more restrictive than JP-5 for this ship-aircraft. Therefore, we selected Figure 13 to represent the probability of success for a quick response mission using the dual fuel policy. The threshold that separates the areas representing the probability of mission risk and success in the chart is 140,000 liters (C_D). Under this parameter, the simulation demonstrates an 85% chance that the naval patrol ship will not need replenishment before accomplishing a 5.65-day quick response mission.

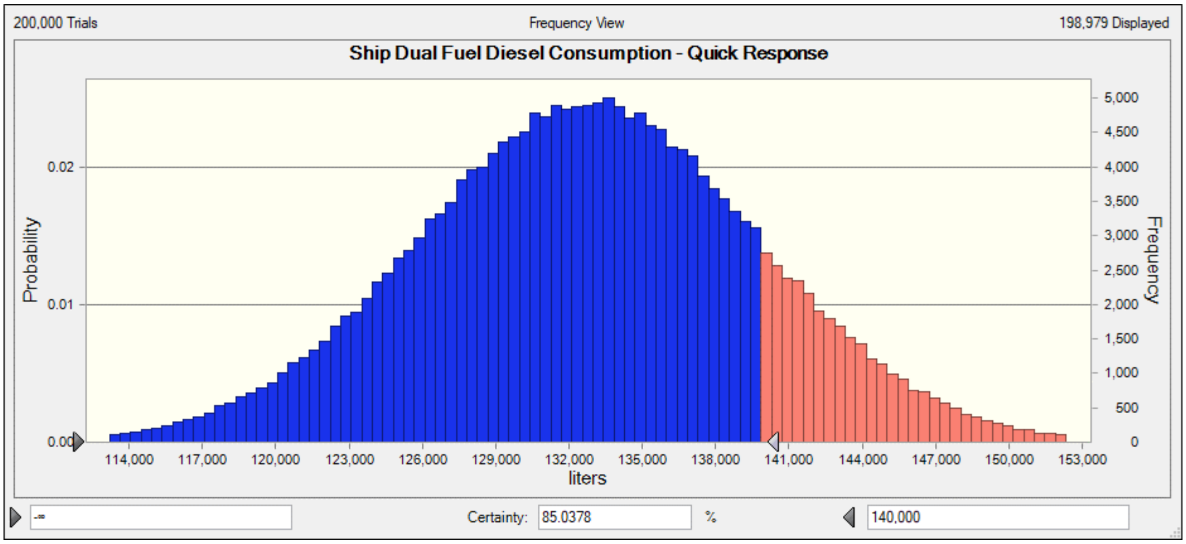

Figure 13. Diesel consumption during a 5.65-day quick response mission (status quo).

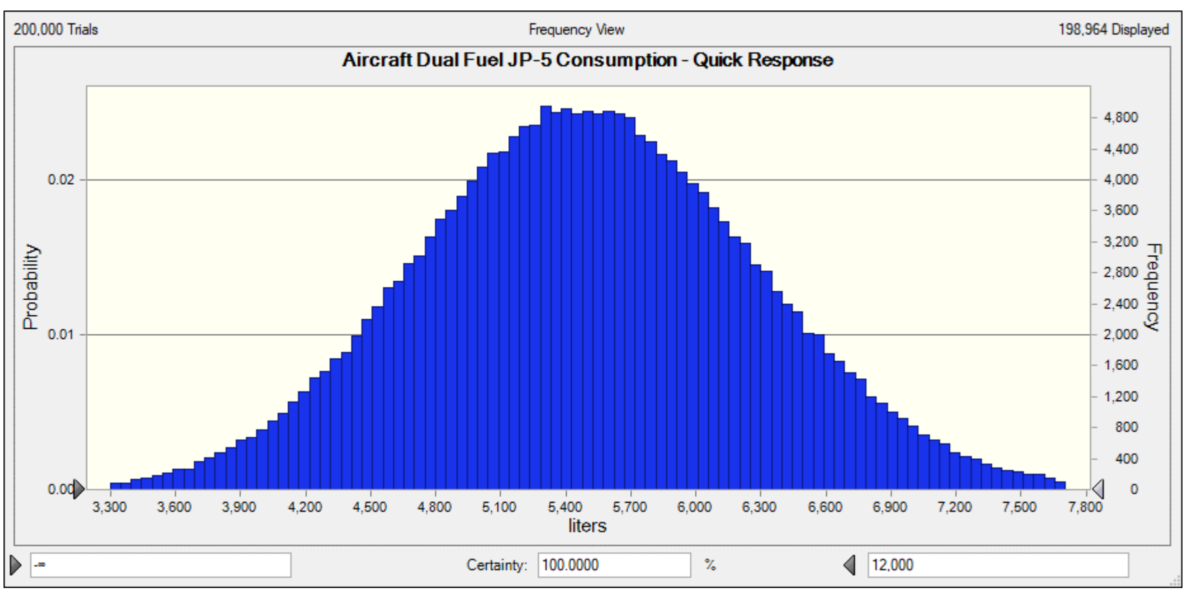

Figure 14. JP-5 aircraft consumption during a 5.65-day quick response mission (status quo).

3. Single Fuel Concept

Figure 15 depicts the results regarding the quick response mission under the SFC policy. Considering the 152,000 liters combined fuel tank capacity (C_C), the chart indicates the probability that ship and aircraft will accomplish their mission before needing fuel resupply is 92.6%.

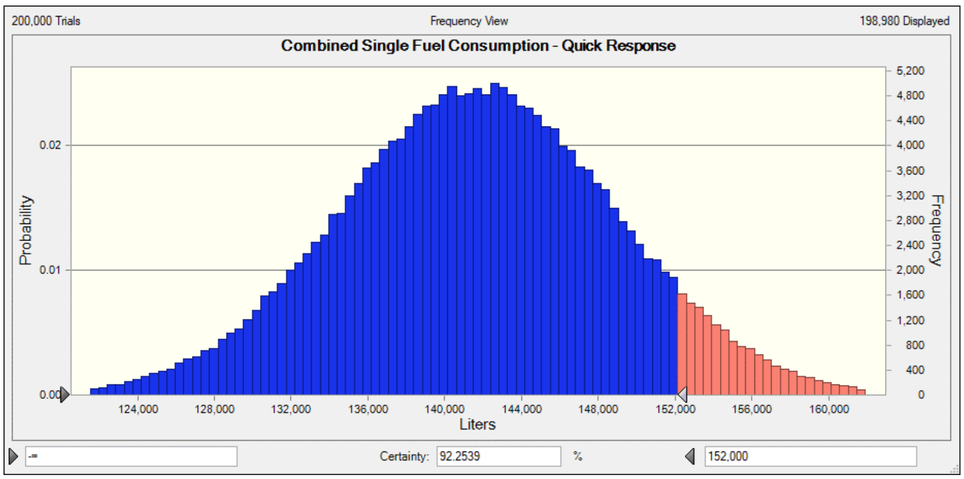

Figure 15. JP-5 combined consumption during a 5.65-day quick response mission (SFC).

4. Status Quo vs. Single Fuel Concept

Finally, the comparison of the outcomes described in Figures 13 and 15 demonstrates that SFC adoption considerably reduced mission risk even in quick response missions. The 15% mission risk measured in the dual fuel approach diminished to 7.8% due to the SFC implementation. Accordingly, the probability of mission success increases by 7.2%, representing a noteworthy improvement in the Brazilian Navy's capability to intercept threats and apply suitable measures within the Brazilian jurisdictional area.

C. FUEL PRICE HISTORY

A price comparison between diesel and JP-5 is another critical factor that can affect the decision of which fuel policy is more favorable to the Brazilian Navy. Figure 16 displays the historical fuel prices from 2012 to 2022. JP-5 prices are stable and reflect the one-time purchase for a long period that allows refineries to produce a unique aviation kerosene used in the Brazilian Navy ships. In contrast, diesel prices fluctuate, slightly increasing during the first nine years. However, the prices skyrocketed in 2021 and surpassed the flat JP-5 monetary values. In this case, the effects of a lower JP-5 price can overcome the efficiency loss effect that causes the ship to burn more fuel, making JP-5 even more interesting when compared to diesel. Then, these changes in the relative prices impact the total operational cost depending on the fuel policy.

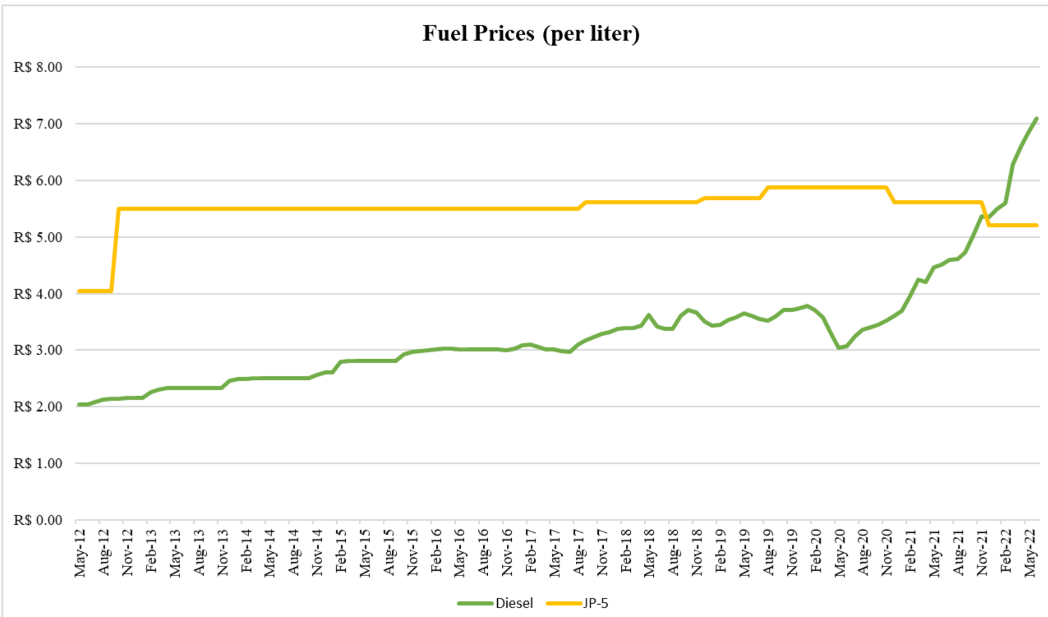

Figure 16. Diesel and JP-5 Brazilian Navy purchase price history. Source: Brazilian Navy's Supply Systems Command (2022).

The variations in the fuel relative prices show that there are times during which JP-5 would cause dramatic expenditure savings in the case of SFC adoption. Figure 16 depicts that the lower diesel price is not an immutable fact. The mere possibility that JP-5 can become consistently cheaper than diesel increases the relevance of this study. Therefore, besides reducing the operational risk, the SFC can also represent critical cost savings, enhancing BN's effectiveness in protecting the Blue Amazon.

VII. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

This thesis aimed to investigate the SFC adoption's potential impacts on the Blue Amazon protection in Brazilian Navy naval patrol operations. After applying the Monte Carlo simulation methodology in different contexts, we observed a substantial decrease in the mission risk from the status quo dual fuel to the single fuel policy. As with pooling problems, the variance of each fuel consumption contributes to early fuel depletion. Hence, the employment of the SFC provides higher chances of enduring the planned time at sea before replenishment. Consequently, implementing the SFC would enhance the Brazilian Navy patrolling power over the Blue Amazon, preventing the occurrence of illegal activities within the Brazilian jurisdictional maritime area. This improvement translates into better oceanic wealth protection by reaching criminals sooner to catch them in action and realizing a greater number of interrogations, inspections, and interventions.

Other studies demonstrate that the SFC simplifies the supply system through ease of handling, reduced possibility of cross-contamination with another fuel type, improved inventory rotation, reduced transportation risks, improved fuel supply chain resiliency, and increased flexibility and availability of weapon systems. Our analysis, in turn, proved that the SFC at sea can also improve the effectiveness of Brazilian Navy operations, even considering small particles, such as the naval patrol ship-aircraft duo, in ordinary and extreme situations, increasing the chances of accomplishing its missions.

B. RECOMMENDATIONS

Although multiple studies address the implementation of the SFC at sea by the U.S. Navy, several areas require research specifically focused on the opportunities, obstacles, and trends in the Brazilian context. Therefore, we recommend further investigation on the following topics to better support the Brazilian Navy authorities in deciding on the SFC adoption.

1. Financial Analysis

The recent rise in diesel prices prompts the exploration of alternatives to this fuel type. Future financial analysis can explore the behavior of JP-5 and diesel prices as an argument for the decision of whether or not to adopt the SFC. If diesel remains much more expensive than aviation kerosene, the option for the single fuel could cause significant cost savings for the Brazilian Navy in terms of operating expenses.

2. Logistical Implications

The transition to the SFC entails a series of logistical implications that motivates additional research. For instance, the vertiginous increase in JP-5 demand by the Brazilian Navy ships requires a profound study of the production capacity of the domestic refineries. Furthermore, the augmented amount of fuel purchased potentially causes a drop in price that could aggregate critical justification towards the SFC. Another discussion arises from the transportation perspective as a greater demand for JP-5 with specific chemical composition necessitates meeting certain shipment requirements. Those changes should be identified to evaluate their possible impacts on cost, time, and procedures. Finally, one could investigate the logistical benefits a single product generates regarding the simplification and specialization of the fuel supply chain.

3. Technical Issues

Previous research holds enough evidence supporting the technical feasibility of using JP-5 to power an extensive range of marine engines, mostly U.S. Navy vessels' engines. These studies demonstrated no significant maintainability harm but, rather, some improvements when shifting from diesel to JP-5 in some cases. However, a few manufacturers explicitly mentioned that mechanical adjustments would be necessary for their machines to operate satisfactorily with kerosene. Therefore, we recommend further investigation into the technical feasibility, maintainability, and power efficiency of using JP-5 in Brazilian Navy vessels' engines.

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