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Optimizing Operational Efficiency of the Vaquita USV

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Abstract: MITRE's Vaquita is an unmanned surface vessel that offers a potential solution to the problem of resupply in the South China Sea during a conflict. Our project aims to develop a tool that will enable MITRE to optimize the on-site manufacturing and operational deployment of the Vaquita, factoring in potential losses of Vaquitas during resupply missions. Our interactive tool will be based on the results of our simulation models.

Keywords: Unmanned Surface Vehicle, Last Mile Logistics, Discrete Event Simulation

1. Introduction

The South China Sea emerged as a critical point of contention over the past decade, with China's expansive claims and assertive actions creating tensions with neighboring nations and the United States. The United States has shifted its policies and military focus toward preparing for a potential conflict in this region, particularly against a near-peer adversary like China. A significant challenge in such a conflict is ensuring logistics and resupply for forward-deployed forces. Conventional resupply methods face significant risks due to China's advanced military capabilities, including anti-access/area denial systems.

To address these challenges, new methods of resupply must be developed, and unmanned surface vessels (USVs) present a promising solution. This paper focuses on the Vaquita, an unmanned surface vessel designed by our project partners, the MITRE Corporation, to solve logistical challenges in contested environments like the South China Sea. The Vaquita offers a low-risk, low signature, and scalable resupply option. The U.S. Navy has highlighted the importance of unmanned technologies in its Department of Navy Unmanned Campaign Framework, emphasizing the need for systems that provide "lethal, scalable, and survivable effects" (Harker, M., & Berger, 2021). Our research goal is to develop a model to evaluate when the Vaquita is the optimal choice for resupply. Our analysis is based on a scenario in the South China Sea, given to us by MITRE, which focuses on resupplying EABs (Expeditionary Advanced Bases). We used Simio, a discrete event simulation platform (Pegden & Sturrock, 2010), to model the effectiveness of the Vaquita.

The remainder of this paper includes our literature review in Section 2, which discusses similar capstones and how our project expands on their research. We discuss the scenario and data our Simio simulation is based on in Section 3 and the simulation model and results from our simulation analysis in Section 5. The Simio model provides simulated estimates on the time it takes to manufacture, ship, and deploy the Vaquita under a variety of operating conditions including losses during a resupply mission. Finally, in Section 7 we discuss operational insights arising from our analysis regarding the deployment of the Vaquita in contested waters.

2. Literature Review

The increasing focus on supply logistics in the Indo-Pacific (INDOPACOM) region has led to a plethora of research addressing this challenge. We found several studies that used simulation modeling to optimize production and deployment in the military logistics domain. This problem was approached several ways by researchers, but all had a common theme: does this method of operating utilize our resources efficiently? Most of the projects that we encountered were conducted by military researchers, such as at the Naval Postgraduate School (Sim, 2020; Law, 2022) or for previous US Naval Academy Capstones

(Dickstein, Oliver, & Ghali, 2024; Lim, Reasbeck, & Wagner, 2024; Lusby, Morales, Quo, & Sanchez, 2023). Most of the projects focus on analyzing the sensitivity of vehicle performance with respect to different parameters in a simulation model. These projects demonstrate the necessity for continued research connecting vehicular production with military operations in a contested environment.

The 2024 MITRE team produced an Excel decision tool that allows the user to input different variables and receive an optimized deployment schedule for the Hopper Unmanned Aerial Vehicle (UAV)(Lim et al., 2024). This group's tool tells the user "when it makes sense" to deploy the Hopper UAV. We would like to use Simio to model scenarios in a contested Indo-Pacific and conduct analysis to provide recommendations for the manufacturing process and operational strategies. Our project adds to the research done before us by creating a method to gauge the effectiveness of a new vehicle, MITRE's Vaquita, that could be used in a future conflict. It also accounts for lost vehicles along the resupply process which has not been researched before.

3. Centralian Sea Vignettes

Our model is based on a scenario in which United States' Expeditionary Advanced Bases (EABs) are located on several different islands in the "Centralian Sea", representing the Indo-Pacific theater of operations. The EABs must be resupplied from an island in a partner country. The scenario is composed of four different vignettes representing different phases of conflict: shape, deter, seize, dominate. Each phase of conflict changes the supply requirements, the distance from the point of origin to the destination, and the risk of detection of resupply platforms. The supply requirements and distances are listed in Table 1. The rate of detection is accounted for in the Vaquita "survivability" parameters (see Section 4). The survivability for each vignette decreases by 5% (in every sea state) as tensions grow with each phase of conflict and enemy forces are more likely to interdict the Vaquita.

In the shape stage of conflict, the focus is on maintaining access to the operational area, which means that the required supplies are mostly items needed to survive (Class 1: food and water, and Class 4: construction materials) and travel (Class 3: fuel). In the deter phase of conflict, the focus is on showing a strong presence in the operational area to prevent any conflict. This shifts some of the supply requirements to include materials that could indicate creating a stockpile of weapons (Class 9: repair parts and components). The seize phase of conflict represents the start of full-scale conflict. In this phase of conflict, the demand shifts to more fuel to support more vehicles, ammunition that soldiers would need (Class 5), and medical supplies for those injured in combat (Class 8). The domination phase of conflict is the continued growth of full-scale conflict and the end of the conflict. Since this is only a growth of conflict, we only see increases in the supply requirements from Vignette 3 for fuel and ammunition.

Table 1: Supply Requirements (lbs) and Distance to EAB (NM)

Vignette	Class 1	Class 3	Class 4	Class 5	Class 8	Class 9	Distance
1 - Shape	48	150	300	0	0	0	100
2 - Deter	48	200	0	0	0	50	75
3 - Seize	48	250	0	90	75	0	75
4 - Dominate	48	500	0	100	75	0	100

4. Vaquita Properties and Operations

The Vaquita parameter values used in our model are based on professional estimates from MITRE's Vaquita team. Some of the parameters are constant and others vary according to the stage of conflict and sea state. Table 2 provides the speed of the Vaquita, as well as its volume and weight transport capacities. The speed is variable due to the changing sea state as shown in Table 4. Using common weights and volumes of each supply type, we determined how many units of each class of supplies one Vaquita can transport. These values are provided in Table 3.

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Table 2: Vaquita Attributes

Characteristic	Value	Stochastic model	Varies with Sea State
Speed	1-8 knots	Uniform distribution	Yes
Size	3.5 m^3	Fixed	No
Capacity	500 lbs	Fixed	No

Table 3: Supply Capacity for each Vaquita

Supply	Description	Vaquita Capacity	Loading (min)	Unloading (min)
Class 1	Subsistence	200 units	30	45
Class 3	Petroleum, Oils, and Lubricants	80 units	60	75
Class 4	Construction Materials	50 units	45	60
Class 5	Ammunition	400 units	30	45
Class 8	Medical Materials	100 units	30	45
Class 9	Repair Parts and Components	75 units	25	35

The survivability of the Vaquita is based on estimated sea state conditions and detection levels. Our project partners, MITRE, gave us rough estimates based on the Vaquita's projected capabilities shown in Table 4. The values in Table 4 refer specifically to vignette one, shape. Survivability decreases by 5% in every successive phase of conflict (in every sea state). As the Vaquita has not yet been manufactured or tested, our current goal is to develop a model that can be refined with real-world sea state survivability and interdiction data once production and testing are completed.

Table 4: Speed and Survivability

Sea State	Speed	Survivability
1	5-8 knots	.65
2	4-7 knots	.60
3	3-5 knots	.50
4	2.5-4 knots	.30
5	1-3 knots	0

All of the Vaquitas are manufactured in a partner country and assembled near the launch point. The production of a complete Vaquita requires three key components that can be processed simultaneously: the hull, the motor, and the batteries. The hull is produced through blow-molding, the motor is 3D printed, and the batteries are charged. We assume that the total assembly time for one Vaquita is determined by the maximum time required for any of these three processes. We assume that blow-molding the hulls takes about five minutes and the 3D printing and battery charging process takes 24 hours to complete.

After the individual Vaquitas are manufactured, they are loaded with supplies at the launch point. We assume an amphibious beach landing and that 10% percentage of Vaquitas are dismantled for parts and do not return. Before the Vaquita returns, it must be charged with solar panels. It takes a singular battery between 3 and 5 days, depending on weather conditions, to be fully charged. We assume that EAB personnel will relaunch the Vaquita for a return journey as soon as charging is complete. The same risk factors apply on the return journey as the initial transit to the EAB.

5. Simulation Model

To model each of the vignettes, we used Simio, a discrete event simulation software. Figure 1 provides a flow chart of the model. Before describing the simulation, we discuss two key aspects of the model: sea state and supply loading. Sea states are represented by a Markov Chain with states of 1, 2, 3, 4, and 5; 1 being the most calm and 5 the most rough seas. The sea state is updated with a pre-set transition probability matrix, and the time between transitions is normally distributed with a mean of three hours and standard deviation of 0.5 hours. Sea state affects both the speed and survivability of the Vaquita.

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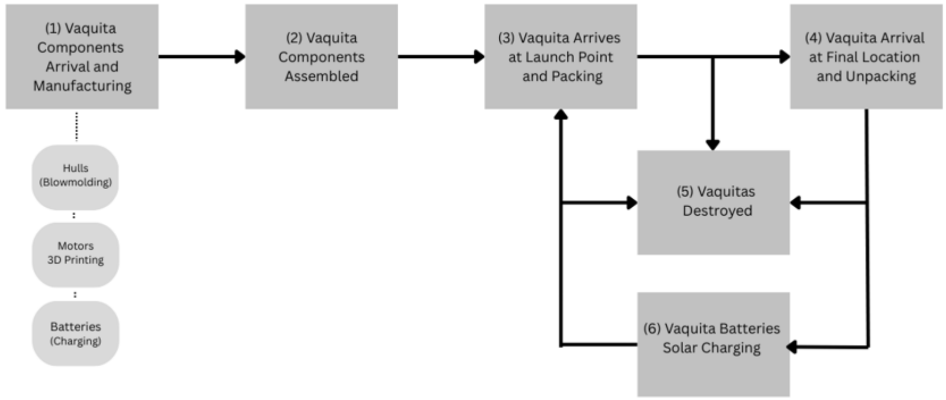

Figure 1: Simio Model Flow Chart

The selection process to determine the class of supply assigned to a given Vaquita is governed by a cumulative distribution function (CDF) constructed from the relative demand and capacity associated with each supply class. This CDF is designed to promote a balanced long-term distribution of supply classes among Vaquitas, proportionally reflecting the demand across those classes. To construct the CDF, we first define a scaling factor for each class i:

$$\rho_i = \frac{\text{Demand}_i}{\text{Units per Vaquita}_i}. \tag{1}$$

This value represents the normalized demand for class i, accounting for how much of that supply a single Vaquita can transport. The probability that a Vaquita is assigned to class i is then calculated as:

$$P(\text{Class } i) = \frac{\rho_i}{\sum_{k \in C} \rho_k}, \tag{2}$$

where C represents the set of supply classes. These probabilities form the basis of a CDF, which is subsequently used to randomly assign supply classes to Vaquitas. By generating a uniform random number and mapping it through this CDF, each Vaquita is probabilistically matched to a class of supply. Over a large number of assignments, this method yields a distribution of supply classes that is proportional to demand relative to transport capacity.

We turn our attention to the model flow chart in Figure 1. The model tracks the delivery and destruction of supplies, providing real-time metrics on Vaquita effectiveness. The simulation begins at cell (1) with the manufacturing stage. The components combine into a fully assembled Vaquita in cell (2). After assembly, the Vaquitas are transported to the launch location in cell (3), where no transit time is assumed between manufacturing and launch. At the launch location, each Vaquita is assigned a class of supply based on the picking mechanism explained above.

The time it takes for the Vaquita to load a Vaquita is fixed and dependent on the class of supply being sent as shown in Table 3. After being loaded with supplies, each Vaquita begins its journey toward the delivery location at a speed that is chosen based on a uniform distribution of the range of speeds in Table 4. Each Vaquita either completes the journey to the EAB or is "destroyed", which means that it either malfunctions and sinks, or is intercepted. Once at cell (4), the Vaquita is unloaded. The time it takes for the Vaquita to unload a Vaquita is fixed and dependent on the class of supply being sent as shown in Table 3.

After the supplies are delivered, there are two courses the Vaquita can undertake. The probability that a Vaquita is dismantled is 10% which means that it would not be used again to deliver supplies. The rest of the Vaquitas are stationed to solar charge at cell (6). Solar recharging at cell (6) prepares the Vaquitas for relaunching, with a recharge time determined by a uniform distribution. Once recharged, the Vaquitas return to the launch location under the same conditions as the initial journey. If the Vaquita returns safely to cell (3), it is reloaded and sent out again. Vaquitas are continually reloaded, recharged, and relaunched until they are destroyed or dismantled. All Vaquitas that are lost either during transit or due to being dismantled by the EAB enter cell (5).

6. Computational Analysis

Initially, we focused exclusively on the manufacturing process, with the goal of identifying the production levels of each component that will lead to a given Vaquita daily production level. Next, we focused on operations, with the goal of

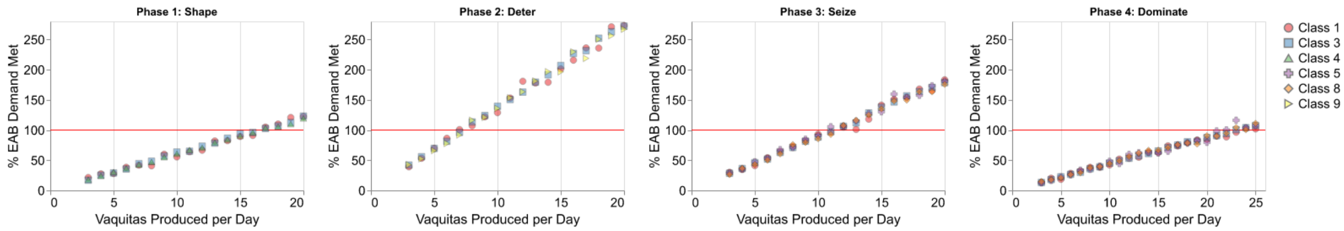

Figure 2: Percentage of cumulative demand met across the entire time horizon as a function of Vaquita daily production rates.

determining the number of Vaquitas that must be produced each day in order to fully supply the EAB during each level of combat. We implemented our model using the Simio Discrete Event Simulation Software.

The manufacturing section of the model does not change per vignette, so this analysis applies across all warfare levels. In a real situation the push/pull factors of wartime production would dictate the variability of manufacturing, but for simplification we assumed consistent parameters. In order to identify an ideal range of component production, we created reference properties in order to change the assembly time of our Vaquitas. In order to further our analysis, we created a reference property to analyze the effects of assembly time on production rate. This allowed us to confirm that assembly time can range up to the maximum time to complete one Vaquita component before impacting the overall rate of production. It is important to model both processes in the same simulation in order to capture the effect of the limiting factor on the vessels' operations.

For stage two of our analysis, we replaced the manufacturing phase of our model with a daily Vaquita production rate. This allowed us to analyze the simulation based on the number of Vaquitas being made every day. We analyzed each of the four vignettes for different levels of Vaquita production ranging from 3 to 26 Vaquitas made per day. For every vignette and level of production, we ran 100 iterations of the simulation and kept track of the quantity of each class of supply that the EAB received each day. We used these graphs to determine the minimal daily production rate needed to reach a weekly average sustainment rate of 100% for all classes of supply in the vignette shown in Table 5 From Phase 1 to Phase 2, we see a decrease of 17 vaquitas in Phase 1 to 8 vaquitas in Phase 2 because there is no more demand for Class 3 supply and minimal demand for Class 9. Furthermore, we see an increase of 13 vaquitas in Phase 4 to 25 vaquitas in Phase 4 correlating to the increase in demand of Class 3 and Class 5 supplies. Even though Phase 3 requires one more class of supply compared to Phase 1, it makes sense that we need more Vaquitas for Phase 1 because it requires a large amount of Class 4 supply and a Vaquita can only take 50 units of Class 4.

Table 5: Minimum Daily Production Rates Required per Phase of Warfare

	Phase 1	Phase 2	Phase 3	Phase 4
Daily Production Rate	17	8	13	25

After determining the minimum daily production necessary to achieve a sustainment rate of 100% over a week, we wanted to understand the needs of the EAB on a day by day basis. Using the minimum daily production to achieve 100% in each vignette, we generated a 15 day calendar for three production rates per phase of warfare. We assumed constant daily demand for each class of supply. Across all vignettes it is clear that although a weekly percentage of 100% sustainment can be met, there are individual days where supplies dwindle to the point of demand starvation (there are less supplies on hand than required for that day). This demonstrates the importance of setting a production rate that satisfies demand on a daily basis.

These calendars display the daily excess or deficit for each class of supply at the delivery node throughout the simulation period. The excess for class i on day t is computed using the following equation:

$$\text{Excess}_{i,t} = \frac{\text{Cumulative Deliveries}_{i,t} - (\text{Daily Demand}_i \cdot t)}{\text{Daily Demand}_i}, \tag{3}$$

where Cumulative Deliveries$_{i,t}$ represents the average quantity of supply class i delivered to the node by day t, averaged over 100 independent simulation iterations. This metric normalizes the delivery balance relative to demand, providing a unitless measure of surplus or shortage over time.

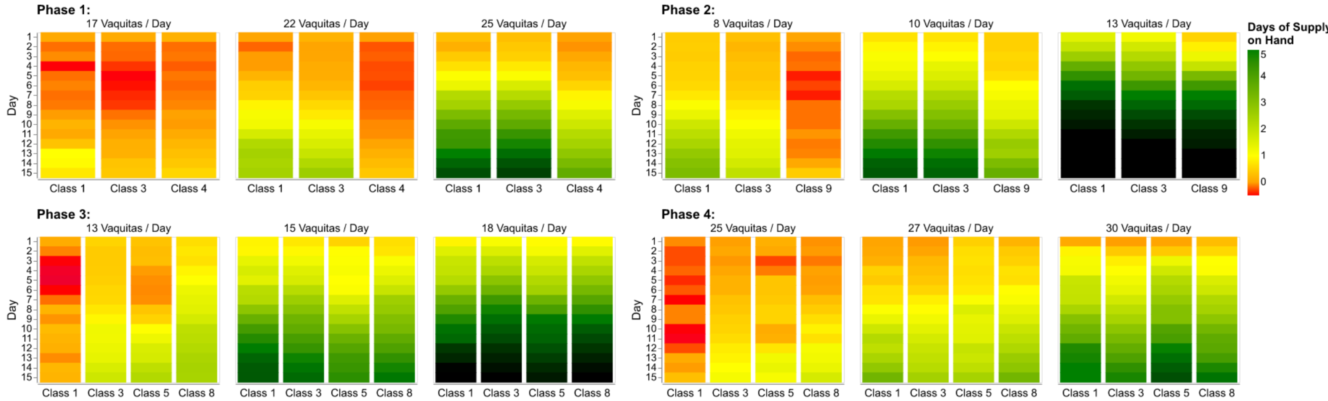

Figure 3: Daily EAB supply levels by vignette and Vaquita daily production levels.

7. Conclusion

The MITRE Corporation's Vaquita USV has the potential to meet the demand needs of forward deployed forces during a conflict in the South China Sea. One of the primary features of the Vaquita is that it is less expensive than traditional manned platforms, which means that it is also more expendable, or "attritable". Thus, any model of the employment of Vaquitas for Indo-Pacific logistics must incorporate the reality that a certain percentage of Vaquitas will be lost, and therefore need to be replaced, to carry out future resupply.

We addressed this requirement by developing a simulation model to perform analysis on the two primary stages of Vaquita deployment: manufacturing and operations. First we performed analysis to determine the level of production of each component that would be required to meet a given daily Vaquita production rate. This information would be used to determine the requirements at the Vaquita's manufacture and deployment location. Next, we isolated the operational model to determine the number of USVs that would need to be produced daily to fully supply an EAB unit, assuming that some of the Vaquitas are lost or repurposed, while others are recharged and reused. Our model can be used, with modified parameters, to help the MITRE Corporation and the U.S. Military understand the operational capabilities of the Vaquita and similar attritable USVs.

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