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Leveraging Autonomous Aerial Vehicles for Intra-Theater Logistical Support

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Abstract: In a conflict with a peer adversary, traditional logistics platforms would be unable to effectively resupply a modern stand-in force. The purpose of our research is to explore the benefits of Autonomous Aerial Vehicles (AAVs) for intra-theater logistics. We apply a linear integer program to minimize missed demand while keeping the risk to personnel within a specified bound. We demonstrate the functionality of our model in the context of a 14-day vignette in the Indo-Pacific.

Keywords: Intra-theater Logistics, Autonomous Aerial Vehicles, Multi-Objective Optimization, Mixed-Integer Programming

1. Introduction

In a high-end conflict, traditional logistics vehicles may be insufficient to sustain a forward deployed force when heightened aggression increases the risk to platforms and personnel. For the military to employ a survivable force, the Joint Chiefs of Staff Logistics Directorate (JCS J4) requires an evaluation of multi-capable platforms that enable resilient logistics. The employment of Autonomous Aerial Vehicles (AAVs) for intra-theater logistical support allows for a more distributed force to operate effectively while managing risk to personnel.

Intra-theater logistics refers to the movement of resources within an area of operation. Supplies arriving at a point of debarkation must be transported to a tactical distribution point for use by forward-deployed forces. Our research concentrates on operations by the United States (US) Indo-Pacific Command (INDOPACOM). INDOPACOM is one of six geographical unified combatant commands. It encompasses all Army, Air Force, and Naval assets in the Asia-Pacific region. This region is particularly complex due to a peer adversary vying for control of the many islands in the South China Sea, creating a uniquely hostile environment for our armed forces. The lack of significant infrastructure and the nature of maritime operations increase the vulnerability of supply chains that are dependent on manned vehicles. AAVs may be a low-cost, highly resilient alternative to reduce the risk of supplying a stand-in force versus employing traditional logistics platforms. We explore the concept of risk in the interest of reducing casualties, knowing that military planners must always consider the trade-off between mission success and the number of casualties. Unlike civilian industries, mission success in the military is often paid for with human lives.

Our goal is to explore the benefits of using AAVs in contested intra-theater logistics. To this end, we developed a mixed-integer linear optimization model that schedules a fleet of autonomous and traditional vehicles to provide material resupply and casualty evacuation (CASEVAC) for a stand-in force over a multi-day time horizon. Our model incorporates vehicle capacities (medical and material), range, crew size, and probability of interdiction, while balancing the competing objectives of minimizing missed demand and minimizing risk to personnel. We apply our model to a 14-day vignette then use model results to address the following questions: (1) Does the addition of AAVs increase the sustainment of forward deployed forces when risk to personnel is a concern? (2) What is the optimal mix of AAVs to traditional logistics platforms in a given scenario?

We contextualize our work within the existing literature in Section 2. In Section 3, we describe the data required by our model in the context of a 14-day vignette involving the resupply of a Marine Littoral Regiment in the South China Sea. We define our model in Section 4, and present and interpret the results of the model in Section 5. In Section 6, we discuss the benefits and limitations of our model, as well as potential model extensions.

2. Literature Review

Preparing for a conflict with a peer adversary is a pressing concern for the US military. Many recent Department of Defense studies focus on the logistics of supporting forward deployed forces in the South China Sea. On the other hand, large delivery companies such as Amazon and FedEx have been studying unmanned aerial vehicles (UAVs) for their use in last-mile delivery: the transportation of a package from a fulfillment center to its final destination. Although civilian UAVs and military AAVs differ, the ideas for implementing them for logistics are similar. However, there is a notable gap in the literature linking research in last-mile delivery via UAVs to the implementation of military AAVs in intra-theater logistics.

In recent years, JCS J4 has requested the examination of alternative logistics platforms. As a result, several US Naval Academy capstone projects have focused on this topic. Dykman, Howell, Rodriguez, and Thompson (2022) simulated the deployment of Offshore Support Vessels (OSVs) to service units in a contested environment. Their model scheduled OSVs at different times and their output analyzed the utilization of OSVs while evaluating a missed supply requirement. The disadvantages of the OSVs, mainly cost, visibility, and irreplaceability, made them unviable. Lusby, Morales, Quo, and Sanchez (2023) simulated the use of Low Profile Vessels (LPVs) for resupplying forward deployed forces in a scenario in the South China Sea. Their objective was to determine the number of LPVs necessary to meet demand while decreasing risk; a "days missed calendar" provided a measure of success. Compared to OSVs, the increased stealth of the LPVs made them less risky; however, they were too inefficient in the delivery of supplies. Dickstein, Oliver, and Ghali (2024), the first to introduce unmanned options, simulated three scenarios: traditional platforms only, AAVs only, and a combination of traditional platform effort and AAVs. Results indicated that AAVs used in parallel with traditional platforms could enhance the military's ability to supply its forward operating bases. Our capstone is the first to apply optimization to model the use of AAVs.

We draw inspiration from many non-military applications that model the use of autonomous vehicles for "last-mile" logistics. Engesser, Rombaut, Vanhaverbeke, and Lebeau (2023) found that autonomous delivery solutions are increasingly suitable for last-mile urban logistics in a study on Autonomous Delivery Robots (ADRs), UAVs, and a two-tier method of pairing conventional vehicles with ADRs or UAVs. Chang, Choe, Mun, and San (2018) developed an optimal deployment schedule for a UAV delivery system, taking into account payload, distance, speed, and maximum flight time.

We contribute to existing UAV research by incorporating a unique military consideration: human casualties. Specifically, we develop an optimal deployment schedule of AAVs and traditional platforms to supply a stand-in force in a contested environment, balancing risk to personnel with minimizing missed demand. In addition to delivering supplies, our optimal schedule also includes casualty evacuations for marines who were killed in action (KIA) or suffered serious injuries.

3. Vignette and Input Data

We performed our analysis in the context of a vignette provided by our partners at JCS J4 to examine the potential benefits of using AAVs for material resupply and CASEVAC for the Marine Littoral Regiment (MLR) in the South China Sea. As defined by Marine Corps Force Design, the MLR is the US Marine Corps' new stand-in force: a self-deployable unit optimized to operate effectively with low signature, mobility, and relatively simple sustainment. The vignette requires supplies to be delivered from a distribution center located on Island 4 to the Marine Littoral Regiment operating on Island 2 (see Figure 1a). Forces from the People's Liberation Army are conducting a hostile landing on Island 1. Direct traffic between Islands 4 and 2 is at high risk of hostile fire, but the route from Island 4 to Island 3 is more protected. Staging supplies on Island 3 enables the use of shorter-range AAVs for the final delivery from Island 3 to Island 2. In addition, enemy strikes have left many marines in need of immediate evacuation. Meanwhile, daily rations and fuel resupply is required for 14 days of expected combat operations, along with ammunition and replacements for damaged weapon systems. If friendly forces located on Island 4 cannot provide the materials required, the MLR will need to retreat from the island.

The MLR must sustain a rate of fire of four Naval Strike Missiles per day. Furthermore, four of nine NMESIS launcher systems were damaged on the first day and each replacement weapon system must be prioritized. Fuel in our scenario refers to bulk petroleum used by vehicles, generally annotated as "Class III" supplies. The CASEVAC demand includes seven wounded marines who need immediate evacuation on day one, nine KIA who must be transported off the island no later than day four, and 11 marines with minor injuries that can be transported at any point during the remaining 10 days. Lastly, rations must be delivered every day and medical supplies are needed from day two to day seven. Figure 1b provides a summary of the 14-day support requirements.

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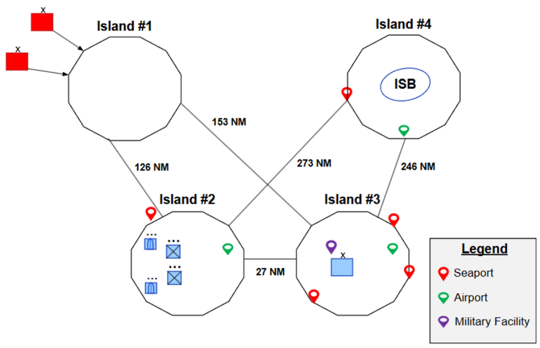

(a) Supplies on Island #4 must be delivered to MLR on Island #2.

Type	14-Day Requirement
Ammunition	61,732 lbs
Fuel	14,600 lbs
Rations/Medical	38,918 lbs
CASEVAC	27 marines

(b) Demand requirements over 14 days

Figure 1: Logistics vignette in the South China Sea

We consider the logistics problem on a network with nodes N (representing the islands) and edges $e = (i, j) \in E$, for some $i, j \in N$. We denote the set of supply, demand, and intermediate nodes as S, I, and J, respectively. Although the network in this vignette is quite simple ($N = \{2, 3, 4\},\ S = \{4\},\ I = \{3\},\ J = \{2\}$), the model is designed to accommodate more complex networks. We denote the set of days in the vignette by T and the set of demand types by Z. The index set $V := \{con, cas\}$ captures the two meta classes of demand types: con ("conventional": ammunition, fuel, and rations/medical) and cas (CASEVAC). For example, Z^{con} denotes the set of conventional demand types, which are measured in pounds.

The model parameters are defined in Table 1. The friendly forces on Island 4 have a mix of theoretical and currently employed logistics platforms, P. Each type of platform $p \in P$ is limited by its range, supply capacity, CASEVAC capacity, and the total number available on day $t \in T$. Only some platform types are equipped for CASEVAC missions. AAVs have a conventional supply capacity between 35 and 5,000 lbs; only the largest AAVs can transport at most one CASEVAC. Traditional logistics platforms have much larger capacities: the CH-53K King Stallion Helicopter, for instance, has a conventional supply capacity of 36,000 lbs or can carry 30 CASEVACs. The largest ships, like the Logistics Support Vessel, can carry an enormous 4,000,000 lbs of supplies. We assume that CASEVAC missions are time-critical and should not overlap with other missions. Therefore, for any given mission, a vehicle must be assigned to either CASEVAC or delivering conventional supplies. Finally, each platform/edge pair has an associated level of risk, and a cumulative level of risk is allowed for the vignette.

Table 1: Model parameters (†lbs for conventional supplies, marines for CASEVAC)

Parameter	Description	Units
$d_{z,j,t}$	demand of supply $z \in Z$ on island $j \in J$ on day $t \in T$	lbs or marines†
c_p^v	capacity for supply type $v \in V$ on platform $p \in P$	lbs or marines†
μ	CASEVAC priority factor	lbs/marine
E_p	set of edges within the range of platform $p \in P$	
$f_{p,t}$	number of platforms of type $p \in P$ available on day $t \in T$	
$r_{p,e}$	risk when $p \in P$ performs mission on $e \in E$	expected casualties
w	maximum cumulative risk	expected casualties

The idea to model risk originates from the idea of performing a cost-benefit analysis in the pursuit of a military objective. The difficult decision a leader makes is ultimately a judgment of the value of human life. The military uses the term "acceptable loss": a euphemism for the number of casualties that is considered to be tolerable to achieve a desired end state. This threshold varies according to the significance of a mission and the broader context of the engagement.

We quantify risk as the expected number of casualties on a given mission, so that we can include a constraint on acceptable loss directly. For each platform $p \in P$ and edge $e \in E$, we define $r_{p,e} := N_p(1 - e^{-\lambda_{e,p}})$, where N_p represents the crew size of p and $\lambda_{e,p}$ represents the expected number of destructive attacks on platform p while traversing edge e. According to the Poisson distribution, $1 - e^{\lambda_{e,p}}$ represents the probability of at least one destructive attack, and $r_{p,e}$ represents the expected number of lives lost, as required. We calculate $\lambda_{e,p} = P(A_p)P(D_p|A_p)R_eT_{e,p}$, where $P(A_p)$ represents the probability that p is detected and attacked within one hour of mission time (i.e., the level of stealth of p), $P(D_p|A_p)$ represents the probability that platform p is destroyed when attacked, and $T_{e,p}$ represents the mission duration in hours when p travels on edge e. R_e modifies the risk of detection and attack based on the level at which the enemy is present on edge e.

4. Mixed-Integer Linear Optimization Model

We present a mixed-integer linear program that selects and routes platforms to deliver supplies each day of the planning horizon to minimize the total amount of missed demand. Our model requires three classes of decision variables:

$x_{p,e,t,v}$:= number of platforms of type $p \in P$ deployed on edge $e \in E$ on day $t \in T$ with mission status $v \in V$;
$m_{z,e,t}$:= units of supply type $z \in Z$ delivered on edge $e \in E$ on day $t \in T$;
$\theta_{z,j,t}$:= units of supply type $z \in Z$ missed at node $j \in J$ on day $t \in T$.

The rest of the model notation is defined in Table 1. The model is as follows:

$$\text{Minimize} \sum_{j \in J} \sum_{t \in T} \left(\mu \theta_{CASEVAC,j,t} + \sum_{z \in Z^{sup}} \theta_{z,j,t} \right),$$

$$\text{subject to} \sum_{p \in P} \sum_{e \in E} \sum_{t \in T} \sum_{v \in V} r_{p,e} x_{p,e,t,v} \leq w; \tag{1}$$

$$\sum_{e \in E} \sum_{v \in V} x_{p,e,t,v} \leq f_{p,t}, \quad \forall\, p \in P, t \in T; \tag{2}$$

$$x_{p,e,t,v} = 0, \quad \forall\, p \in P, e \notin E_p, t \in T, v \in V; \tag{3}$$

$$\sum_{z \in Z^v} m_{z,e,t} \leq \sum_{p \in P} c_p^v x_{p,e,t,v}, \quad \forall\, e \in E, t \in T, v \in V; \tag{4}$$

$$m_{z,e,t} + \theta_{z,j,t} \geq d_{z,j,t} + \theta_{z,j,t-1}, \quad \forall\, z \in Z, e \in E, t \in T \backslash \{1\}; \tag{5}$$

$$\sum_{j:(i,j) \in E} m_{z,(i,j),t} = \sum_{k:(k,i) \in E} m_{z,(k,i),t}, \quad \forall\, z \in Z, i \in I, t \in T; \tag{6}$$

$$\sum_{z \in Z^v} m_{z,e,t} \geq x_{p,e,t,v}, \quad \forall\, e \in E, t \in T, v \in V; \tag{7}$$

$$x_{p,e,t,v} \in \mathbb{Z}^{\geq 0}, \quad \forall\, p \in P, e \in E, t \in T, v \in V; \tag{8}$$

$$m_{z,e,t},\ \theta_{z,j,t} \geq 0, \quad \forall\, e \in E, t \in T, z \in Z, j \in J. \tag{9}$$

The objective function minimizes the cumulative missed demand summed throughout the entire planning horizon. Inequality (1) enforces the "acceptable loss" restriction. Constraint (2) sets the maximum number of platforms available, while (3) and (4) enforce platform ranges and capacities, respectively. Constraint (5) ensures that demand is either fulfilled or accounted for as missed demand. This constraint also makes it so that any missed demand from the previous day is carried over to the next. Constraint (6) ensures that (supply) flow in equals flow out at intermediate nodes. Constraint (7) ensures that no platform travels empty of cargo. Constraints (8) and (9) enforce non-negativity and integrality as required.

5. Computational Results

We want to analyze whether the addition of AAVs increases the sustainment of forward deployed forces. To do so, we consider three different scenarios: No AAVs (I), Limited AAVs (II), and Broad Use of AAVs (III). Specifically, the total number of AAVs in each scenario is 0, 21, and 33 respectively, with the addition of larger AAVs only in III. For all scenarios, only one of each of the six traditional logistics platforms is available: UH-1Y Super Huey, CH-53K King Stallion, Maneuver Support Vessel Light (MSV-L), Landing Craft Utility, Logistics Support Vessel and Expeditionary Fast Transport; Traditional platforms have a crew size between 4 and 35.

We ran 11 iterations of each scenario with acceptable loss values of $w = 0, 5, 10, \ldots, 50$ to find at what levels the model experiences diminishing returns. It becomes harder for the model to minimize missed demand as more effort is made to limit risk, so military planners must choose at what point preventing casualties has a disproportionately large effect on resupply. At chosen w values, we compare scenarios I and III to see the day-to-day effects of implementing AAVs, and how missed demand differs with a low w versus a higher w. Lastly, to find the optimal mix of traditional and unmanned platforms, we produce an optimal daily deployment schedule for our fleet for a chosen scenario at a determined value of w.

Figure 2 shows the cumulative unmet demand on the y-axis and acceptable loss on the x-axis for each scenario. The red line represents all classes of conventional supplies combined, while the blue line represents CASEVAC demand. We see a decrease in missed conventional demand as acceptable loss (w) increases. However, it is clear that the addition of AAVs increases the sustainment of a stand-in force; the amount of missed demand at the same acceptable loss level is lower when AAVs are implemented alongside traditional logistics platforms.

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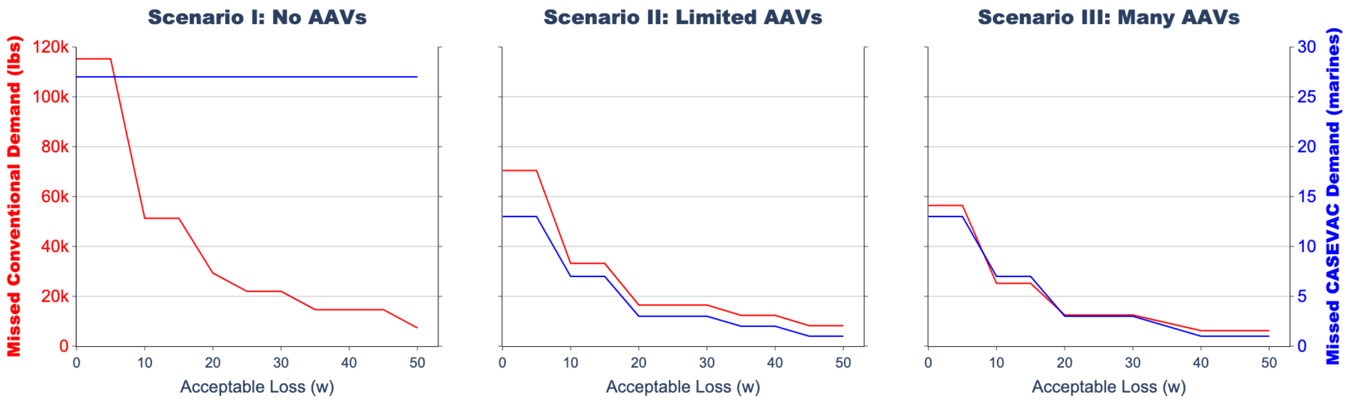

Figure 2: Acceptable loss versus missed conventional cemand (red) and missed CASEVAC demand (blue).

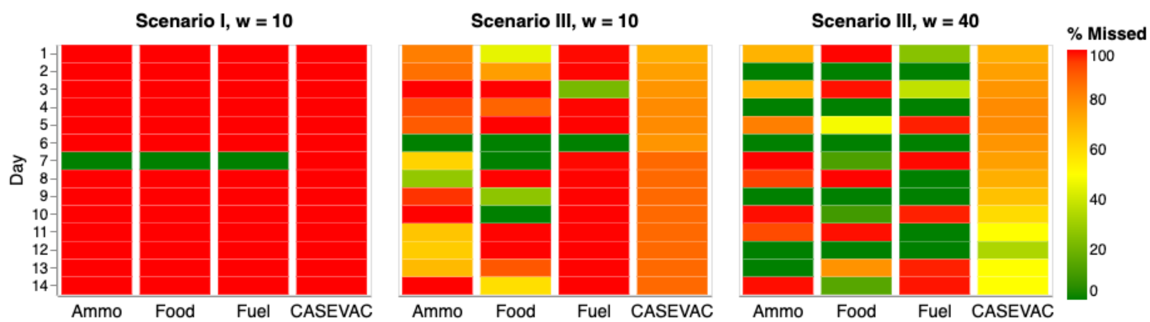

Figure 3: Percent of demand, including demand carried forward, that is missed on each day of the vignette.

CASEVAC demand is unmet in Scenario I but is rapidly fulfilled as soon as AAVs are introduced. This is because our model requires that platforms must be assigned to either resupply or CASEVAC. When we have a large fleet of AAVs, it is easier to account for this specialization; however, without AAVs, the model is dependent on much fewer, larger platforms. We could not generate an optimal solution that sacrifices a "ship's-worth" of resupply for CASEVAC because we set CASEVAC equivalent to 1,000 lbs of missed demand.

In Figure 2, there are two values of acceptable loss that are of interest. The first is $w = 10$. At this level, we see the first major jump in efficiency the end of 14 days. The second point of interest is $w = 50$. At this threshold, we saw a general plateau for both missed conventional demand and CASEVAC for scenarios II and III.

The graphs in Figure 2 show only missed demand (including carry-over from previous days) at the conclusion of the vignette. However, they do not show the level of resupply achieved throughout the 14-day cycle. To more closely compare scenarios, we consider daily missed demand calendars. Comparing the day-to-day impacts on resupply is an important consideration when determining whether or not to employ AAVs. Figure 3 shows the 14-day sustainment at $w = 10$ for Scenario I and $w = 10$ and $w = 50$ for Scenario III, displaying on which days the missed demand is the highest (in red) or the lowest (in green). The ratio of demand missed to demand requested, including any previously unmet demand, determines the percentage of sustainment achieved.

The missed demand calendars show trends similar to what we saw in Figure 2. Without AAVs, all daily demand requirements are virtually unfulfilled. We also see that conventional missed demand decreases slightly with AAVs, but significantly when w increases. CASEVAC demand is best met with both AAVs and a higher acceptable loss. This is because a higher risk tolerance allows for more traditional platforms to deliever supplies, allowing for even more AAVs to focus on CASEVAC.

The missed demand calendars show how the model adapted to "real-world" challenges. The vignette included many requirements for the first week: replacing the destroyed NMESIS weapon systems, delivering additional medical supplies, and evacuating more critical CASEVAC cases. The model schedules large numbers of drones during the first days to fulfill the emergency CASEVAC demand, followed by large platforms to make up for the accumulated missed demand to meet mission deadlines. Therefore, we see a period of "green" resupply around the end of the first week because the logistics fleet meets the required demand while no longer being burdened by additional tasks.

Our second research question was to find the optimal mix of AAVs and traditional logistics platforms in a given scenario. As Operations Analysts, we can provide the optimal deployment schedule that aligns with the decisions made based on the analysis from the previous sections (allotted fleet of AAVs and chosen threshold for w). We can advise military planners about how AAVs will influence mission success and then output a schedule that optimally deploys platforms for each day. For example, the following is the assignment of missions (vehicles to edges) on Day 2 of scenario III with $w = 50$:

Table 2: Platform Schedule for Day 2, Broad Use of AAVs, w = 50

Edge	CASEVAC	Platform
(4:2)	Yes	V-Medium B
(4:2)	Yes	S-Large A
(4:3)	No	MSV-L
(3:2)	No	V-Small B, V-Medium A, V-Large A, E-Medium A (16), E-Large B (4)

One interesting result is that there were instances where the model selected a large platform to transport supplies to the intermediate node, and then AAVs to complete the trip to the contested island. Recalling back to our risk equation, this is because we take into account the geopolitical safety of the water through a risk multiplier R_e, as well as the duration of each mission. The trip from the source to the intermediary node is safer; therefore, it is better to use one large ship. AAVs should make the more dangerous journey directly to the contested island. This happens on day 2 (Table 2) when a Maneuver Support Vessel Light (MSV-L) travels from Island 4 to Island 3, then a fleet of drones finishes the delivery to the MLR on Island 2.

6. Conclusion

As demonstrated by our results, traditional platforms alone are not sufficient to support a survivable force during a heightened conflict with a peer adversary in the INDOPACOM. AAVs are a viable alternative that limit the risk to personnel when resupplying a stand-in force. We introduced the concept of risk to consider how AAVs impact the trade-off between mission success and acceptable loss. However, there are drawbacks to AAVs as well: mostly AAV's smaller load capacity and max range make traditional platforms still necessary in intra-theater logistics. Therefore, our model shows the benefits of a mixed approach of AAVs and traditional platforms. Through missed demand calendars, our model demonstrates increased sustainment of forward deployed forces and develops an optimized schedule to route available platforms in a given scenario.

Our model is limited in certain areas. While it creates an optimized platform schedule, it does not allocate resources to individual platforms. Instead, it uses the maximum capacity of all deployed platforms to track demand delivered. In addition, the model assumes perfect vehicle availability without maintenance downtime, repositioning, or mechanical failure. Lastly, the model standardizes CASEVAC and material resupply (1 CASEVAC = 1,000 lbs of supplies), which in its current tradeoff does not cause one to be prioritized over the other. We see how this becomes an issue in Scenario I when the demand for CASEVAC is never fulfilled. In real life, a marine in need of medical attention would never be left to die because saving them is "suboptimal". For future work, we hope to incorporate maintenance days into the platform availability parameter, providing a more realistic model of operation tempo. Additionally, we would like to introduce platform requests: as most mission planners have to ask a higher command for vessels to be made available to them instead of having a predetermined fleet at their disposal.

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