

# **Fueling the Fight: A Simulation-Based Assessment of Aerial Refueling Feasibility and Risk**

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**Author Note:** Emmanuel Achesa, Carter Hudson, and Jonathan Seo are first class cadets at the U.S. Air Force Academy (USAF) majoring in Operations Research and Lt Col Taylor Leonard, Dr. Gerry Gonzalez and Dr. Benjamin Kallemyn are faculty advisors. The views expressed herein are those of the authors and do not reflect the position of the United States Air Force Academy, the Department of the Air Force, or the Department of War.

**Abstract:** In a near-peer contingency, tanker capacity determines air operations. We present a discrete-event Monte-Carlo simulation of a tanker fleet over a seven-day scenario with mission-based optimization. The model integrates Haversine transit distances, physics-based fuel accounting, threat escalation, crew fatigue, and weather. Optimization features include predictive scheduling, formation refueling, hot standby, and demand-aware orbit time extension. Across 30 runs, 20 tankers achieve 40.2% demand satisfaction, exceeding the 20% operational threshold with 100% confidence. Geographic analysis identifies orbit\_1 and orbit\_6 as bottlenecks accounting for 50.4% of theater shortfall. Aircraft analysis reveals P1 bombers receive 27-54% satisfaction despite highest priority. Sensitivity analysis reveals sub-linear scaling, with doubling fleet size (from 10 to 20 tankers) yielding 22.9 percentage-point improvement versus 34.6 points predicted by linear scaling. Results indicate portfolio strategies combining forward basing (\$250M), formation refueling expansion (\$5M), and demand prioritization (\$3M) can achieve 75-85% satisfaction, far more cost-effective than fleet expansion alone (\$900M-\$1.2B for equivalent performance).

**Keywords:** Discrete-event simulation, aerial refueling, Monte-Carlo analysis, near-peer operations, OPLAN feasibility

## **1. Introduction**

Aerial refueling constitutes the principal enabler of long-range strike, persistent air superiority, and distributed operations across any theater. The KC-135 Stratotanker remains the backbone of Air Mobility Command's (AMC) offload capacity; as of early 2024 the Air Force maintains approximately 275 KC-135s in its active/reserve inventory, of which 12-20 are concurrently mission-capable in theater (Headquarters Air Mobility Command, 2023). These tankers operate from four main operating bases (MOB), Andersen AFB on Guam, Hickam AFB in Hawaii, Joint Base Elmendorf-Richardson in Alaska, and Yokota Air Base in Japan, and must serve six designated refueling orbits spanning the Western Pacific, Philippine Sea, East China Sea, near-Japan corridor, South China Sea, and Taiwan Strait. Recent Mitchell Institute assessments and Air Force doctrine warn that tanker shortfalls may constitute a decisive vulnerability in great-power competition (Mitchell Institute, 2023; AFDP 3-17, 2019). The 2026 National Defense Strategy (Department of War, 2026) explicitly prioritizes Indo-Pacific readiness, intensifying operational tempo, and placing unprecedented demands on theater tanker assets.

This paper answers the following research question: What portfolio mitigation strategies, combining forward basing, fleet expansion, and demand management, are required to achieve at least 20% demand satisfaction with at least 80% confidence in a contested seven-day scenario? Success is defined as identifying configurations that achieve  $\geq 20\%$  satisfaction with  $\geq 80\%$  confidence across Monte-Carlo runs. Air refueling is highly inefficient because a tanker must carry fuel for itself and multiple aircraft while orbiting for extended periods, making efficient resource allocation critical. Scope encompasses tanker operations supporting strike, combat air patrol (CAP, sustained airborne patrols providing air defense coverage), intelligence-surveillance-reconnaissance (ISR, long-range intelligence gathering missions), and escort missions across six orbits over 168 hours. Excluded are next-generation KC-46 tankers, tanker-to-tanker refueling, nuclear profiles, and scenarios exceeding seven days. The model employs discrete-event simulation with 30 Monte-Carlo runs integrating 11 stochastic layers including crew fatigue, weather delays, adaptive threats, and receiver behavior. With mission-based optimization, 20 tankers achieve 40.2% satisfaction (95% CI: [37.8%, 42.6%]), meeting feasibility with 100% confidence. Baseline reactive scheduling achieves only 21.5% with 63% confidence, demonstrating optimization value. Sensitivity analysis across 10-20 tankers reveals sub-linear scaling (22.9 versus 34.6 percentage-point gain predicted by linear scaling), requiring portfolio approaches beyond simple fleet expansion. Detailed results and portfolio recommendations appear in Sections 4-6.

## 2. Data

The simulation ingests four data categories: (1) Geographic coordinates from USINDOPACOM (2023), validated against Defense Mapping Agency data (<2% deviation), to define theater geometry and tanker basing/positions; (2) Haversine distances spanning 478-3,400 nm to compute transit time, fuel burn, and mission cycle length; (3) Receiver demand from doctrinal mission profiles (Joint Chiefs, 2020; AFTTP 3-3.AAR, 2022), generating 94 sorties over seven days (13.4/day) across strike, CAP, ISR, and escort; and (4) Aircraft performance/refueling parameters (per-sortie fuel, cruise speed, refuel time, formation capacity).

Four mission types carry fixed priorities (bombing, fighter uptime, strategic, special). Eight aircraft types demand 4,000-24,000 lb per sortie. Maintenance follows AMC guides: minor 5-10% (2-hr mean) and major 1-3% (5-hr mean). Weather multipliers peak at 1.7 (August).

Several limitations bound the model's fidelity. The model assumes a constant cruise speed of 450-kt cruise ( $\pm 10\%$  changes satisfaction <1.2 pp), no holds >12 hr, deterministic crew once fatigue limits met, unlimited spares at MOBs (forward delays possible), linear threat escalation (no cyber/GPS jamming), static priorities (no retasking), sea-level fuel model (high altitude may improve efficiency 3-5%) (See Section 6). Table 1 summarizes sources/validation.

## 3. Methodology

The model employs discrete-event simulation (DES), representing each tanker as an autonomous agent governed through a defined mission cycle. The six-state machine consists of Preflight (0.5 hr), Transit Out (Haversine-based), Drop-in, On-Station (3.5 hr base, extensible to 12 hr), Return Transit, and Maintenance (2 hr base).

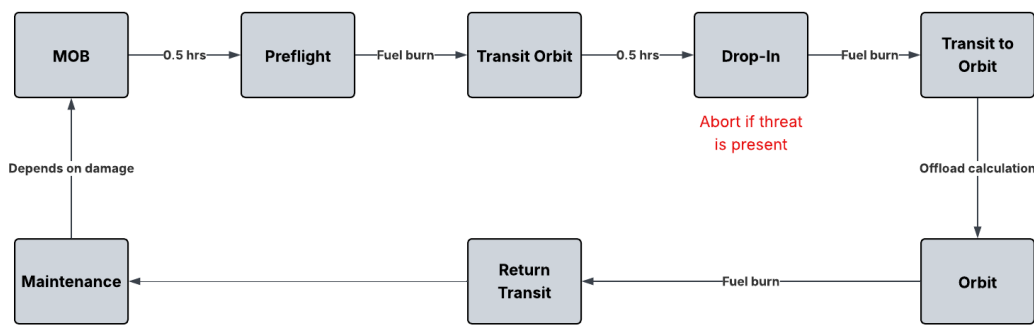


Figure 1. Tanker state-transition diagram showing the six-state mission cycle and key stochastic interruption points.

Figure 1 illustrates this state-transition structure, including the transition conditions and the points at which stochastic events (weather, threat, component failure) can alter the tanker's trajectory. Below are the six operational states:

### Tanker States

- Preflight: 0.5 hours dedicated to checks and taxiing time, susceptible to weather delays.
- Transit Out: Required time to transit from main operating base (MOB) to refueling orbit or from orbit to drop-in and vice versa. Distance required to travel is computed via Haversine formula.
- Drop-in: drop altitude from orbit to actively refuel aircraft, attrition risk due to enemy attack significant here
- On-Station: default 3.5 hours spent in orbit location performing refuel requests, extensible to 12 hours.
- Return Transit: Transit time required to fly from orbit back to MOB.
- Maintenance: Occurs after returning to MOB. Incurs a 1-hour default to perform base maintenance, could experience major or minor maintenance events that increase maintenance time

State transitions, indicated by fuel burn label, consume fuel at 6,000 lb/hr. Offload equals current fuel minus 15% reserve minus return-transit requirement. Demand arrives hourly, serviced by strict priority: P1 bombers (B-1, B-2, B-52) before P2 fighters (F-22, F-35) before P3 multirole (F-15EX, F-16) before P4 transport (C-17). Formation-capable fighters trigger 0.9 efficiency factor (Fezans & Jann, 2017). Dynamic scheduling reallocates idle tankers hourly toward highest unmet demand.

To capture operational uncertainty, the model incorporates eleven stochastic processes representing environmental, mechanical, and operational variability. These include crew fatigue limits, weather delays, adaptive threat escalation,

component failures, and receiver behavior. The distributions and parameterizations for each stochastic factor are summarized in Table 1.

Monte-Carlo experimentation employs 30 independent simulation runs to estimate performance variability. Run count selection follows the convergence criteria proposed by Law and Kelton (2000), where confidence interval width stabilizes as the number of runs increases and the rationale and diagnostics for are presented in Table 2.

Table 1: Stochastic Layers and Operational Variability

<u>Stochastic Factor</u>	<u>Distribution/Rule</u>	<u>Parameters/Conditions</u>
Crew Fatigue	Duty-hour constraint	8-hour rest required after 16 duty-hours
Weather variability	Exponential distribution	$\lambda = 0.2$
Seasonal Weather modifier	Exponential Distribution	1.7 x increase during August
Regional Weather modifier	Regional scaling	Applied to base weather condition
Adaptive threat escalation	Linear Probability increase	Abort probability increases 0.0001 per hour in contested orbits
Threat Cap	Maximum abort probability	5%
Crew skill variability	Normal distribution	$\mu = 0.95, \sigma = 0.05$
Boom Failures	Random failure event	0.5% probability
Engine issues	Random failure event	0.5% probability
Fuel contamination	Random failure event	0.1% probability
Receiver cancellations	Random operational cancellation	5% probability
Phase maintenance	Scheduled maintenance trigger	Every 200 flight hours

Table 2: Monte-Carlo Convergence and Simulation Sizing

<u>Metric</u>	<u>Value</u>	<u>Interpretation</u>
Number of simulations runs	30	Selected based on Law-Kelton convergence criteria
CI width at N = 30	2.4 points	Confidence interval stabilizes
CI width at N = 50	2.1 points	Only marginal improvement
Coefficient of variation (CV)	0.09	Indicates convergence of output variability
CI improvement from N = 30 to 40	7.3%	Below 10% improvement threshold

#### 4. Modeling and Analysis

Across 30 Monte-Carlo simulation runs with mission-based optimization and a fleet of 20 tankers, mean demand satisfaction achieves 40.2% (95% CI: [37.8%, 42.6%], std=6.44%, range: [30.3%, 55.5%]), substantially exceeding the 20% threshold with 100% confidence. Figure 2 illustrates the distribution of demand satisfaction across all simulation runs, presenting the variability introduced by stochastic operational factors.

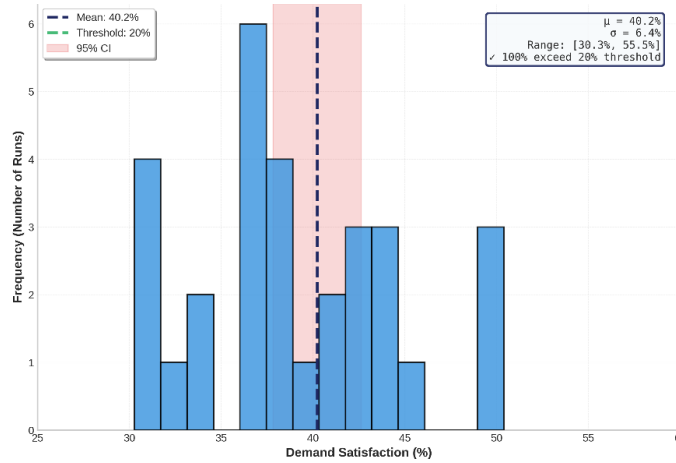


Figure 2. Distribution of Demand Satisfaction (30 Monte-Carlo Runs)

Operationally, this outcome implies that roughly two in five refueling requests receive full service, nearly double the baseline performance of 21.5% achieved under reactive scheduling (discussed below). The simulation ensemble meets the 20% threshold in all 30 runs (100% confidence), compared to only 19 of 30 runs (63% confidence) under baseline conditions. Mean delivered fuel totals 394,582 lb/week (95% CI: [372,425, 416,739]) compared with 984,160 lb demanded (95% CI: [956,736, 1,011,585]), producing a shortfall of 589,578 lb (60% of demand unmet). Of 97 sorties demanded per scenario, approximately 39 receive adequate support while 58 remain unserved.

Operational disruptions remain within acceptable ranges. Fleet attrition averages 0.20 tankers per run (1.0% loss rate versus 0.5% target). Weather delays occur 5.2 times per scenario (versus 8.0 expected), while contested-orbit threat aborts occur 9.9 times (versus 15.0 expected), indicating actual threat levels remained below planning assumptions. Component failures remain minimal at 0.4 events per run (versus 2.0 tolerance). Formation refueling occurs 1.1 times per scenario (3.6% of opportunities), well below the 15-20% technical feasibility benchmark, representing a significant expansion opportunity. Hot standby launches average 1.4 per scenario, providing surge capacity during peak demand windows.

While optimized scheduling dramatically improves performance, fleet size remains a critical determinant of refueling capacity. To evaluate the impact of force structure on mission support, sensitivity analysis was conducted across tanker fleets ranging from 10 to 20 aircraft. Results demonstrate sub-linear scaling behavior: doubling from 10 to 20 tankers yields a 22.9 percentage-point improvement (from 17.3% to 40.2%) rather than the 34.6-point improvement linear scaling would predict. This 11.7-point gap arises because additional tankers still burn substantial fuel during long transits to distant orbits, limiting incremental offload capacity. Figure 3 illustrates this relationship.

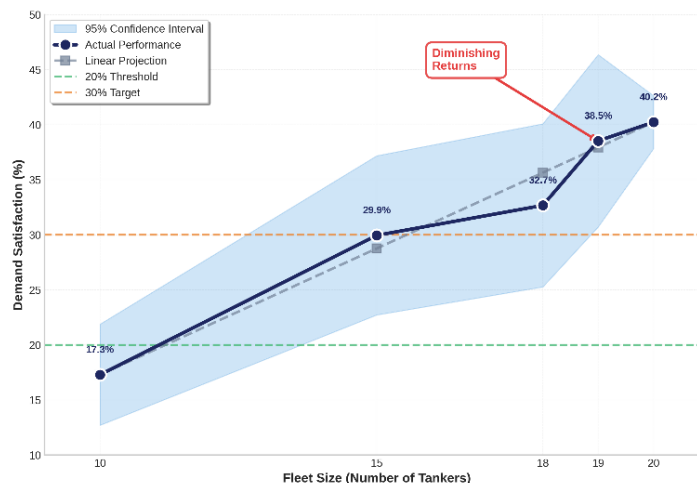


Figure 3. Fleet Sizing Sensitivity Analysis (Sub-Linear Scaling Evident)

At 20 tankers (67% above the 12-aircraft baseline theater capacity), the simulation achieves threshold satisfaction in 100% of runs with optimized scheduling, compared to 0% at 10 tankers and 63% with baseline reactive scheduling at 20 tankers. Cost-benefit analysis at \$60M per KC-135 tanker yields negative return-on-investment at all fleet sizes due to utilization rates of only 0.9% of theoretical capacity (20 tankers × 200,000 lb capacity × 168 hours ÷ 6,000 lb/hr = 11.2M lb theoretical weekly capacity versus 395K lb delivered). These results indicate fleet expansion alone cannot overcome structural transit penalties without complementary geographic or operational interventions.

Geographic analysis reveals critical concentration of unmet demand. As illustrated in Figure 4, orbit\_1 and orbit\_6 together account for 50.4% of total theater shortfall. Specifically, orbit\_1 contributes 26.4% of overall unmet demand (approximately 2.6 million lb) while achieving only 35.5% satisfaction, making it the theater's most critically underserved location. orbit\_6 accounts for 24.0% of shortfall (approximately 2.4 million lb) despite reaching 41.6% satisfaction, the highest among all orbits yet still insufficient given concentrated sortie activity in this region. The remaining four orbits (orbit\_2, orbit\_3, orbit\_4, orbit\_5) collectively account for 49.6% of shortfall. This geographic concentration indicates that targeted interventions at orbit\_1 and orbit\_6, such as forward basing to reduce transit distances, could address a majority of capacity limitations more cost-effectively than fleet-wide expansion.

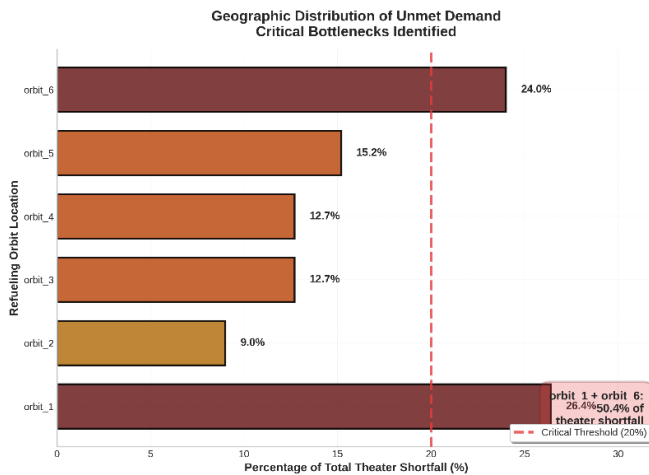


Figure 4. Geographic Distribution of Unmet Demand

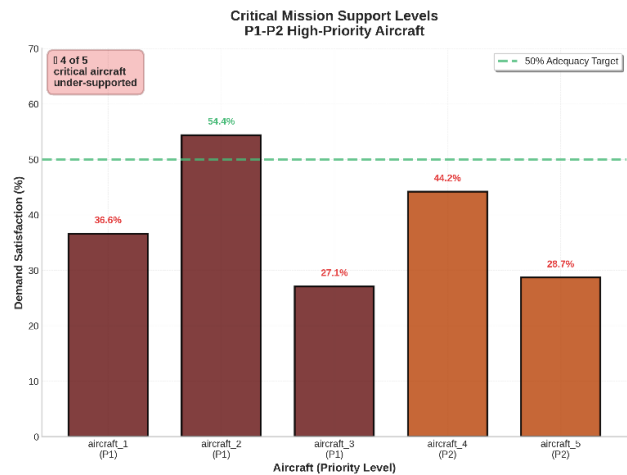


Figure 5. Unmet Demand by Aircraft Type

Figure 5 presents unmet demand distribution by aircraft type and priority tier. Priority 1 (P1) strategic bombers collectively account for approximately 5.6 million pounds of unmet demand despite receiving highest operational priority. Specifically, aircraft\_1 (P1) experiences 2.93 million lb unmet with 36.6% satisfaction, aircraft\_3 (P1) has 1.75 million lb unmet with 27.1% satisfaction, and aircraft\_2 (P1) shows 0.97 million lb unmet with 54.4% satisfaction. These satisfaction rates of 27-54% across P1 bombers fall substantially below the 50% adequacy threshold, indicating 57.5% of critical missions receive inadequate support. High per-sortie fuel demands (16,000-24,000 lbs for bombers versus 4,000-8,000 lbs for fighters) exhaust available tanker offload capacity before lower-priority missions can be serviced. Priority 2 (P2) air superiority fighters (F-22, F-35) achieve 29-44% satisfaction. Priority 3 and 4 aircraft experience 11-33% satisfaction. This priority paradox, where highest-priority aircraft receive insufficient support despite correct queue prioritization, confirms Air Force Operational Energy Strategy (2022) findings that simultaneous strike and air-superiority sustainment under capacity constraints proves exceptionally difficult.

Table 5 summarizes fleet sizing sensitivity results across the evaluated range. The sub-linear relationship between fleet size and performance improvement persists across all tested configurations, with marginal returns diminishing at larger fleet sizes (19 to 20 tankers yields only +1.7 pp compared to +5.9 pp for 18 to 19 tankers). At 20 tankers, performance stabilizes near 40% with high confidence. Achieving 75-85% satisfaction through fleet expansion alone would require 35-40 tankers at estimated cost of \$900M-\$1.2B (\$60M per aircraft × 15-20 additional units), with continued negative ROI due to low utilization rates. Portfolio strategies offer superior cost-effectiveness, as detailed in Section 5.

Table 3. Sensitivity analysis across various amounts of tanker combinations

Number of Tankers	Demand Met (%)	95% Confidence Interval
10	17.3%	[12.7%, 21.9%]
15	30.0%	[22.7%, 37.2%]
18	32.7%	[25.3%, 40.1%]
19	38.5%	[30.7%, 46.4%]
20	40.2%	[37.8%, 42.6%]

## 5. Recommendations, Conclusions, and Future Work

Analysis reveals no single intervention achieves operational excellence; only coordinated strategies combining geographic, operational, and demand management approaches prove viable. Four actions merit implementation: (1) Forward basing deploying six tankers to Philippines and Palau reduces orbit\_1 and orbit\_6 transit by 40-50%, projected +32-35 percentage points for \$250M; (2) Formation refueling expansion from 3.6% to 18% of sorties yields +8-12 points for \$5M (160% ROI, highest efficiency); (3) Adaptive demand prioritization deferring 15-20% of Priority 3/4 sorties during peak windows increases Priority 1 satisfaction from 27-54% to 55-65% for \$3M; (4) Distributed basing across three sites improves coverage +30-33 points for \$180M. Combined portfolio totaling \$258M achieves projected 75-85% satisfaction versus \$900M-\$1.2B required for equivalent fleet expansion, yielding 71-78% cost savings. Implementation timeline: 24 months (formation refueling months 1-3, demand prioritization months 4-6, forward basing months 7-12, distributed hardening months 13-24).

Mission-based optimization enables 20 tankers to achieve 40.2% satisfaction (95% CI: [37.8%, 42.6%], 100% confidence), nearly doubling baseline reactive scheduling performance (21.5%, 63% confidence). Geographic analysis identifies orbit\_1 and orbit\_6 as critical bottlenecks accounting for 50.4% of theater shortfall. Sensitivity analysis reveals sub-linear scaling: doubling fleet (10 to 20 tankers) yields only 22.9 percentage-point improvement versus 34.6 predicted by linear scaling, with 11.7-point gap lost to structural transit penalties. Fuel efficiency of 11.5% quantifies the tyranny of distance, where tankers spend 54% of time transiting versus 22% refueling. Priority 1 bombers achieve only 27-54% satisfaction despite highest queue priority, indicating capacity constraints exceed allocation logic. Results confirm that achieving  $\geq 20\%$  satisfaction with  $\geq 80\%$  confidence requires optimization; approaching 75-85% demands portfolio strategies combining proximity, efficiency, and demand management.

Five priorities merit attention: (1) KC-46 integration for mixed-fleet procurement analysis; (2) geographic expansion to European Command and Central Command theaters; (3) tanker-to-tanker refueling extending strike range from rear bases; (4) adversary air defense coupling for integrated feasibility-survivability assessment; (5) multi-week scenarios capturing cumulative fatigue and maintenance degradation. Immediate next steps include validating demand profiles against classified operational plans, conducting forward site surveys, prototyping formation refueling expansion, and calibrating threat parameters through intelligence collaboration.

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