NAVAL POSTGRADUATE SCHOOL

OA4602 JOINT CAMPAIGN ANALYSIS

Constructing Anti-Submarine Warfare Requirements for the Carrier Air Wing of 2045 through Simulated Operations

This analysis is an unclassified demonstration only. All weapons and system capabilities are represented by unclassified parameters.

BY

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1 Future Carrier Operations

The American super carriers (CVN) has served as a means to project power onto land. Illustrative examples of power projection include carrier operations in support of Operation Desert Storm in 1991, Operation Allied Force over Kosovo in 1999, Operation Inherent Resolve against ISIS, and most recently Operation Prosperity Guardian against the Houthi forces in Yemen. However, by 2045 if America finds itself operating in a contested ocean, the carrier air wing (CVW) embarked on a CVN must be able to support the security of the sea lanes of communication for friendly forces (merchant marine convoys, surface combatants, etc.) while denying the sea to adversaries (from the air, surface, and subsurface attack vectors). How, then, should the composition of the CVW of this future scenario be built to accomplish this task?

2 Building the CVW for 2045

2.1 Tasking

A team of officers at the Naval Postgraduate School during their Joint Campaign Analysis course was tasked with developing a new CVW for such CVN operations in this articulated 2045 scenario. Put more simply, the goal is for the CVW to provide sea control out to 750 nautical miles (nm) around the CVN. It should be said as well that the tasking also allowed for the inclusion of in-development concepts and technology one can reasonably expect to be fielded by 2045 when building the CVW.

2.2 Approach

The approach taken was to iterate on an optimization model attempting to maximize the warfare ability and range of the CVW while solving for key constraints and requirements. The iterations included solving the optimization, checking the underlying assumptions and platforms with publicly available information, and refining the model until a simple, powerful CVW with reasonably defensible assumptions was reached. The iterative approach and optimization attempted to ensure adequate platform allocation for the critical support roles like intelligence, surveillance and reconnaissance (ISR) and command and control (C2) elements of the CVW, while also trying to maximize a measure of effectiveness (MOE) developed for the project referred to as Adjusted Warfare Efficiency (AWE).

2.3 Adjusted Warfare Efficiency

The AWE equation is below and serves as a metric of "scoring" aircraft in terms of their range (R), endurance (E), payload capacity (P), and an aircraft's warfare capabilities by multiplying them all together. The warfare capabilities seen below are anti-air warfare (AAW), anti-submarine warfare (ASW), and anti-surface warfare (ASuW) and are either a 1 if the aircraft can support or a 0 if the aircraft cannot. Then the equation allows for some flexibility with the tuning parameters α, β, and λ that can give more importance to different warfare areas, but for the project these weights are all set to 1.

$$AWE = \sum_{\text{CVW aircraft}} (R \times E \times P) \times \frac{(ASW \times \alpha + ASuW \times \beta + AAW \times \lambda)}{(ASW + ASuW + AAW + 1)} \tag{1}$$

AWE is a stand-in metric developed during the project in order to try to give large scores to CVW compositions which included aircraft delivering the most payload, at the furthest range, for the longest time, and against as many target types as possible. This AWE metric necessarily assumes that to ensure sea control out to more extreme ranges, the CVN will require aircraft that can remain on-station for long periods of time with a dynamic set of capabilities.

2.4 CVW 2045

Given the iterative approach the team pursued, along with the constraints on their design, they ultimately arrived at the below CVW composition. This CVW only includes one platform currently within the CVW, the F-35, and includes multiple aircraft that are in development and can be reasonably expected to be in the fleet themselves, or perhaps a similar platform, by 2045. Appendix C includes details on the platforms included in the teams proposed CVW.

Primary Function	Aircraft	Manned (Y/N)	Current		Proposed	Proposed % of CVW
AAW, AsuW	Collaborative Combat Aircraft (CCA)	N	0	→	**48**	55%
ASW	MQ-9	N	0	→	**6**	7%
Refueling/C2/AWAC	MQ-25	N	0	→	**5**	6%
ISR/C2	Global Observer	N	0	→	**5**	6%
AAW, ASuW	F-35C	Y	12	→	**24**	27%
AAW, ASuW	F-18	Y	36	→	0	0%
ASW	SH-60	Y	6-10	→	0	0%
Logistics	CMV-22	Y	3	→	0	0%
AWAC	E-2	Y	6-10	→	0	0%

Legend for Cell Colors
New aircraft not in current CVW
Aircraft in current CVW, but number is changing
Aircraft in current CVW that are removed

To illustrate the differences in terms of the MOE for this project, the AWE scores are shown below. The 2045 CVW developed by the team of officers has **7 times greater AWE** than that of the current CVW.

AWE Scores	
Current CVW	*2045 CVW*
20,000	**140,000**

Appendix A shows the optimization model utilized and includes details on the constraints and assumptions made during the iterative optimization process that were not explicitly stated here.

3 Stress Testing ASW Capability

3.1 Initial Assumptions

One of the constraints in the optimization model was a minimum number of aircraft supporting the ASW mission was set to 6. Additionally, the aircraft chosen for ASW support was an adapted MQ-9 drone called the MQ-9B SeaGuardian (pictured below).

The MQ-9 platform is commonly associated with its long endurance ISR and precision strike missions in support of ground operations[1]. The minimum number of 6 was chosen heuristically, and not derived with any quantitative rigor beyond the basic assumption was that 6 long endurance drones like the MQ-9, could reasonably maintain contact with 3 submarines within the 750 nm range, assuming the MQ-9's worked in pairs allowing one aircraft to be flying to/from the sub or receiving maintenance on board the carrier, while the other is on-station over the submarine. This is obviously a simple assumption and putting some analytical rigor toward quantifying if this is at all reasonable is worth the effort, especially if we are defending our recommendations to a decision maker in charge of building this future CVW.

3.2 Discrete Event Simulation

The method with which one can apply some rigor to the ASW assumptions is by simulating ASW operations from a carrier. The simulation method chosen is a discrete event simulation[2], which has its best application

[1] Article detailing the development of the MQ-9B here: `https://www.twz.com/38843/new-pods-will-allow-reaper-drones-to-hunt-submarines-and-launch-small-weapons-and-drones`. Here is a fact sheet built by General Atomics: `https://www.ga-asi.com/images/products/aircraft_systems/pdf/mq9b-seaguardian-datasheet-feb2023.pdf`

[2] An introductory article to discrete event simulation can be found here: `https://softwaresim.com/blog/a-gentle-introduction-to-discrete-event-simulation/`. WikiPedia entry on discrete event simulation: `https://en.wikipedia.org/wiki/Discrete-event_simulation`

Figure 1: MQ-9B SeaGuardian by General Atomics

in systems that involve "customers" queuing such as a retail store or an emergency room (ER). The goal of this kind of simulation is to assess how well the current model of serving the customers holds up while capturing key metrics like average wait times, max wait time, max number of customers in a queue, etc. The key feature of this type of simulation is that it allows for probability distributions to be injected into the model for **capturing data more closely resembling real-world randomness**. For example, instead of making an ER model where each patient waits for exactly 15 minutes in the triage stage of the ER, a discrete event simulation can pull a random number for how long that wait time will be. This allows for the simulation to account for patients that get through quick and others that wait unusually long times, making the model to more accurately show what a real-life version of the ER looks like. The key thing underlying these simulations is also realistic assumptions for the probability distributions that the randomness will be drawn from.

3.2.1 Concept of Operations

In order to model ASW missions in the simulation, we must first develop a concept of operations. The basic concept of operations is that a submarine is located and an aircraft is sortied out to track the submarine, and once they reach their endurance limit they return to the carrier for refueling and post-flight maintenance. No attrition events are modeled for the submarine or the aircraft. We will make an assumption that at some point during the mission a second aircraft is sortied out to complete a hand-off and maintain continuous contact with the submarine. This concept can also be adapted to allow for in-flight refueling operations to extend the endurance of a sortied aircraft up to some refueling count limit.

To be more specific about how this concept can be modeled in a simulation lets follow the flight of one MQ-9B without any refueling. First, the submarine is "found" (*distance is randomly chosen*) and the MQ-9B flies to get into contact with the submarine (*speed of flight randomly generated*). Then, the MQ-9B loiters over the submarine to keep contact. The last 2 steps are the MQ-9B flying back (*again speed randomly generated*) and going "down" for post-flight maintenance (*a time value that will be randomly generated to account for variable maintenance times*). Additionally, within the simulation we will schedule the aircraft that will assume the hand-off from the aircraft currently on station at the submarine (*following the same sequence described above*). The sequence of one MQ-9 can be visualized in the below graphic.

3.2.2 Simulation Metrics

How could a simulation with this concept of operations help us understand the CVW requirements for maintaining submarine contacts? As we run a simulation tracking all the MQ-9B's flying back and forth and undergoing maintenance, we will also be tracking how many aircraft are being used at any given time during the simulation. The maximum number of aircraft being used during the simulation is the required amount of aircraft we would have needed to complete the operations as we have conceptualized them during a given simulation run.

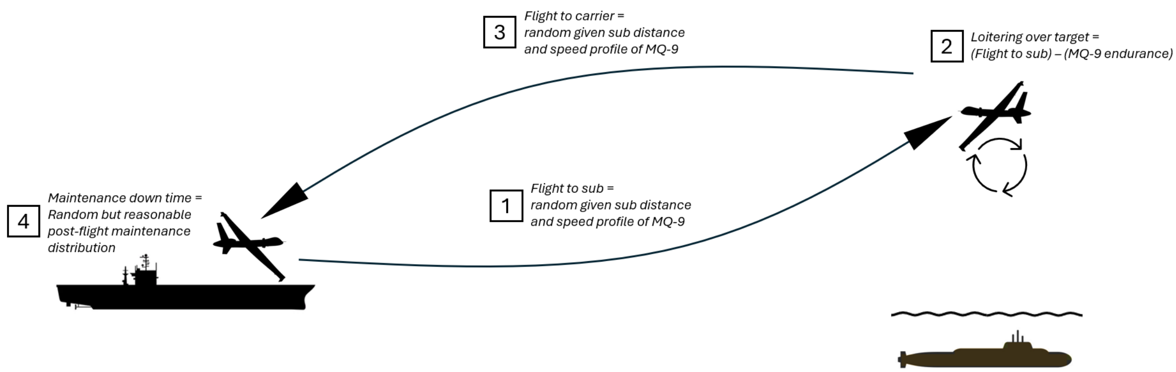
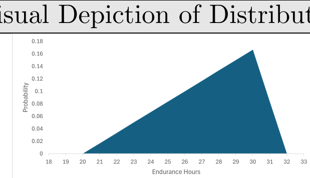
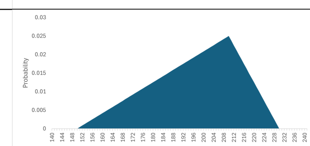
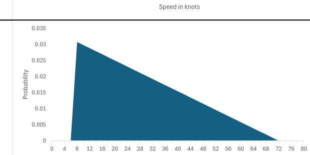
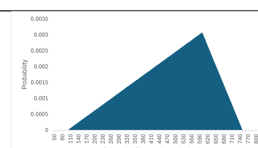


Figure 2: MQ-9B ASW Concept of Operations

3.2.3 Simulation Setup

Details on the simulation structure are in Appendix B and online in the GitHub repo for this project: `https://github.com/KurtPask/ASW_DES_Paper`. However, we should cover some of the main parameters here. Regarding the randomization of the simulation, a common probability distribution employed is a triangular distribution. They are very simplified stand-ins for more common distributions (like normal/Gaussian distributions) in discrete even simulations, because triangular distributions allow for explicit maximum and minimum random values, whereas other distributions can *theoretically* allow for near infinite random values that may break some underlying assumptions of the modeling process. The below table shows the triangular distributions utilized for the random values employed.

Table 1: Parameter Values

Parameter	Value/Distribution	Visual Depiction of Distribution	Source
Endurance	∼T(20, 30, 32) hrs		Mean from General Atomics
Speed	∼T(150, 210, 230) knots		Mean from General Atomics
Maintenance Time	∼T(7, 8, 72) hrs		Guess.
Sub Distance from CVN	∼T(100, 600, 750) nm		Derived from problem.

Assuming the concept of operations developed and employed in the simulation is correct, the best way to update any model like this would be to validate and change these underlying random distributions. For instance, the post-flight maintenance times modeled are unfortunately a relatively naive guess. The speed and endurance distributions derive their mode (peak of triangle) value from averages reported by General Atomics, but the edges of the triangles are also guesses. If we had historical data on maintenance, endurance, and speed, we could construct custom distributions based on reality and therefore better simulate that reality in our model.

The next key feature to mention of how we setup the simulation is that the operations covered a 4 week period. Beyond this, there are other specifics that can be reviewed in Appendix B.

3.3 Results of Simulation

The information we hoped to extract from the simulation was how many aircraft would be required to maintain the concept of operations built into the simulation as we vary the number of submarine contacts the CVW is tasked with maintained over a given period. Because we modeled 4 weeks of operations, we hoped to capture the relative highs and lows on the aircraft demands. In Figure 3, we can see some basic metrics captured by one run of the simulation over time. We can see by the orange line that we always have at least 10 aircraft on station over the 10 submarines with some overlap of aircraft as it jumps above 10 at times. The green line simply shows how many aircraft are en route to their assigned submarine over time. The blue line shows how many aircraft are either in the air or in a maintenance cycle as the simulation progress. The blue line data is what we are going to use to inform the decision maker on how many they should include in their CVW

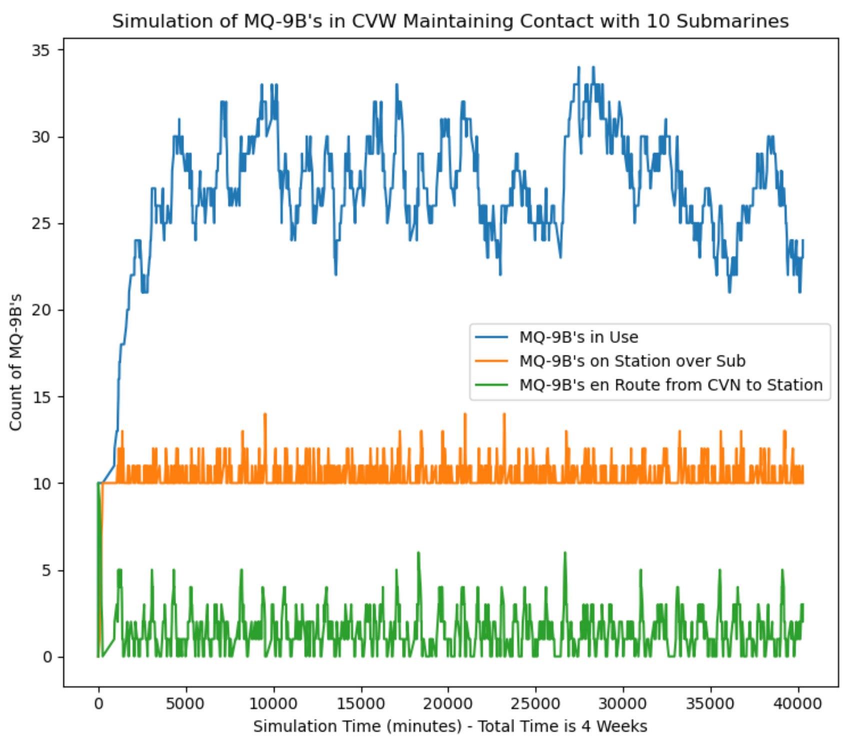


Figure 3: One run of the simulation with 10 submarine contacts over a 4 week period.

Given this setup and a sense of how the simulation runs based on Figure 3, we want to show a decision maker how many aircraft are required to provide a high percentage of mission coverage. Mission coverage being the percentage of instances in the simulation runs that a given number of aircraft could have satisfied the needs of the ASW mission modeled. An example would be if we had 10 aircraft and across 100 time snapshots in the simulation we needed more than 10 aircraft 20 times we would have 80% mission coverage ($1 - \frac{20}{100} = 0.8$ or 80%). In this case we chose 95% and 99% mission coverage as the level we want to report to the decision maker. The below figure shows how the simulation produces variable results on the amount of aircraft required given the number of submarine contacts while showing what is takes to have 95% and

99% percent mission coverage. The numbers are reported in partial aircraft, so the assumption should then be to round up to achieve that percentage of greater mission coverage based on this simulation.

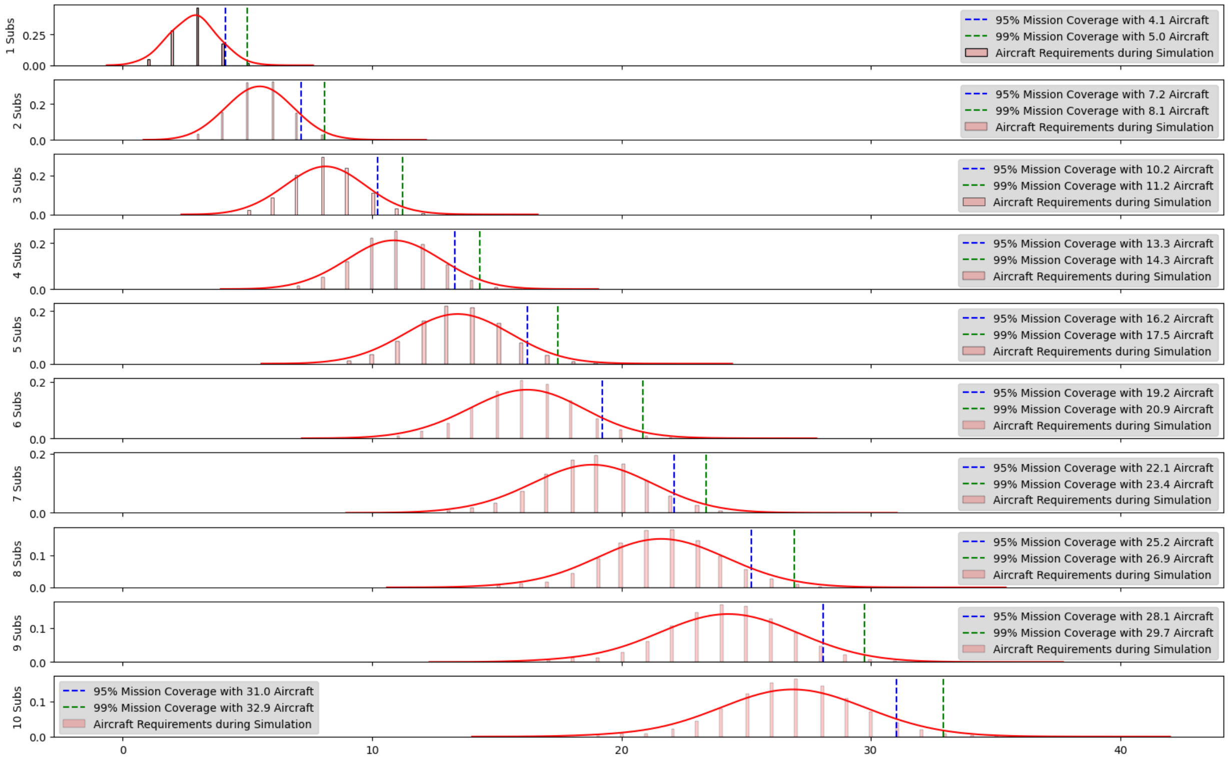


Figure 4: Histograms showing number of MQ-9B's required at any given time to maintain constant contact with given number of simulation contacts during 100 replications of the simulation at each level (total of 1000 simulations). Top plot shows MQ-9B requirement data from 100 simulations of a scenario with 1 submarine contact and the bottom plot shows the same, but for the scenario with 10 submarine contacts.

Figure 4 is a rich graphic, containing lots of information from 100 simulations at each of the 10 scenarios (*1 submarine contact in top plot and 10 submarine contacts in bottom plot*), but one could easily assess there is a linear relationship between the 95% and 99% values throughout the simulations. If we perform some post-simulation analysis and apply a simple linear regression to these 95% and 99% levels across the 10 scenarios shows the relationships in Equation 2 for 95% mission coverage and Equation 3 for 99% mission coverage. In both cases the R^2 value was nearly 1, indicating an almost perfect representation of the data the regression was fit on.

$$MQ9B_{count} = 2.99 \times (Submarines_{count}) + 1.24 \tag{2}$$

$$MQ9B_{count} = 3.10 \times (Submarines_{count}) + 1.93 \tag{3}$$

What does this mean for the decision maker? If we have guidance on how many submarine contacts our CVW needs to maintain contact with, and if this simulation is a decent representation of real operations, we should have about 3 times as many MQ-9B's as expected submarine contacts on board plus and additional 1 or 2 MQ-9B's to be able to maintain contact almost all of the time. If the decision maker is uninterested in the detailed reports from our simulations we could simply provide the below equations as our findings or our simplified version, provided we can say the simulation results are based on realistic operations and underlying probabilities of events.

4 Conclusions and Future Work

This white paper showcases how we can articulate a relatively simple concept of operations, build a simulation to test this concept over simulated time, and arrive at intuitive insights that can provide some quantitative rigor behind platform allocation decisions (*subs*3 + 2 ... easy!*). This process also allows for the decision maker and their team to easily tune the model and results to their mission needs and expert understanding. This makes this a dynamic approach that does not corner the decision maker or the analyst too much while also ensuring the answers provided to the decision maker are unambiguous and simple.

This model could also be easily extended to consider other aircraft with different underlying characteristics or a different concept of operations (especially if any assumptions made were wrong). This model could also be drastically improved with data-derived probability distributions (*not just triangle distributions*) that can inform the randomness of the simulation in a more realistic way.

There are lots of possible directions an analyst could direct and improve a project like this, but if nothing else, hopefully this showcased the benefit analysis this could be to the decision making process.

Appendices

A Optimization Model Utilized

Below is the NPS format of the problem that was solved using the Microsoft Excel Solver tool.

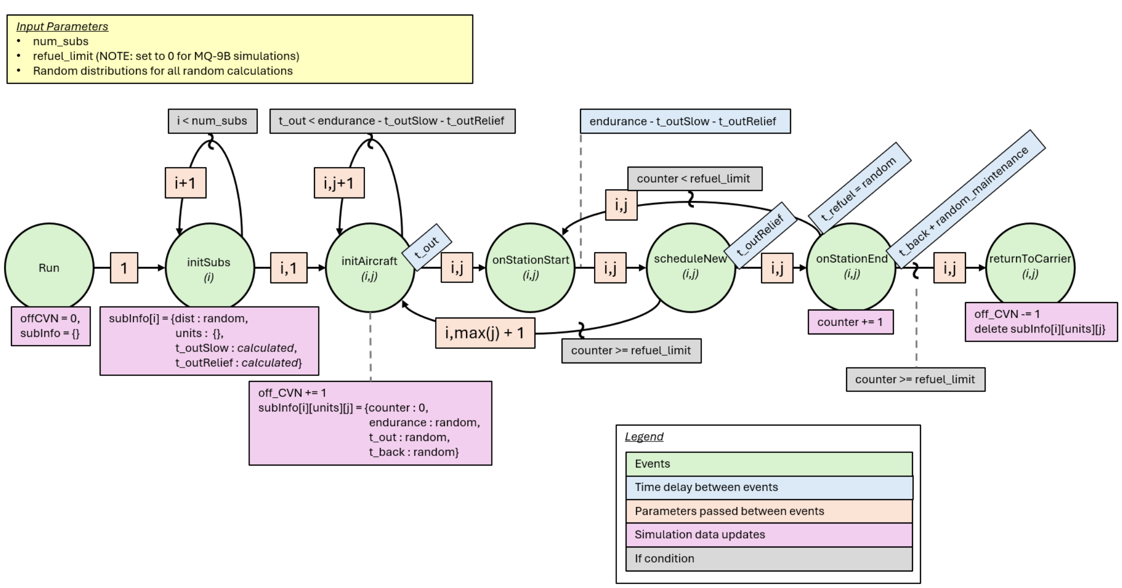
Index Use	$i \in I, \quad \text{where } I = \{ASuW, AAW, ASW, ISR, C2, Refueler, Manned\}$
	$j \in J, \quad \text{where } J = \{F-35C, MQ-9B, MQ-25, GlobalObs, CCA\}$
Given Data	$\text{capable}_{i,j}$, indication of whether aircraft j can support warfare area i, $0 = \text{no}, 1 = \text{yes}$
	range_j, range of aircraft j in nm
	endurance_j, endurance of aircraft j in hrs
	payload_j, weapons payload of aircraft j in lbs
Decision Variables	AIRCRAFT_j, number of aircraft type j in CVW
Formulation	$\text{maximize} \quad \sum_{j \in J} \text{AWE}_j$

$$
\begin{aligned}
\text{s.t.} \quad & \sum_{j \in J} \text{AIRCRAFT}_j \times \text{capable}_{\text{ISR},j} \geq 5 \\
& \sum_{j \in J} \text{AIRCRAFT}_j \times \text{capable}_{c2,j} \geq 10 \\
& \sum_{j \in J} \text{AIRCRAFT}_j \times \text{capable}_{\text{Refueler},j} \geq 5 \\
& \sum_{j \in J} \text{AIRCRAFT}_j \times \text{capable}_{\text{ASW},j} \geq 6 \\
& 2 \times \text{AIRCRAFT}_{\text{F-35C}} \leq \text{AIRCRAFT}_{\text{CCA}}
\end{aligned}
$$

B Discrete Event Simulation

The discrete event simulation was coded in Python using the DESPy package. All code and other files are hosted in a GitHub repository here: `https://github.com/KurtPask/ASW_DES_Paper`

Below is the event graph utilized in the simulation. This a common representation of discrete event simulation models and contains all the primary logic employed for this simulation.



C Platforms in the CVW 2045

F-35C

- Cost: $90 million
- Range/Endurance: 1,500 nm / 3 hrs
- Role: AAW, ASuW
- Status: In production/in fleet

Global Observer

- Cost: $57 million
- Range/Endurance: 15,000 nm / 144 hrs
- Role: ISR, C2
- Status: Prototype built and tested.
- Relevant article: `https://www.homelandsecurity-technology.com/projects/global-observer-unmanned-aircraft-system-uas/`

CCA

- Cost: $3-12 million
- Range/Endurance: 3,000 nm / 20 hrs
- Role: AAW, ASuW
- Status: Concept/Prototype in development. Relevant article: `https://www.airforce-technology.com/projects/collaborative-combat-aircraft-cca-usa/`

MQ-25

- Cost: $40 million
- Range/Endurance: 500 nm / 12 hrs
- Role: Refuel, AWAC
- Status: Testing with US Navy. Relevant article: `https://www.boeing.com/defense/mq25`

MQ-9B SeaGuardian

- Cost: $30 million
- Range/Endurance: 1000 nm / 20 hrs
- Role: ASW
- Status: Updated design in testing. Relevant article: `https://breakingdefense.com/2022/04/versatile-multi-domain-mq-9b-seaguardian-has-revolutionized-anti-submarine-warfare/`